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Mapping, Modelling and Predicting Prehistoric Coastal Archaeology in the Southern Red Sea using New Applications of Digital Imaging Techniques

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Abstract

Over 3000 shell midden sites have been located in the southern Red Sea using digital imaging techniques, in a combination of palaeo-landscape reconstruction and remote survey. The primary methods include digital imaging techniques – high-resolution satellite images, false colour images, and radar data. Surveying and recording these sites during excavation has also been enhanced using digital photogrammetry – allowing high-resolution site level data to be incorporated into wider landscape reconstructions. The resulting data are combined to construct site location models that have been proved and tested in other areas of the southern Red Sea. We also show how satellite imagery can be modified and exploited for seabed mapping and the search for underwater sites.

Key Words: Shell Middens, Red Sea, Digital Imagery, Coastal Archaeology, Submerged landscapes, Farasan Islands

Introduction

This paper develops novel applications of digital imaging and shows how the integration of imagery at different scales ranging from the intra-site scale to the regional landscape can be used to create site location models that enhance the analysis of known sites and predict the location of new ones. We apply these new methods to mid-Holocene shell mounds in the southern Red Sea. We show how these methods can be used for the rapid survey of larger areas of the landscape than is possible by conventional survey methods, the reconstruction of past landscapes on land and under water, and the location of new sites. At the local scale, we develop new methods of photogrammetric 3D modelling techniques to enable visualization of stratigraphic sections in narrow excavation trenches, and the location of a site in relation to its surrounding environment.

Archaeology as a discipline has always been keen to utilise new technology as it becomes available, by the mid 1850s archaeologists were already using early photography (Kristiansen 2002). Our obsession with technology has hardly faltered, with archaeological science now a major component of most projects. Digital imagery is still at the forefront of research (eg Beck and Philip 2013), and a major interdisciplinary tool for investigation. Interdisciplinary research is always a core part of archaeological research, no more so than here, where a range of high-tech applications have been utilised, not only to answer old questions, but also to raise and address new ones.

Archaeological background

The archaeology of Saudi Arabia has only recently become a focus for research, not least because of the hypothesis of a *southern dispersal route* as part of the *out of Africa* story (Bailey *et al.,* 2007a; 2007b; Bailey 2009; Lambeck et al., 2011). Through research on this theme, the Farasan Islands have come to prominence for the quantity of shell midden sites, when features previously interpreted as natural shell banks were discovered to have anthropological origins. In a series of field seasons between 2006 and 2013, we have conducted exploration and excavation to determine the history and significance of these sites. However it became clear that new approaches would be needed in addition to traditional field methods, due to the number of sites now known to exceed 3000 (Bailey et al., 2007a; 2007b; Williams, 2010; Bailey et al., 2013; Alsharekh and Bailey, In press).

The Farasan Islands are situated in the southern Red Sea 40km offshore in Saudi Arabian waters, close to the border with Yemen. Due to their proximity to the border, they were a restricted military area until relatively recently, and local population density is low, so that archaeological features have been relatively well protected from developmental impacts. Shell mounds were first identified on the islands in the 1980s as part of the Comprehensive Archaeological Survey Program of Saudi Arabia (Zarins *et al.* 1980, 1981; Zarins and Zahrani 1985; Zarins and Al-Badr 1986). However, the abundance of sites was not apparent at this time, and it was over twenty years before their true extent and significance was realized.

These shell mounds vary in size from prominent landscape features up to 6m high to extensive surface scatters. The majority of these sites are on palaeoshorelines located at varying distance from the modern shoreline, some being as far as 3km inland. Dating of selected sites has shown that they originate in the mid-Holocene from 5500–4500BP, and excavation shows that the sites were used for fishing and hunting of gazelle as well as shell gathering (Demarchi *et al*., 2010; Bailey et al., 2013). Stone artefacts are rare but include ground stone tools made on volcanic material imported from the mainland. The dominant shell species is a small gastropod, *Strombus fasciatus*, which grows on sandy substrates, but other species are also present, sometimes in considerable quantities, including rocky reef species such as the large gastropod *Chicoreus* *ramosus* and bivalves such as *Chama reflexa, Pinctada* spp. and *Spondylus marisrubri*, and bivalves that live in sandy habitats such as *Arca avellana*. Two excavated sites with surface and basal dates seem to demonstrate relatively rapid accumulation. When taken into account with the evidence of dynamic coastal change, this would suggest a short period of intense activity targeting an ecological window of opportunity.

From an early stage in the research, it was clear that new survey and excavation strategies were needed in order to maximise ground coverage whilst minimising the time and cost involved. One answer to this problem is the use of digital imagery, which has allowed the development of a better sampling strategy for field survey and individual site analysis. Although it is desirable to survey every site in the field, in reality this is not always practical. By remotely surveying sites and selecting a sample to be examined in detail, a more efficient sampling strategy can be developed that allows for coverage of larger areas within the constraints of time and money. At the site level, the demand is for excavated data from stratified sections in as large a number of sites as is feasible, and this necessarily requires relatively narrow and deep trenches in which the sections are difficult to draw and impossible to photograph using conventional techniques. Here too, we show how digital imaging techniques can overcome these limitations and also bridge the gap between the individual site and its immediately surrounding landscape setting.

The presence of much earlier sites on the mainland (Zarins et al., 1980; 1981; Zarins and Zahrani, 1985; Zarins and Al-Badr, 1986) also raises the possibility of finding equivalent coastal sites underwater, on coastlines that have subsequently been inundated by rising sea level during the Holocene. Again this poses problems in terms of time and cost; existing bathymetry maps have very low resolution, and lack the detail to pick out landscape features such as palaeoshorelines. Without a good knowledge of the landscape, finding sites or even areas with a more favourable configuration for human exploitation is like finding the metaphorical needle in a haystack. A targeted approach is needed, and here too digital imagery can play a key role.

Methods

Digital imagery can have a number of uses in landscape-wide archaeological survey. First it can allow characterisation of the landscape into areas that are likely to have higher archaeological potential, and better archaeological visibility. Where there are active processes modifying the landscape, reconstructing the palaeolandscape is essential. This can be done using satellite images, constructing false colour composite images and digital surface models. Here, we use NASA SRTM and ASTER GDEM data (USGS, 2013a; ASTER GDEM is a product of METI and NASA) to produce Digital Surface Models (DSMs) using ArcGIS. Other options such as DSM's derived from high resolution stereo images were considered, but not used due to time and cost limitations. Landsat 5 images were used to construct the false colour composite (USGS, 2013b), processing the images using software such as ENVI. Bands 7, 5 and 3 produced the best results to best distinguish between calcareous sands and fossil coral, though other combinations were tested. High resolution Google Earth and SPOT images were also used (Google Earth Images include QuickBird and World View 1 and 2). We show how it is also possible to identify many archaeological sites from their spectral signature on satellite images. This can feed back into the landscape analysis, whereby site locations give an indication of areas suitable for settlement and can be used to construct site location models.

Site and intra-site analysis has been enhanced using photogrammetry and Agisoft Photoscan software to create high-resolution 3D models of trench sections and of individual sites in their local setting.

We also show how the use of false-colour composite maps derived from Google Earth images can be used to reconstruct underwater bathymetry to a first order of approximation, allowing a reconstruction of the now submerged landscape and the extension of site location models to the search for new sites under water.

Results

Landscape-scale reconstruction

The palaeoshorelines observed in the first seasons of fieldwork suggested that there had been significant changes in coastal landscapes since the deposition of the shell middens. The first step in reconstructing this landscape was to construct a digital surface model using NASA SRTM radar and ASTER GDEM data (USGS, 2013a). This data was manipulated in ESRI ArcGIS to produce an elevation map of the islands that can be displayed in a number of different ways, including in 3D (ESRI was particularly useful). In this instance the SRTM data proved to be more accurate than ASTER in some areas, therefore was more heavily relied upon. In Figure 1 the location of all known sites has been overlaid onto the DSM, giving an indication of how the distribution of sites is related to height contours. The average height of the palaeoshorelines is 2m above modern sea level; however there are local variations, some due to the errors mentioned above, but also real differences caused by localised salt doming and uplift of up to 20m above modern sea level.

FIGURE 1 ABOUT HERE

The DSM is very useful, but it is not the only tool available for this kind of landscape reconstruction. False colour composite images can also be used to help determine the type of sediments present, and therefore give an indication of the type of processes that might have contributed to landscape change.

A false colour composite for the Farasan Islands is shown in Figure 2 using bands 7, 5 and 3 of Landsat 5 data (USGS 2013b); here it is possible to readily identify depositional sediments that correlate well with the DSM (Figure 1). These are primarily carbonate sand marine sediments deposited during the period when the palaeoshorelines were forming and the shell midden sites were accumulating. However, there is some aeolian reworking as well, leaving coarser lag deposits. Ground truthing of this data is required, and has been undertaken during the field seasons in selected locations. It is possible to drape these images over the 3D DSM model in order to gain a further perspective on the distribution of sediments; however, when doing so it is important to consider errors in the DSM discussed above, as these will be displayed in the 3D model. The patterns of sediment distribution in these images correlate well with palaeocoastal features seen in the field during survey, such as beach ridges and wave cut/dissolution features that constrain sedimentation.

FIGURE 2 ABOUT HERE

Using high-resolution satellite images to detect archaeological sites is nothing new (eg Kennedy and Bishop, 2011; Beck and Philip, 2013). The Farasan Islands are favourable for this kind of survey due to the arid climate and historically low population densities. The aridity plays a twofold role, firstly it means that geomorphological processes are restricted, only accelerating during rare precipitation events; and secondly, there is little vegetation cover (meaning the season of data collection has little impact, other than occasional hazes caused by humidity or dust). The nature of the archaeology also lends itself to this methodology; the shell middens are a different colour to the bedrock on which they have accumulated. The bedrock is uplifted fossil coral that weathers down to a dark grey/brown colour; the shell mounds on the other hand are predominantly composed of much lighter-coloured shells. Although the surface composition of the shell mounds can vary, a direct result of the shellfish species that form the surface layer of the site, the spectral signature of the shell mounds is unique and constant for all the shell mounds. There is some variation depending on the surface composition of a site (the shellfish species present), but this is accountable through ground truthing.

Figure 3 shows a high-resolution (sub-metre) satellite image from Google Earth (2013). The light patches are all shell mounds, ranging in size from scatters only a couple of metres across, up to mounds 3m high (inset in Figure 3). A difference in the surface composition of shellfish species can be seen between those sites in the centre of the image, and those in the upper right hand corner, which appear slightly darker in colour. In this case the lighter white sites have a surface composition dominated by *Strombus fasciatus*, whilst those in the top right have a mixture of *Strombus fasciatus, Spondylus marisrubri,* and *Chama reflexa*. It is also useful to note that scatters as small as 0.5m across are visible on the images, suggesting that the archaeological record for shellfish gathering activity is well represented.

FIGURE 3 ABOUT HERE

This combination of techniques has been important in allowing survey of the coastlines of the main Farasan islands. An important contributor to the success of this method has been the DSM and false colour composite data, which has allowed a targeted approach, whereby areas with probable palaeoshorelines have been investigated first. However we have also found a small number of shell mounds in less obvious locations, some up to 1km inland of known palaeoshorelines, suggesting that in these cases there have been other factors influencing the location of sites, rather than the proximity of the shell beds (e.g. Bird and Bliege Bird, 1997). There are no obvious reasons for these sites to located so far from the (palaeo)coast, however this highlights the need for broader scale survey, even if it is only a sample of the total area and demonstrates the worth of spectral analysis beyond the region where sites would be expected. With the exception of these few sites, shell mounds were found to have a strong association with palaeoshorelines features – breaks in slope detected on DSMs or changes in sediments visible on false colour images.

Using the combination of high-resolution satellite images, DSM and false colour composite images, over 3000 shell midden sites have been identified. So many have been discovered that it has not been possible to visit them all. However remote sensing has allowed the prioritisation of groups of sites for further research. Fieldwork has focused on these groups, with a further selection process in the field to prioritise those suitable for more detailed examination and excavation. This has saved substantial amounts of field time and allowed for a more targeted approach.

Site-scale reconstruction

Excavation formed the major activity of field seasons, once the initial task of assessing different groups of shell mounds for priority had been accomplished. The excavation strategy was ambitious, aiming to excavate as many sites as possible within the shortest time without compromising the highest level of data retrieval. In the most recent field season (2013), narrow trenches were excavated into the centre of the mound at 18 sites. This necessitated a program of high-resolution digital recording to complement traditional visual and written records. Photogrammetry is not new to archaeology, being widely used in studies of historic buildings and similar features; however its use in prehistory, particularly on shell mounds is. A further innovation shown here is to link the site-scale record with the landscape models described above in a GIS, providing local high-resolution snapshots of the wider landscape, and how the sites are related to it.

For the example shown here (Figure 4), Agisoft Photoscan was used. In order to construct the model (eg De Reu et al., 2013; Verhoeven, 2011), a sequence of photographs needs to be taken of the target; the photographs can be taken at a variety of angles to the vertical trench – an obvious advantage in a confined space – and as long as the photographs overlap, the software can stitch the images together. The higher the resolution of the images taken, the better the texture of the model, but the longer the processing time. In one case, we photographed the entire shell mound, the excavated section, and the immediate landscape surrounding the site, involving more than 1500 images, with up to 50% overlap of images (owing to the narrow trench restricting movement). Using this technique each area was covered by 2 or more images, taken from different angles. This greatly increased coverage, especially in order to achieve a detailed 3D reconstruction of every shell in the section; this allowed the texture of the section to be reconstructed. Reference points were marked in order to maintain accurate scale relations during the reconstruction, and to mitigate errors in the stitching process. In the case of the Farasan shell mounds, every individual shell in the excavated section and on the surface of the mound is reconstructed in 3D. It is therefore possible to see layers as they would appear on the section drawing, but also to zoom in to individual shells, and look at the composition of the excavated layers (Figure 4 section). Although more time consuming, the greater resolution significantly increases the usefulness of the final image as a complimentary tool with section drawings. It may even reach a point where these compositions can be produced so rapidly that digitally annotating these will replace traditional section drawing.

Figure 4 also shows the exterior of the shell mound and its local landscape in the same detail. In this way the broad landscape dataset and the in-depth site data can be brought together and joined in the GIS.

FIGURES 4 ABOUT HERE

The 3D imaging of the site is important to help link the site into the immediate locality of the site as well as the broader landscape. It helps to determine why sites are located where they are; for example to show whether they are in the most sheltered part of a bay, or on the most prominent and exposed location. At a finer resolution, it can show whether sites are located on the strand line, or further back behind the beach. Questions such as these help to determine not only the best location to find sites, but also the best location to find preserved sites, and appropriate observations to answer such questions can be recorded and combined to construct models for site location.

Palaeolandscape reconstruction and site location model

The combination of the methods described above has allowed a reconstruction of the palaeolandscape as it would have been during the formation of the shell mound sites. Further, dating (Demarchi *et al.,* 2010) has shown that many of the sites (and therefore palaeoshorelines) are contemporaneous, meaning that the palaeoshorelines can be associated, rather than forming different fragments of a composite longer-term history. Figure 5 shows a reconstruction of the Farasan Islands from this data; it is clear that the islands were once broken up into smaller islands, with many more shallow bays and inlets. The vast majority of the shell mounds are located in these places, with the emphasis being on accessible shallow marine sub-tidal environments, where highly productive shell-beds are prevalent.

FIGURE 5 ABOUT HERE

Using this data it is possible to create a predictive model for shell mound site location; the more sites that are found, the better the model can be tested and refined. The key requirements of the model are: a shallow sloping topography, since this promotes productive shell beds; a break in slope indicating the presence of a palaeoshoreline; a change in sediment, often from carbonate sand to fossil coral. Most palaeoshorelines are located at about 2m a.s.l. with shell mounds associated with these slightly higher; therefore the model is weighted towards this height (2-6m a.s.l.), but without excluding other areas due to the variability caused by local salt tectonics. The mean basal height of sites is 5m a.s.l. (with a standard deviation of 2.5); the highest site is located at 33m a.s.l.. The spectral signature of the shell middens on high-resolution satellite images then allows their identification.

Many of the larger sites are located at prominent points in the landscape, and excavation has demonstrated the presence of large numbers of fish bones in these sites. Fischer's fishing site model fits well with the location of these larger sites (Fischer, 1993; Benjamin, 2010), and this appears to be an important factor in addition to the presence of shallow accessible shellfish beds.

On every island in the Farasan archipelago that the model has been applied to, sites have been found. In order to test the model further, we applied it to other coastal environments in the region. The Dahlak Islands are on the opposite side of the Red Sea, and have a similar geology to the Farasan Islands, making them an ideal test of the model. Figure 6 shows an overview of the application of the model and the resultant sites found. The sites match those on the Farasan Islands in every way.

FIGURE 6 ABOUT HERE

Underwater reconstruction

Having successfully found new sites on land using the model and techniques outlined above, the next stage was to look underwater. On the mainland there are sites dating back to 9000BP (Zarins *et al.* 1980, 1981; Zarins and Zahrani 1985; Zarins and Al-Badr 1986); sea level would have been at least 20m lower than today (Siddall *et al.* 2004). We have hypothesised that earlier sites ought to exist on now submerged palaeoshorelines in the Farasan region, and that there should be evidence located on palaeoshorelines formed at depths down to -20m. Existing bathymetric charts lack the resolution to reconstruct the submerged landscape in sufficient detail. However, a digital imagery technique offers the possibility to overcome this deficiency.

The method uses the principles of false colour composite imagery. However, rather than discerning the composition of the substrate, here the method is used to model depth. Different wavelengths of light are absorbed at different rates through water, meaning that the colour will change with increasing depth; therefore ratios of colour can be used to assess water depth. There are problems associated with using only one ratio (such as blue/green), however using multispectral data and using more than one ratio can help to overcome these limitations. In addition there are several processes that have been developed to help address problems such as differences in substrate-albedo caused by sandy substrates (e.g. Stumpf *et al*., 2003). Once the bathymetry has been calculated, the data is treated as a Digital Terrain Model, and in the same way as with the satellite images. High resolution satellite data can be draped over the DTM (in this case using ENVI), resulting in a 3D model of the sea bed (Figure 7). There are, however, some limitations to this type of modelling. Depth reconstruction to -20 m can only be achieved where the high-resolution satellite images were acquired on clear days. Otherwise the turbidity of the water (such as surface waves, sediment load, organic context in the water affected by season, etc.) become the main limiting factor (Stumpf *et al.* 2003).

FIGURE 7 ABOUT HERE

This process has only just begun, and it is anticipated that once enough of the seabed has been reconstructed, the site location model will be applied, creating a targeted approach to underwater prospection for archaeological sites. Ground truthing has not yet been applied, therefore no sites have been found. In underwater work, the restrictions on extensive field reconnaissance and ground-truthing are even more severe than on land. Also, it is critical in underwater work to identify locations that have good potential for the preservation and visibility of archaeological material, as well as locational and environmental features attractive for human activity (for a review of current models see Benjamin, 2010). Boats of varying size can be equipped with sonar equipment such as multi-beam and side-scan for seabed mapping, but this is a costly procedure. Therefore there are strong factors for developing methods that can achieve major savings of time and resources and improve the chances of pin-pointing suitable targets for more detailed underwater examination.

Discussion

Digital imagery is a powerful tool in the archaeological armoury, and is becoming ever more diverse and relied upon as technology advances. The first archaeological projects on the Farasan Islands did not have access to the same range of digital imagery resources now available. As a result they were unable initially to identify the scale of the mid-Holocene shell-midden record. Even when an entire field season was devoted to survey on the Islands, with three separate survey teams, only a fraction of the total sites were surveyed, often with a level of detail now exceeded by high-resolution satellite images. Very little palaeolandscape data could easily be acquired during these ground surveys. Further work would have required time and resources not available to the project. Digital imagery, in contrast, offers the opportunity to cover large areas at a relatively high-resolution, relatively rapidly and cost effectively.

At the same time, it should be recognized that digital imagery also has drawbacks compared to field survey. For example, it is fairly simple to measure the plan of individual shell-mound sites from remote images, but assessing the height of a shell mound, though possible through stereo paired images, is time consuming, even with numerous oblique high-resolution images. Also, though it is possible to make some inferences about the surface composition of the sites, accurate recording still requires site visits. With the huge wealth of images available, cloud cover, time of day, and even season are no longer problems, as was once the case when the archive of satellite images was smaller.

It was much harder to explore the relationship of the sites with their surrounding landscapes before the use of satellite data – good topographic maps of the Farasan Islands do not currently exist, but relatively high-resolution digital elevation data does. When this data is combined with false colour composite images of the surface geology it is possible to reconstruct the palaeolandscape; again this is significantly aided by knowing where the archaeological sites are found. The addition of photogrammetry for local high-resolution site and landscape reconstruction adds another layer of data, and the combination of all these techniques has successfully contributed to the construction of a site location model that has been used to find new sites, not only on the Farasan Islands but elsewhere.

The number and concentration of sites strongly suggests that the gathered shellfish originated locally, and that they were carried the shortest possible distance to dry land after gathering. Therefore the species composition represented within the mound should give an indication of the local palaeoenvironment, assuming that this pattern is not obscured by changes in cultural preferences or gathering practices. In this respect the use of photogrammetry to record trench sections highlights these changes in species composition, and allows them to be explored rapidly and in high-resolution as a valuable complement to column sampling and dating. The creation of photogrammetry images also encourages the conception of site documentation as a three-dimensional record, rather than a two-dimensional one consisting of sections and linear stratigraphy.

The methods presented here demonstrate the intensive investigation of an archaeological phenomenon at a range of scales. Importantly the different scales are brought together, rather than kept in separate research compartments, and used to inform on future research in a feedback loop. Both landscape and site level research is not done independently, but rather each informs on the other. This process helps in constructing models for exploring new areas and finding new sites. In addition, we have shown how remote-sensing data can be manipulated to extend beyond the boundaries of the original research and to aid underwater exploration.

An important aspect that must also be mentioned is compatibility; with all computer related work the outputs (and inputs) must be saved in backwards-compatible formats. New programs often necessitate new file formats: if, in ten years' time, earlier work can no longer be accessed because if has been saved in an obsolete format, then a large part of the original effort will have been wasted or its results lost to future generations.

Conclusions

This paper documents the use of some mainstream techniques, and development of some more novel approaches to digital image use in archaeology. Digital imagery has become an essential archaeological tool, and is rapidly developing with the greater availability of high-resolution multispectral data and ever-increasing program capability and computing power. Here we have demonstrated the development of a project relying heavily on digital imagery, from palaeolandscape reconstruction, site discovery and remote survey, to new recording strategies, site location models, and back to the start of the cycle in a new generation of palaeolandscape reconstruction and site discovery. The time-savings in using these techniques have been demonstrated.

Using these techniques, over 3000 shell midden sites have been recorded on the Farasan Islands, and hundreds of previously undiscovered shell midden sites have been located on the Dahlak Islands of Eritrea.

The use of digital imagery to guide underwater archaeology is also an innovative use of new technology, building on the existing methods developed on land as part of this project.

All of these techniques have a demonstrable advantage over more traditional techniques, whether this is in terms of cost, time, additional information gained, or simply that they are the best technique for the job in this region. The results presented here also highlight the importance of combining different techniques and integrating the information in a feedback process, both to increase their usefulness for archaeological purposes and also as a mitigation of the limitations of each technique when applied in isolation.

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Figure captions

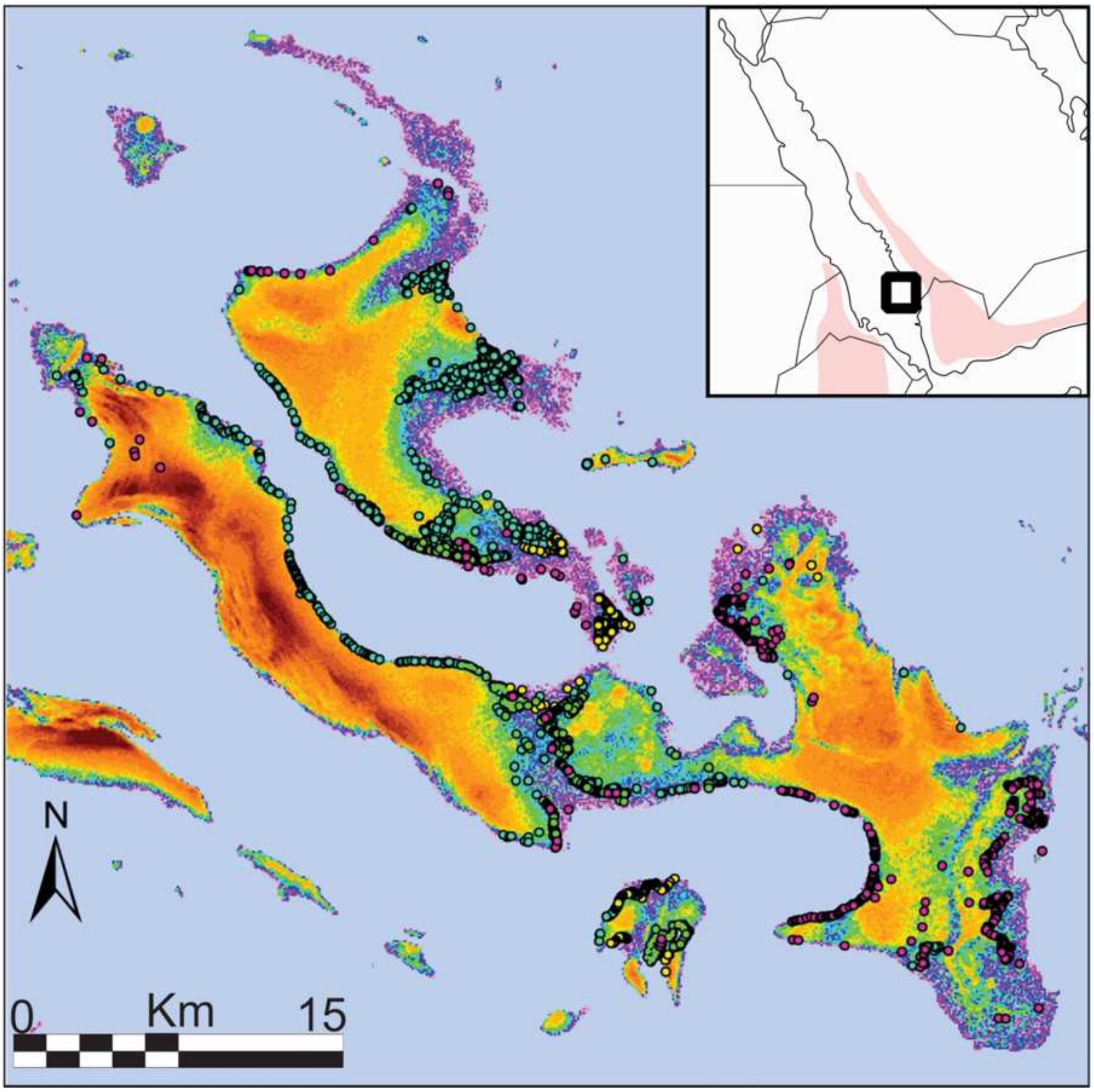


Figure 1: A Digital Terrain Model (DTM) of the Farasan Islands constructed from SRTM radar data (USGS, 2013a). Greys are lower lying topography, whites higher.

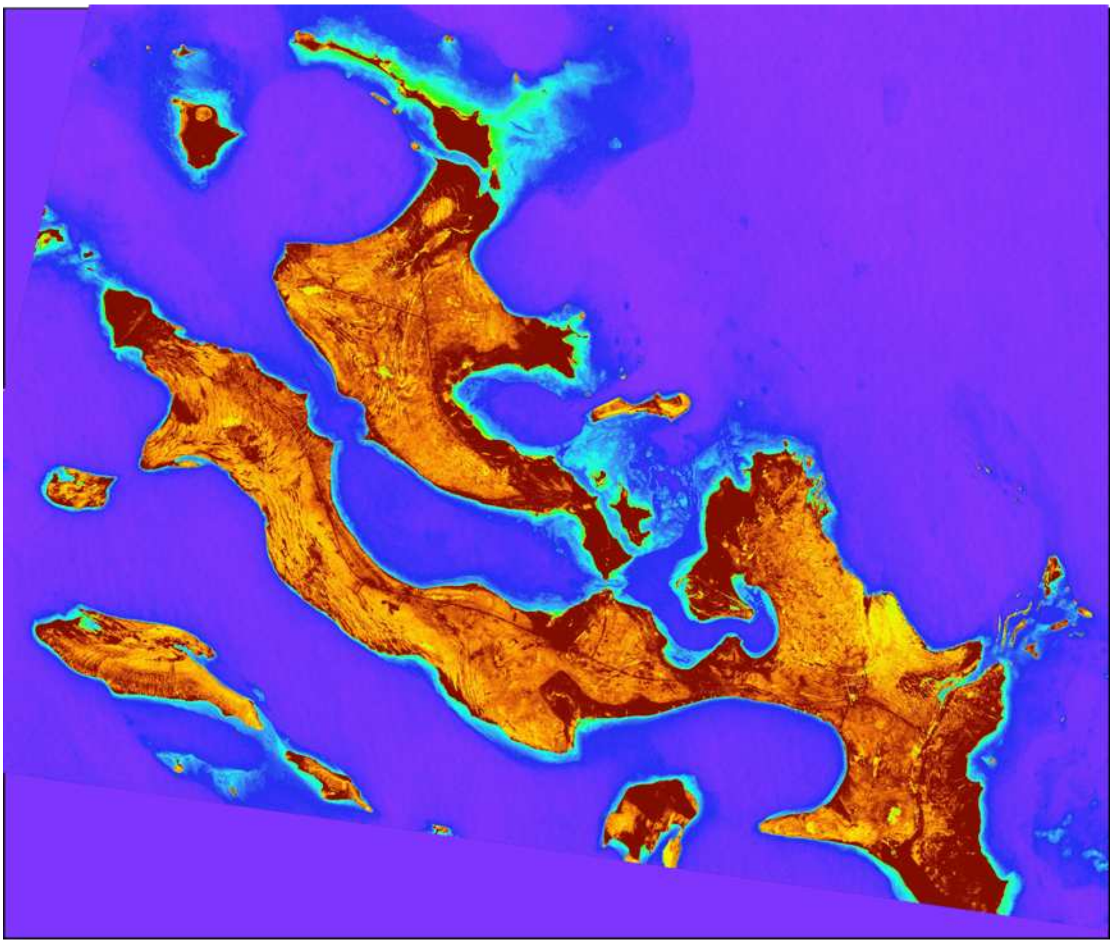


Figure 2: A False Colour Composite image derived from Landsat data (USGS, 2013b). Darker colours indicate depositional sediments.

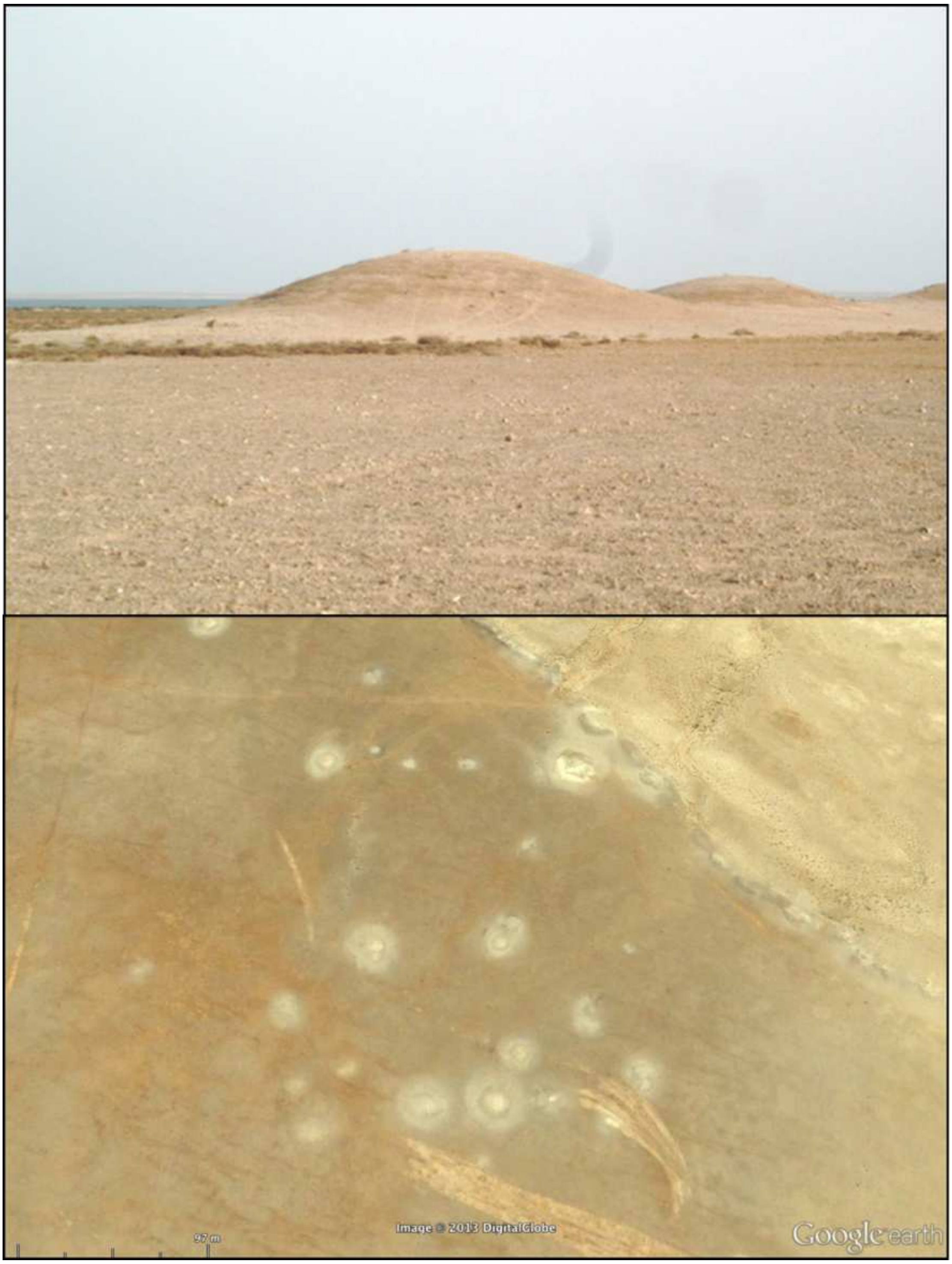
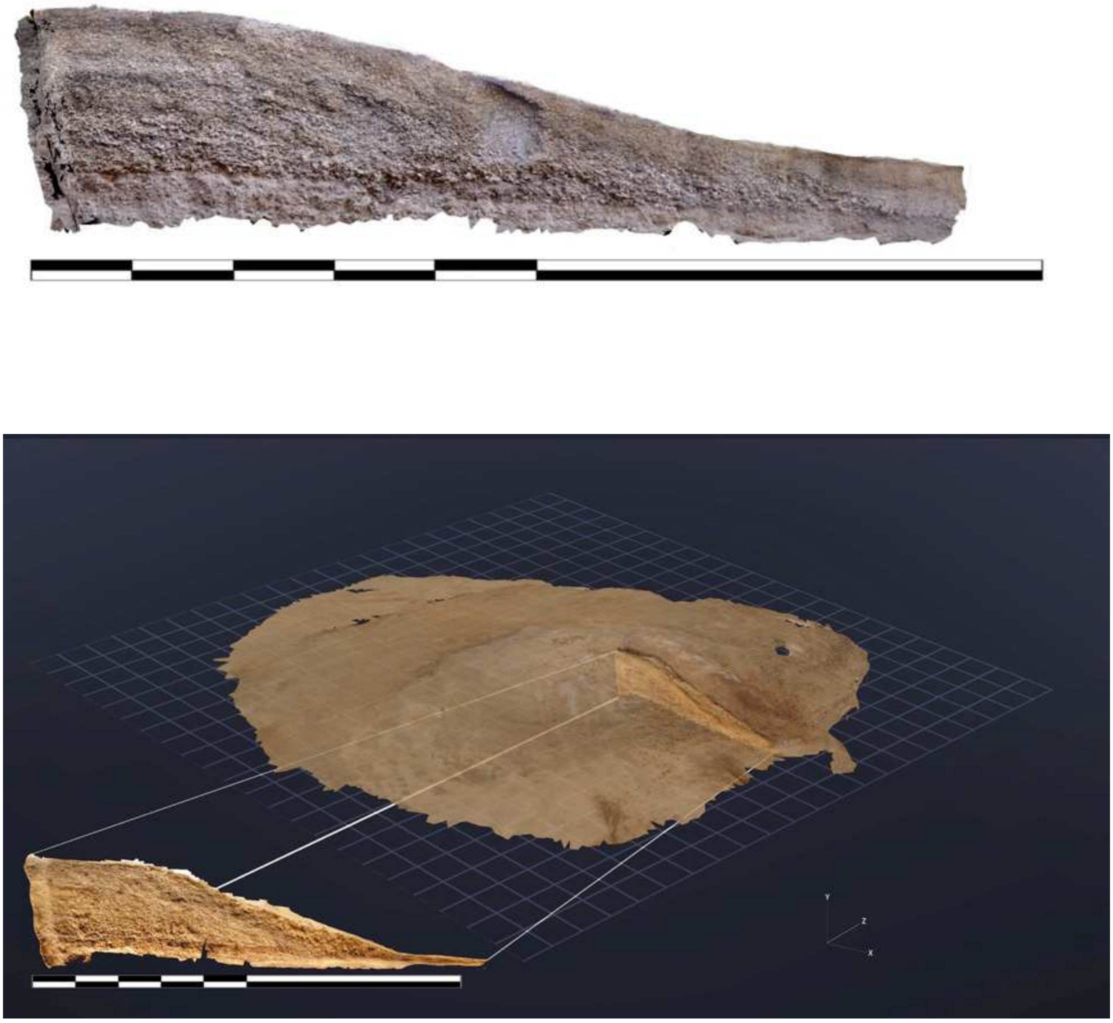


Figure 3: Top image is a three-meter high shell mound (photo M. Meredith-Williams); lower image is a Google Earth image showing shell mounds as lighter areas on a darker background (Google Earth, 2013).



Figures 4: Main: Photogrammetry 3D model of a section from one of the excavated shell mound sites, scale bar is 10m. Inset: Photogrammetry 3D model of the exterior of an excavated shell mound (N. Hausmann).

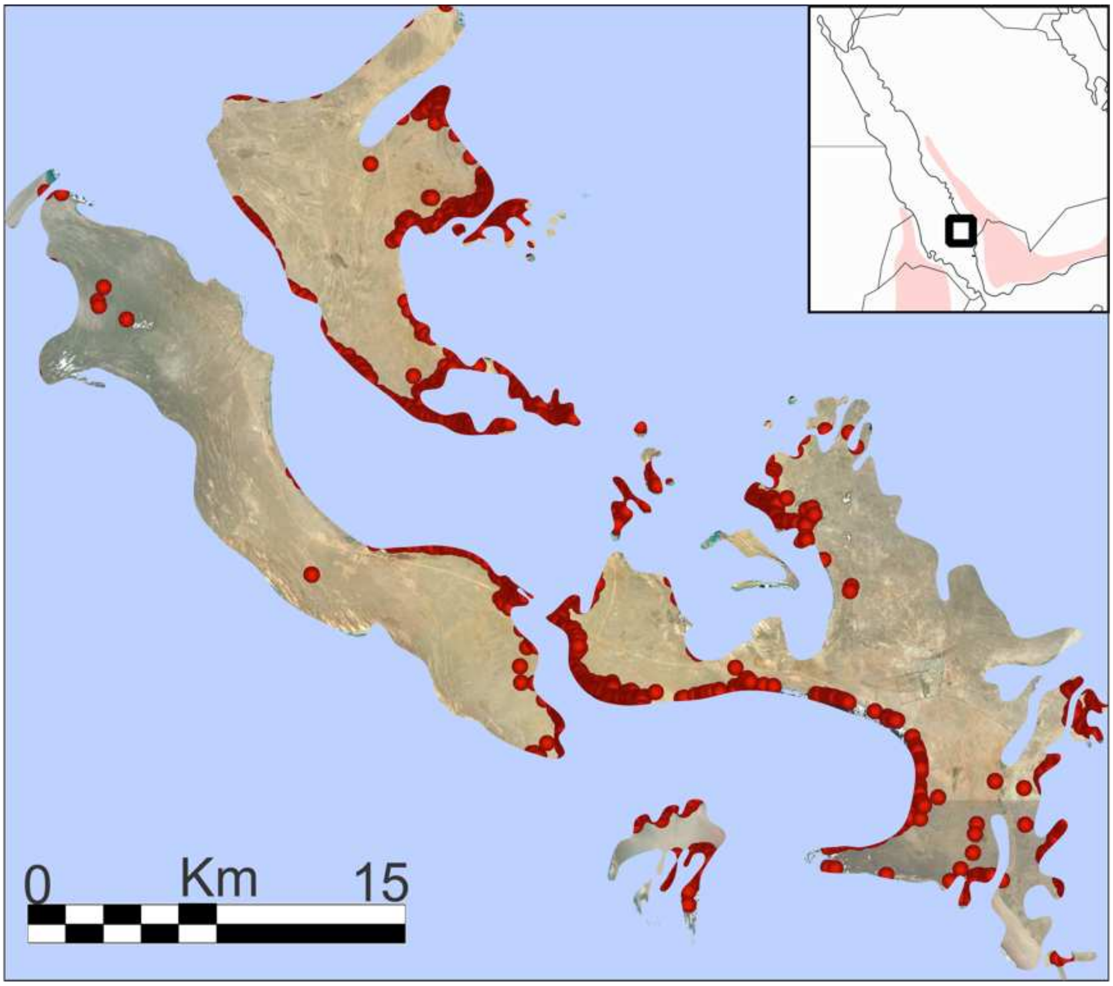


Figure 5: A reconstruction of the palaeoshorelines of the Farasan Islands from the combined data sets (Landsat/SRTM).

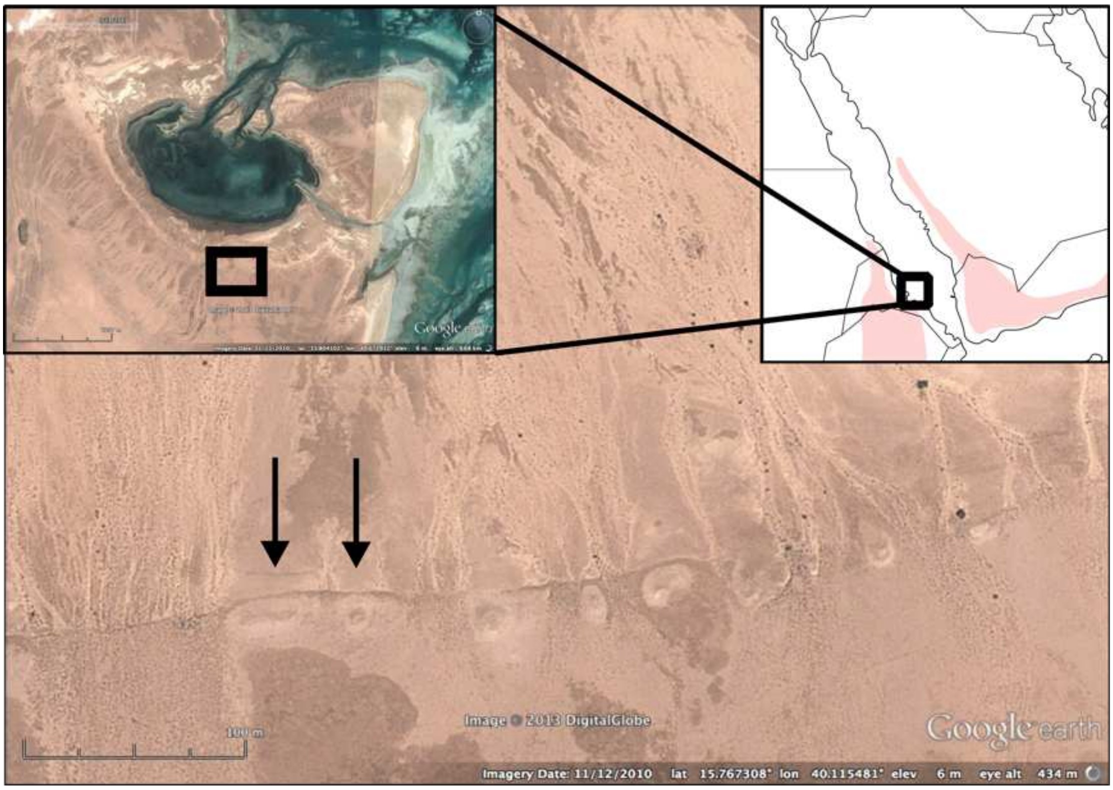


Figure 6: Application of the site location model to find new sites on the Dahlak Islands, Eritrea (Google Earth 2013).

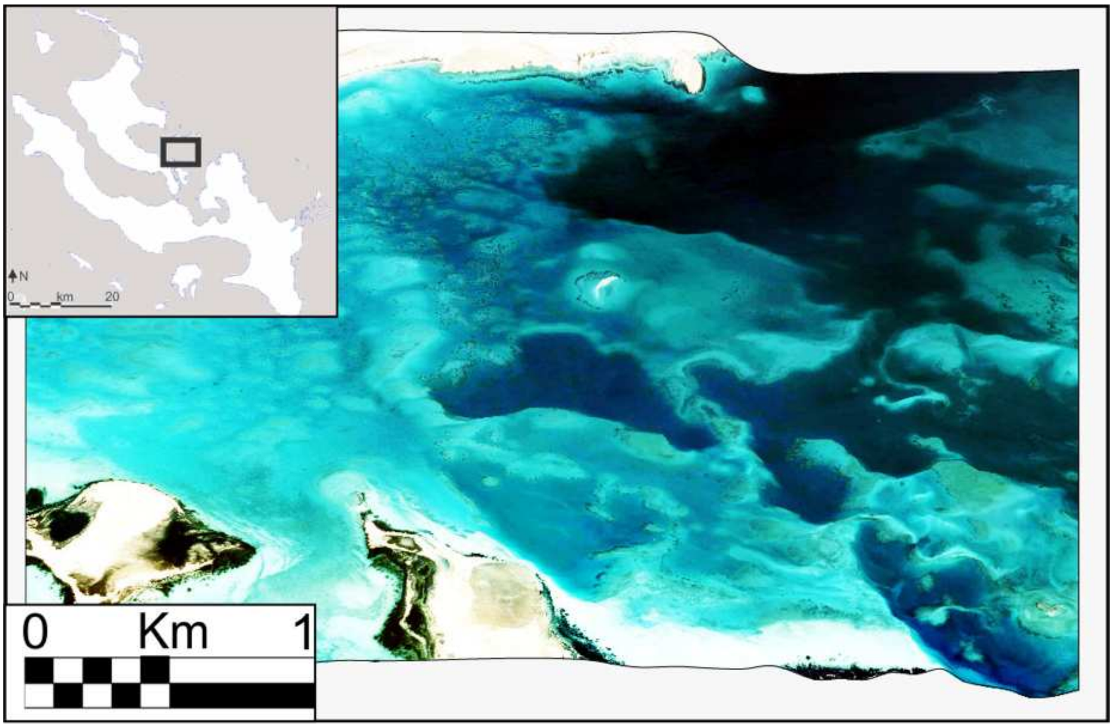


Figure 7: A 3D model of bathymetry, derived from colour ratios converted into a DTM, with a high-resolution satellite image (Google Earth, 2013) draped over it. Oblique angle looking north.