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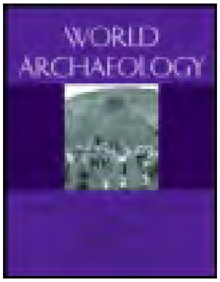

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If a picture is worth a thousand words…3D modelling of a Bronze Age tower in Oman

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If a picture is worth a thousand words… 3D modelling of a Bronze Age tower in Oman

Michael James Harrower, Kathleen M. O'Meara, Joseph J. Basile, Clara J. Hickman, Jennifer L. Swerida, Ioana A. Dumitru, Jacob L. Bongers, Cameron J. Bailey and Edwin Fieldhouse

Abstract

Three-dimensional imagery is rapidly transforming the reconstruction, visualization and conceptualization of ancient monuments. We report (and reflect on the value of) digital reconstruction of a third-millennium BC megalithic tower and surrounding landscape using a combination of architectural drawing, 3D photogrammetry and geographic information systems (GIS) mapping. Our results indicate that at least 181 metric tons of limestone (mean boulder weight 386kg) were hewn to create a monument 20m in diameter and at least 4m high. In addition to considering possible practical functions, including water extraction and a potential defensive purpose, we argue that this tower's central significance lay in its monumentality. At least sixty comparable Umm an-Nar period towers are known; and, as much as the model itself, the process of planning and executing a 3D model led us to recognize that a community of skilled builder/architects used a sophisticated mental template (with variation on a theme) to design and construct them.

Keywords

Oman; Arabia; 3D modelling; geographic information systems; photogrammetry; monumentality.

The 4,500-year-old Umm an-Nar (Mother of Fire) period towers of southeast Arabia (Figs 1 and 2) are among the world's least understood ancient monuments. More than sixty towers, some megalithic in construction, spanning 20 to as much as 40m in diameter and standing up to 8m tall, are known across the United Arab Emirates and the Sultanate of Oman (Cable and Thornton 2013; Potts 2012; Thornton, Cable, and Possehl 2013). This region, known in third-millennium Mesopotamian cuneiform as Magan (Glassner 1989, 1996, 2002), was an important node of maritime trade and nascent political complexity. Archaeologists have long recognized

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Figure 1 The Safri 1 tower looking east with cultivated date palm fields and mountainous terrain in the background.

the significance of ancient monuments (Osborne forthcoming; Scarre 2011), most notably as a central hallmark of ancient sociopolitical complexity (Childe 1950), as means to express claims to territories (Renfrew 1976), as costly and ostentatious symbols to promote the power and authority of leaders (Trigger 1990; Marcus 2003), and, perhaps less widely, as symbols of communal identity (Pauketat 2000). Emergent 3D imaging technologies now offer powerful means to generate advanced digital reconstructions for research, education and preservation in ways that complement traditional drawings and photographs and help us to evaluate alternative scenarios of design, construction, meaning and purpose (e.g. Favro 2006; Forte 2010; Gruen 2009; Pavlidis et al. 2007; Sullivan and Wendrich 2009; White 2013). Magan's ancient towers are very different from contemporary monumental architecture in neighbouring regions, such as temples and palaces in Mesopotamia or Iran, and therefore offer a unique perspective on the rise of early complex polities. Deeper understanding of Umm an-Nar peoples and their impressive towers, which encode a complexity of information and meaning, is thus central to understanding the dynamics of ancient Arabian complex polities and their similarities with and differences from societies elsewhere.

Towers and monumentality in ancient Arabia

What inspired ancient Magan's impressive towers? How were they designed, constructed and used? In many contexts worldwide ancient builder/architects designed and constructed substantial monuments, often without benefit of a writing system or sophisticated schematic drawings. It was not until very recently, in the eighteenth century AD, that the field of descriptive geometry – advanced means of drawing 3D objects in two dimensions – emerged. Yet as early as the Old Babylonian Period the Akkadian term *uṣurtu* referred to 'design, drawing, plan…plan of a building, traces of a building in

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the ground', and in one instance was used in a caption to a building design sketched on a clay tablet (Roth 2010, 290–1). Despite the interconnected, rapidly globalizing nature of the Persian/Arabian Gulf during the third millennium (Cleuziou and Méry 2002; Edens 1992; Potts 2009), Oman's Umm an-Nar towers are unique to the region yet highly standardized within genres that include megalithic, small-stone and mud-brick styles. This suggests an intricate common template in the minds of the builders/architects who designed and constructed them that predates evidence of writing in southeast Arabia or any vestige of architectural drawing.

In southeast Arabia, small-scale monument building traditions began around 3200 BC with highly visible individual and family tombs, known as Hafit tombs, which often mark the cliff lines of rugged mountainous landscapes (Frifelt 1975). By 2500 BC Hafit tombs had evolved in size and form, eventually giving rise to much larger, more carefully constructed Umm an-Nar tombs sometimes holding many hundreds of individuals (Blau 2001; Frifelt 2002a; Weeks 2010). Umm an-Nar tombs are most commonly found, not along cliff edges, but in lower-lying areas (Giraud 2009, 2010). The specifics of links between different tomb types, land, water and early agriculture form a topic of deep significance that warrants spatial analyses beyond the scope of this article (see Cable 2012; Cleuziou 2002; Deadman 2012; Harrower et al. 2013, forthcoming; Williams and Gregoricka 2013). Yet even a qualitative understanding suggests that Umm an-Nar tombs and towers often appear together in water-rich areas, signalling the importance of agriculture, mortuary practices, monuments and monumentality in the rise of early complex polities (Cleuziou 2001, 2007; Tengberg 2003, 2012; Potts 1994; Yule and Weisgerber 1998). Although approximately fifteen towers (including megalithic, small-stone and mud-brick styles) have been excavated since the early 1970s, archaeologists have yet to agree on why these towers were built or what they were used for (see, e.g., Cable and Thornton 2013; Cleuziou 1989, 2007; Frifelt 1989, 2002b; Gentelle and Frifelt 1989; Orchard 2000; Orchard and Orchard 2010; Possehl, Thornton, and Cable 2008, 2009, 2010; Potts 2012; Thornton, Cable, and Possehl 2013). A well can frequently be identified within towers, and ditches that sometimes surround towers may have, in some cases, been linked to irrigation systems (Cleuziou 2001; Frifelt 2002b; Orchard and Orchard 2010). The interior areas of the towers are sometimes divided by walls forming small compartments that could have been used for storing food or some other goods or commodities; alternatively these inner walls may have simply been built for structural purposes. Perhaps towers were storehouses for leaders who accumulated food and sought to control the water supply. Possibly they served a defensive purpose as refugia when oasis areas were attacked. Or maybe they were simply highly visible monuments that were meant to promote community solidarity, establish claims to territories or inspire devotion to emerging leaders. Better understanding of the precise layout and dimensions of the towers can assist in revealing their purpose and meaning and the skills required to envision and construct them. Yet megalithic-style towers are extremely difficult to excavate or physically reconstruct without heavy equipment to move fallen boulders, making digital modelling a productive means of recording and evaluating design schemes and alternatives of purpose and expression.

Methodology

With the support of the Sultanate of Oman Ministry of Heritage and Culture, the Archaeological Water Histories of Oman (ArWHO) Project from Johns Hopkins University

(JHU) and the Maryland Institute College of Art (MICA), conducted fieldwork in winter 2011–12 and winter 2012–13. We used 3D photogrammetry (measurement from photographs), traditional architectural drawing and satellite imagery to digitally reconstruct the megalithic tower known as Safri 1 in Yanqul, Oman (Yule and Weisgerber 1998, 197–9) and its surrounding landscape.

The megalithic nature of many towers of this period makes excavation difficult – we estimate that some of the largest blocks of Safri 1 weigh more than 2,200kg with an approximate average weight of 387kg. Moreover, moving blocks that have fallen or been dislodged could potentially endanger many towers because of their fragile structural and aesthetic condition, making digital reconstruction a superior first option even if actual reconstruction may later take place. Because the massive size and weight of blocks used to construct megalithic towers requires coordinated effort to move them, most blocks appear to be either still in place or less than 30m away (Fig. 2) from where they were set, providing an opportunity to digitally reconstruct the dimensions of the original structures. The fact that these towers are circular is also of particular significance: although an architect can easily draw a circle on paper with a compass, this radius-based layout is impractical even with today's survey equipment. It is not uncommon in contemporary practice to measure an array of parallel lines from a baseline in order to locate points along the circumference of a circle. Through analysis of siting (base and top elevations), geometry (circumference, radius, variations in stone types, sizes, courses) and architectural features (openings, and orientations relative to features of the surrounding landscape), our study examined design principles. We not only produced an advanced digital record of the tower but also gained a far better understanding of how ancient architects conceptualized the design and orchestrated the construction of these structures. Through this prototype methodology and work flow, the ArWHO team developed efficient means that we hope to use and improve to model other towers and reveal variability of layout, purpose and contribution to visual landscapes.

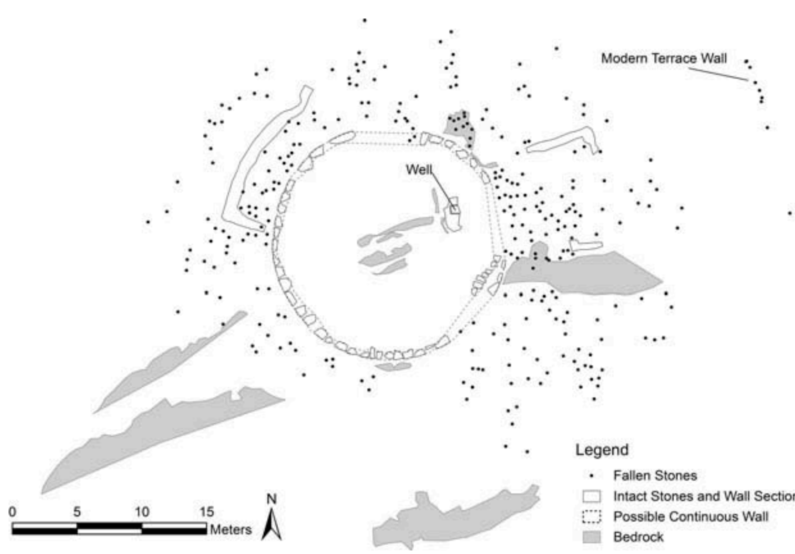

Figure 2 Plan map of Safri 1 showing areas of collapse, fallen stones and areas of surrounding bedrock.

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Our study digitally reconstructs the Safri 1 megalithic tower as a 3D model, using photo overlays on an underlying mesh. This was accomplished using 2cm accurate kinematic GPS mapping and a suite of 3D modelling software (EOS Photomodeler, Meshlab, Rhino and AutoDesk 3DS Max). The general approach employed Photomodeler to create a 3D point cloud from digital photographs that is similar to those created by laser-scanning technologies (Forte et al. 2012; Kersten and Lindstaedt 2012; Gruen 2009). First, it uses stereoscopic photo pairs to generate a three-dimensional point cloud by matching pixels in photograph sets and comparing their deviation in space. These photo sets can be ground or aerial-based, and are best taken from a camera that has been calibrated with the software. After creating basic 3D point clouds, Photomodeler subdivides points to create editable point meshes known as dense surface maps (DSM). Finally, these meshes can be triangulated into vector meshes and textured with source photos.

The following is a step-by-step description of our field methods with Photomodeler and subsequent software, including changes and adaptations we made while working with equipment and software. The process of experimentation with the software and shooting the tower took three people approximately one month with an additional three weeks of post-processing.

Step 1: calibrating camera and lens combinations

Photomodeler operates by calculating the distortion in photos taken with a particular lens. To do this, one must calibrate the lens by taking a series of photographs at different angles of a constant that the software can identify. This is done by using a series of RAD (ringed automatically detected) targets made in Photomodeler that can be customized for the type of project; we created nine sheets with a total of fifty-four targets (six per page) each with an inner diameter of 9mm. We then took a series of eight concentric photographs with each lens/camera combination from 360° around the calibration sheets, set up in a 3 × 3 block. These photo sets were run through Photomodeler which measures the effectiveness of a lens by giving numerical values for residual margins of error per pixel. The smaller the number, the more accurate results are likely to be in subsequent projects. We tested two cameras and four different lenses in different focal lengths (Table 1). We began in the field with the Nikon D80 camera and the fixed (prime) 35mm lens as it had the lowest residual, but eventually switched to the D80 and Tokina wide-angle lens because it succeeded in capturing the most information per photo.

Table 1 EOS Photomodeler camera/lens combination calibration residuals

Camera	*Lens*	*Results/Residual*
Nikon D80	Nikkor DX 35mm (f/1.8)	0.16
Nikon D80	Nikkor DX 17–55 (at 17mm)	5.35
Nikon D80	Tokina 1224 mm (at 12mm f/4.0)	0.35
Nikon D80	Tokina 12–24mm (at 24mm f/4.0)	N/A
Nikon D5100	Nikkor DX 18–55mm (at 18mm)	0.98
Nikon D5100	Nikkor DX 18–55mm (at 55mm)	1.84

Step 2: shooting the subject

Safri 1 tower sits at the north end of a ridge or fin of limestone bedrock where uneven ground and the height of the tower above surrounding terrain made it difficult to fully capture the tower and its relationship to the surrounding landscape. In initial trials, we tried shooting 10m sections, hoping to later combine smaller projects into a single whole. Although the Nikon D80 with the 35mm lens had the lowest residual, its narrow angle required a much larger set of photos which complicated processing. Photomodeler was able to recognize the curvature of the coursework but from the distance required to capture large sections of the tower we could not achieve the level of detail required and numerous gaps and voids were evident. After running many partially successful projects with many hundreds of photos with mostly minimal overlap and low depth range we decided to switch to the D80 with the Tokina wide-angle lens and use a monopod as a boom arm. Even with the higher residual, the wide-angle lens was able to shoot larger areas from more practical distances, while still giving us the amount of detail needed in each photograph. We also began to realize the role of lighting conditions, particularly the impact of soft versus hard light, and began shooting near dusk/dawn to reduce distortion, gaps and voids and obtain better colours and model textures. When processed in Photomodeler we had more complete results that had both breadth in scale and the desired amount of detail. After approximately two weeks of experimentation, shooting the entire 20m diameter tower became more or less formulaic and could be done in less than three hours.

Step 3: processing photos

Running a project in Photomodeler involves a series of steps in which the software recognizes and orients pixels in multiple photographs. The software first creates a low density point cloud, and then a dense surface map (DSM) from pairs of photographs. These DSMs contain point meshes with much higher density than initial point clouds. DSMs can be created from almost any set of overlapping photos, but Photomodeler gives a compatibility rating for pairs of photos depending on base-to-height ratio (the base is the distance between camera locations in a stereo pair and the height is the distance from the camera to the object being photographed). With EOS Photomodeler, base-to-height ratios of approximately 0.3 are deemed optimal, below 0.5 acceptable, but we found values up to 0.8 sometimes gave good results (see Collins, Riseman, and Schultz 1995; Hasegawa et al. 2000).

We used Photomodeler's smart match system which does not require photo targets and our first tests ran projects using from ten up to more than 200 photographs with varying results. Photomodeler can handle large amounts of source material as long as there is sufficient overlap and suitable angles among photos, yet there was also an issue with the software creating unwanted mesh of background areas or the sky. We found that to prevent such inaccuracies in the mesh, it was often necessary to define parameters using DSM trims around each photo pair. If a DSM has a large amount of quality data, with a few residual outliers, it is possible to edit the point mesh using the temporary select tool and point mesh edit tool.

Using iterative methods and substantial trial and error we were eventually able to create a rather detailed mesh for the entire tower surface. At first we attempted to separate the tower into sections to provide smaller, highly detailed and manageable projects, but these needed to be exported and stitched together in what proved to be a complicated workflow. Eventually, by using the photos taken with the wide-angle lens and the boom arm we were able to create a

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single model from roughly 200 photographs that encompassed the entirety of the tower. Photomodeler initially rejected around forty photos each run, giving us several incomplete point clouds, but the third and fourth times we ran the project, it matched all 200 photos and created our final point cloud for the entire tower (in about four hours on a MacBook Pro 2.6 Ghz with 16 GB of RAM running Windows 7 via Boot Camp). The resulting model had the detail we required without the need for complex stitching of separate clouds, but it still included gaps and voids and would need to be edited, textured, and coloured.

Step 4: editing, texturing and situating the tower model

After numerous iterations we generated a relatively complete tower model; yet it became clear it would require substantial editing and processing, and would greatly benefit from complementary drawing and GIS methods to help contextualize and situate the tower. We created a series of analytical architectural elevation drawings that recorded dimensions, revealed construction techniques and helped check and evaluate our model. We also mapped the tower with a 2-centimetre accurate Trimble kinematic GPS system in which polygons collected around the circumference of top course stones helped orient our model to real-world measurements (Fig. 2).

To finalize our 3D model we used Meshlab software to fill in gaps and voids in the latticework mesh of the tower that we could not effectively fill with Photomodeler, and then used Autodesk 3DS Max software to add texture and colour from photographs. The final step in the production was to create a version that could be easily disseminated. A short video clip of the tower rotating was created in 3DS Max and saved in Quicktime format so it could be embedded in a PDF document of this publication (Fig. 3). Thus we are able to share a record of the Safri 1 tower that we feel is considerably more visually informative than a static photograph.

Rhino software was used to process our architectural elevation drawing of the tower's outer facing and create a conjectural reconstruction (Fig. 4). We devised a system whereby fallen

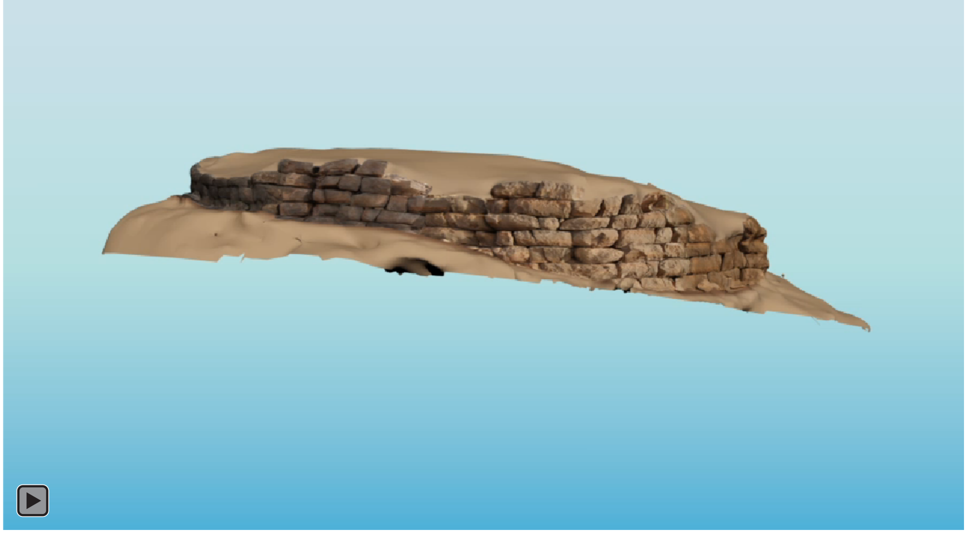

Figure 3 The 3D model of the Safri 1 tower (in the digital version of this article click play in the lower left corner to play the video clip, please note the video plays best in Adobe Reader and may not play properly on mobile devices or from within a web browser).

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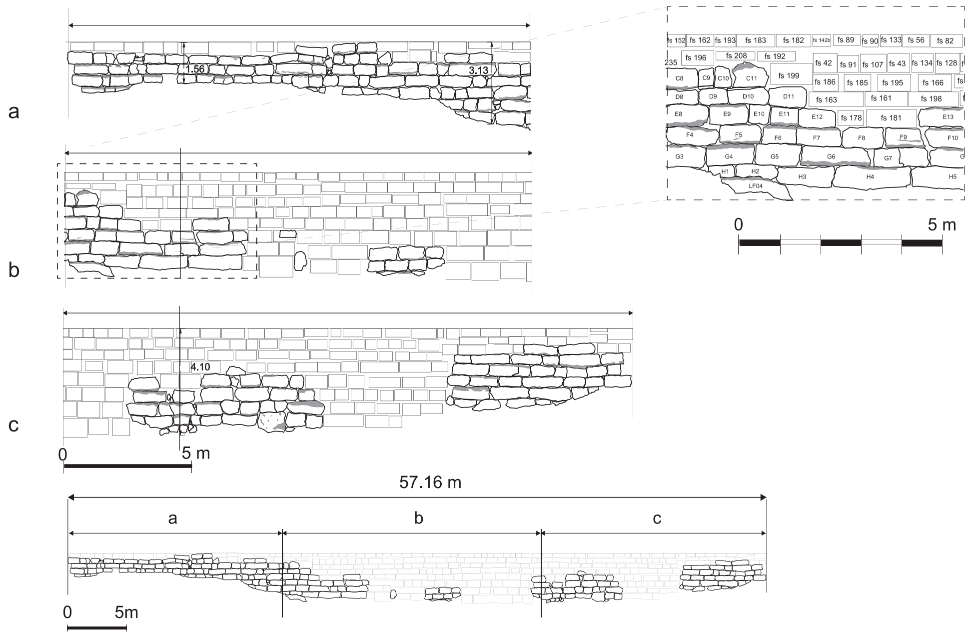

Figure 4 A rollout elevation drawing of the tower with fallen stones (dimensions recorded during field mapping) drawn in to generate a reconstruction of the tower in antiquity.

stones (which were measured, photographed and mapped by GPS in the field) could be used to fill in the areas of collapse recorded in the drawing. Fallen stones were mapped into the most proximate areas of collapse (in the east, northeast, southeast and west areas of the tower) using their actual dimensions to determine their most likely location relative to extant courses – that is, fallen stones were placed into the elevation drawing in courses where existing blocks have similar height and length measurements. This created a hypothetical reconstruction of the tower, which reveals minimum total height from the bottom of the lowest course to the top of the highest course with almost all the fallen stones replaced (4.10m). These data also allow us to calculate the approximate total weight of limestone used in construction (468 stones x 0.148m^3/stone (average) x 2611kg/m^3 for limestone = 180,848kg or 181 metric tons).

To consider the surrounding landscape context we used satellite imagery for wide area coverage and GPS for the terrain in the immediate vicinity of the tower. For the area within a 100m radius of the tower we collected streaming 10cm accurate kinematic GPS data and created a local digital elevation model (DEM). For the wider surrounding area, we used a 5m resolution DEM for a 36 x 36km area produced by JAXA (Japanese Aerospace Exploration Agency) from ALOS-PRISM (Advanced Land Observing Satellite – Panchromatic Remote-sensing Instrument for Stereo Mapping) satellite imagery. Worldview-2 multispectral satellite imagery for a 60sq km area was overlaid on the ALOS-PRISM DEM to help envision the landscape context of the area (Fig. 5). The ALOS-derived DEM also facilitated GIS viewshed mapping (Fig. 6) that reconstructs the locations throughout the surrounding landscape where at least one of the three megalithic towers in the area (Safri 1, Safri 2 or Al-Joghnah) would have been visible (assuming original tower heights of 4m and an observer height of 1.5m). While watchtowers would

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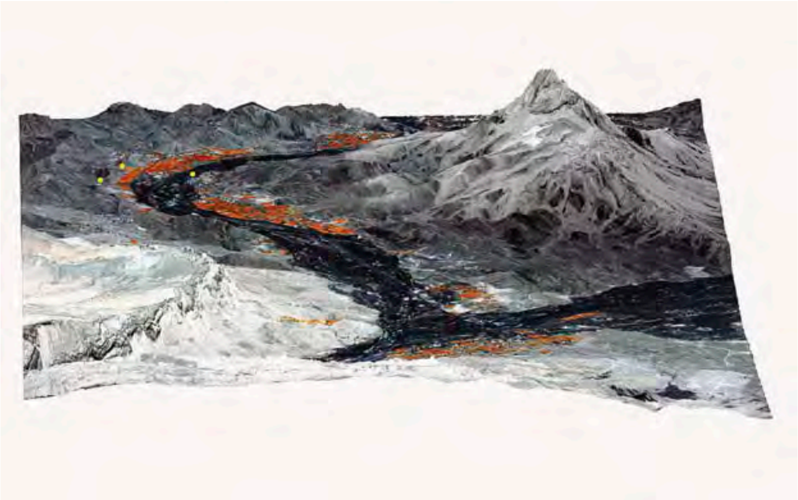

Figure 5 The landscape context of the Safri Megalithic towers depicted via Worldview-2 satellite imagery overlaid on ALOS PRISM 5-m Digital Elevation Model. Dots show the location of the 3 megalithic towers in the area (Safri 1, Safri 2 and Al-Joghnah). Modern vegetation (predominantly irrigated date palms) is appears orange in the digital version of this article.

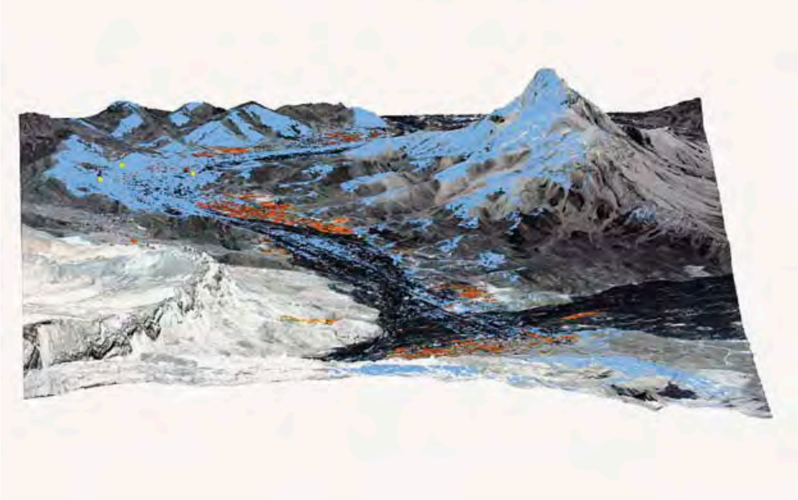

Figure 6 The combined viewshed of the megalithic towers near Yanqul. Dots show the location of the three megalithic towers (Safri 1, Safri 2 and Al-Joghnah). Shaded area (light blue in the digital version of this article) show areas from which one of the three towers would have been visible.

probably have been constructed in areas that allowed maximum possible surveillance of the surrounding landscape, monuments would have instead been built to be most visibly prominent to observers. As Llobera (2007) has outlined, the prominence of a monument in a landscape depends on its size relative to the distance from which it is observed, which can be approximated by objects in the foreground encompassing >15° of visible space, objects in the middle

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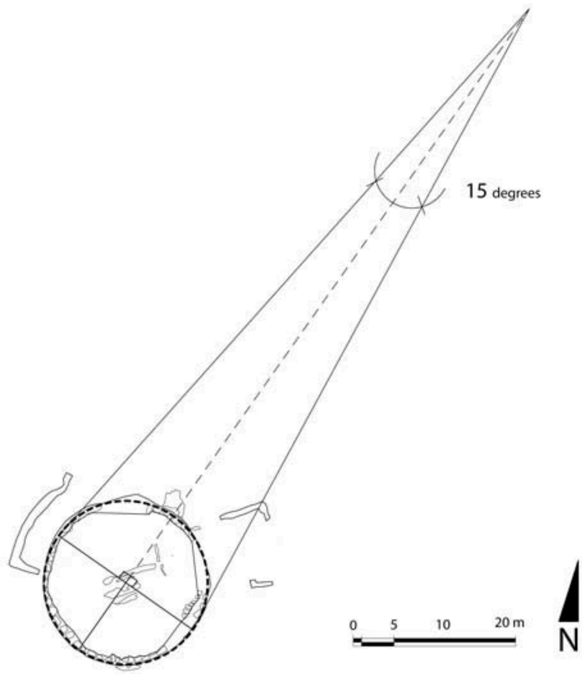

Figure 7 Plan map showing the 15° viewing angle from a distance of 76m below which the tower would become dominant in the foreground of a viewer's vision.

ground 0.5–15° of visible space and objects in the background from 0.1° to 0.5° of visible space (Llobera 2007, 58). If we take these estimates as guidelines we can calculate the approximate distance from which a 20m-diameter tower would have been visibly prominent to an observer, resulting in values of 76m, 2293m and 11,455m for foreground, middle ground and background respectively (Fig. 7). These ranges help illustrate the towers' significance in terms of visual prominence: if the towers served as watchtowers or lookouts one would expect they would have been built on higher terrain, but instead they were constructed on slightly elevated areas where they would be highly visible to passers-by (see Ogburn 2006).

Implications for meaning and function

Our results indicate that Safri 1 was built as a monument built to be visually prominent across a water-rich oasis area and was designed by a builder/architect(s) with considerable expertise who was in communication with a sizeable community involved in the construction and use of similar monuments across a wide area of the UAE and Oman. Workers prepared a foundation course of stones to fit a highly irregular ground surface, they moved and shaped heavy, precisely dimensioned stones and set them into at least eight courses with a consistent curvature to form a carefully dressed outer facing. Careful design, teamwork, skill and organizational expertise must

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all have been part of constructing these monuments, which must have held considerable social meaning. Significantly, this structure must have been conceived of while in at least periodic contact with at least some of those constructing comparable Umm an-Nar towers over tens of thousands of square kilometres from Tell Abraq (UAE) in the north to Ibra, Oman, in the south (Cable and Thornton 2013), demonstrating a wide area of interaction. There are also a variety of possible functions to be considered, including defence, storage and water control, that certainly are not mutually exclusive with monumentality. Our efforts help evaluate these alternatives and point to possibilities for future research to better reveal the meaning, use and role in political complexity of Umm an-Nar towers.

While some tower features point to a defensive purpose, other features contradict a primarily defensive interpretation. Cable and Thornton (2013, 6) critique the term ‘tower’ and suggest they might be more accurately referred to as ‘raised circular platforms’ (after Humphries 1974), but, as they note, it is likely that the already widely prevalent term ‘tower’ will remain in use. In the case of Safri 1, our model and architectural drawing show an approximate minimum height of 4.10m (once fallen stones are replaced to fill collapsed areas), making the structure quite substantial, particularly considering its location on a prominent, naturally raised area a few metres above the surrounding valley floor. It is possible (but difficult to prove or disprove) that a mud-brick superstructure was constructed on top of the stone architecture. Some towers (including at Bat, Bisya and Hili) were surrounded by a ditch making their effective height from the point of view of would-be attackers substantially higher (Cleuziou 2001; Frifelt 2002b; Orchard and Orchard 2010). Without such features to extend their height, many towers might not have been high enough to have served as defendable refugia. In the case of Safri 1, if the walls were only 4m high, ascending the slope to the south would have afforded quite a good view down into the tower’s interior, rendering it vulnerable to attack. A concentric wall along the outer north-western side of Safri 1 perhaps could have served as a sloped gauntlet entryway (Fig. 2) that would have helped fortify the tower. Similar concentric walls may also be apparent along the southeast side of the Kasr al-Rojoom towers at Bat (Thornton, Cable, and Possehl 2013, fig. 18) and Matariya (Cable 2012, 129, fig. 48) but these are not conclusively fortifications and their purpose remains unclear. Indeed, if one sought to construct a fortified watchtower in the area around Safri 1 there are numerous better places to do so, as is true for many towers. Similarly, the purpose and use of rectilinear walls around the outside of towers (Fig. 2) is not well understood, although such external walls often do appear to be roughly contemporaneous with the towers themselves.

A connection with water and irrigation systems has long been proposed for Umm an-Nar towers (Cleuziou 1989, 2001; Frifelt 1989, 2002b; Orchard 2000; Orchard and Orchard 2010) and, while they often do seem to be located in or near water-rich areas, the central well features are often neither positioned nor designed for optimal water extraction, suggesting (at least for some towers) a symbolic rather than solely practical function. Safri 1 has one of the few tower wells that remains open; it descends 6.69m with the bottom measuring 544.68m MSL (mean sea level). Comparatively, the oasis floor roughly 200m to the southeast measures 539.97m MSL so the bottom of the well is nearly 5m higher than agricultural fields in use today. Some of this might be accounted for by debris falling into the well and by erosion over the past few thousand years along the wadi. However, it is difficult to rule out the suggestion that, for some towers, the wells may not have been functional or may have been some other type of deep vertical shaft (Cable and Thornton 2013). Indeed, in the case of Safri 1 (and at Hili, Cleuziou 2001, fig. 7) the

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well was not only dug into the ground but was also built up above the ground surface within the interior of the tower, further supporting a symbolic and monumental rather than purely water-extraction purpose (*contra* Frifelt 1989).

In the case of Safri 1 and some other megalithic examples such as Khadil 1, the outer facing of the tower was far more carefully constructed, and therefore probably more important, than the interior of the tower. In both of these cases, we have no clear evidence for an interior grid of compartments such as are apparent for other towers at sites like Bat and Hili (Cable and Thornton 2013; Cleuziou 2001). Such compartments could have been used to promote structural integrity or for storage (but if so, what was stored inside remains unknown). Instead, the interior of Safri 1 consists of irregular outcroppings of bedrock and rubble with no apparent usable interior space other than the well (Fig. 2). The blocks and coursing are highly standardized with average heights of the blocks in the eight courses from top to bottom of 38, 39, 44, 41, 42, 45, 44, 45cm. Interestingly, this is roughly a cubit (the distance from elbow to tip of middle finger, often approximating to 44cm). The naturally convenient manner in which the limestone bedrock cleaves into roughly half-metre-width blocks in this location may account for some consistency. Yet it is nevertheless noteworthy that standard units of measure, including a 72cm unit used as early as the Ubaid and at late fourth-millennium BC Tepe Yahya and a much later 50cm Sumerian *kuš*, were used in adjacent regions (Beale and Carter 1983; Kubba 1990). The coursing does exhibit numerous joins that are vertically aligned along courses, suggesting a possible lack of familiarity with the structural vulnerability these cause and correspondingly incipient architectural expertise.

The monumental nature and social importance of towers are further supported by evidence that they were reused, or at least revisited, for many thousands of years after they were constructed. This reuse is evidenced by the site's ceramic assemblage and the array of petroglyphs decorating the structure's exterior surface. The sixty-plus diagnostic sherds we analysed from the site are stylistically datable not only to the Umm an-Nar period (55 per cent), but also to the Wadi Suq period (20 per cent), the Iron Age (11 per cent) and the early Islamic (5 per cent), with some 9 per cent un-attributable. A total of eighty-three petroglyphs are also found on outer facing stones of Safri 1, including a boat (Fig. 8), forty-six mounted equids (Fig. 9), seven unmounted equids, twenty-two possible or unidentifiable examples and seven separate instances of Arabic writing. Although petroglyphs are notoriously difficult to date confidently, the Safri 1 examples appear to range from the relatively recent past (as in the Arabic text) into antiquity. The boat, in particular, is roughly comparable to reed-bundle boats known to have been used in the Gulf as early as the sixth millennium BC (Carter 2006) and indicates the importance of maritime subject matter more than 70km from the coast. Similarly, some of the individuals riding equids (which could be donkeys, horses or in a few cases perhaps camels) appear to be carrying spears (or drawing bows?) indicative of hunting or violent conflict (Fig. 9). Comparable ceramic and petroglyph evidence is also known from other megalithic Umm an-Nar towers, including at Khadil and Bat, suggesting re-visitation or reuse, perhaps for very different reasons, over succeeding millennia.

Concluding remarks

The deep social significance of monuments has long been recognized by archaeologists working in a vast array of different regions and contexts worldwide. Considerations of ancient monuments have

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Figure 8 Boat petroglyph on Safri 1. This image may depict a reed-bundle boat known to have sailed the Persian/Arabian Gulf as early as the sixth millennium BC and in widespread use by the third millennium, but its precise character and age are uncertain.

Figure 9 A selection of mounted equid petroglyphs depicted on Safri 1. Riders sometimes appear to be carrying a spear (or drawing a bow?) suggestive of hunting or violent conflict.

often centred on their role in promoting the power and authority of kings, chiefs, elites and other leaders, but, as Cleuziou and Tosi (Cleuziou 2003, 2007; Cleuziou and Tosi 2007) have argued, towers, large collective tombs and associated iconography of Bronze Age Magan are better described as highlighting communality, solidarity and group cohesion rather than autocratic leadership. If so, this pattern significantly deviates from much of what is traditionally envisioned regarding aggrandizement and inequality (see Pauketat 2000) and is of deep importance in examining the social logic of political complexity (Flannery and Marcus 2012) in ancient Magan. New technologies for visualizing and analysing built environments including GIS and 3D modelling are thus well suited to assist in this effort by further clarifying the role and message of monuments.

Over the past few decades, geospatial technologies including satellite imagery, global positioning system (GPS) and geographic information systems (GIS) software have rapidly become widely prevalent in archaeology (Kvamme 1999; McCoy and Ladefoged 2009). Similarly, laser scanning and photogrammetric 3D modelling are increasingly helpful in reconstructing, preserving advanced records of, conceptualizing and analysing built environments (e.g. Forte 2010). New means of visualizing archaeological remains, including techniques that intermix the capabilities of GIS, 3D modelling and virtual reality undoubtedly hold a substantial future for both research and public outreach (Dawson, Levy, and Lyons 2011; Favro 2006; Kersten and Lindstaedt 2012; Sullivan and Wendrich 2009). Indeed, if a picture is worth 1,000 words, then a quality 3D model must be worth at least, perhaps, 1,001. These tools, however, remain relatively expensive, time-consuming and require significant technical expertise. In our view they do not necessarily replace nor do they render obsolete other forms of representation including architectural axonometric drawing (see Adkins and Adkins 1989; James 1997) which can be used to highlight particular characteristics of one's subject matter and can strongly complement and help in the evaluation of 3D models.

Nevertheless, our team's application of 3D photogrammetry, architectural and geospatial analysis was of significant utility in deciphering the original form, landscape context, and considering the potential purpose and use of the Safri 1 tower. By developing template study tools to digitally reconstruct towers, we hope eventually to compare the similarities and differences of many more towers across the region in order to discover which characteristics are consistent and which change among the group. Indeed, nuanced changes in layout and construction offer important insights into the degree and nature of communication during design, improvization and changes over time. Through development of new 3D modelling work flows that incorporate less expensive and less operationally complex technologies rapidly becoming available (see e.g. Koutsoudis et al. 2014) we hope to contribute to the rapidly expanding repertoire of new visualization-based analytical tools in archaeology that in this case help clarify the role of Umm an-Nar tower monuments in ancient complexity and social change.

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