Methodological evaluation of digital photogrammetry in a Middle Stone Age cave context.
A case study from Blombos Cave, South Africa.

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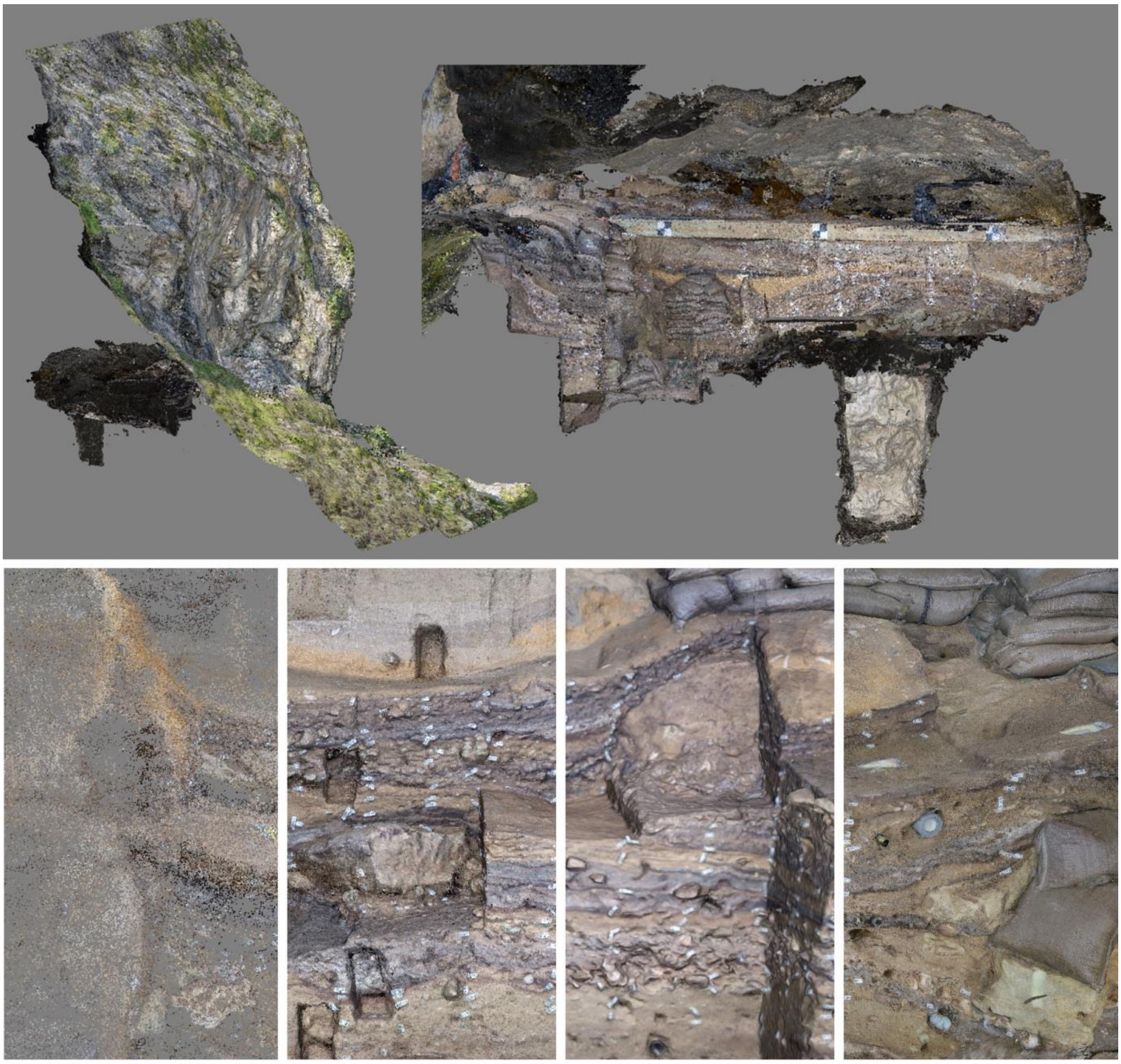
Master's Thesis



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Front-page figure. Above is a west side perspective of BBC and its immediate exterior (left) and east side perspective of the interior (right) displayed as point clouds. Below is an example of the 4 stages PhotoScan used to generate a 3D model exemplified through the south section of BBC.

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II ENGLISH ABSTRACT

In this thesis, I investigate how digital photogrammetry can be used as a standalone method of visual and spatial recording at the South African Middle Stone Age site of Blombos Cave (BBC). The method has become popular in the field of archaeology, thanks to advances in computer power and the introduction of powerful, automated and intuitive software solutions. The dark, confined and at times fragile nature of a cave, however, often presents a particularly challenging subject for many recording methods. This includes photogrammetry because it relies on a large number of high-quality photographs to generate a detailed 3D model of a site. Most methods of recording are only capable of producing data on current phenomenon; however, as photogrammetry generates data on the basis of images, it can generate information on things that no longer exist. If and how a photographic archive can be used to generate spatial information about archaeological features that no longer exist is therefore investigated.

During the work with this thesis, a successful strategy and workflow was developed; and this allows for the recording of BBC and its surrounding landscape. The strategy only utilizes equipment that is already part of the excavation project. Also, a strategy to successfully obtain new spatial information from archive images is also established and presented. To evaluate the spatial quality of the newly recorded data, a comparison is performed against the data collected using laser scanning in 2011. The results show that the photogrammetric dataset has similar spatial accuracy and has produced a complete record. To determine the relevance of introducing this new method, a methodical comparison and theoretical evaluation of the data I created, is also performed. Different methods of spatial and visual recording currently employed at BBC are specifically evaluated to determine if photogrammetry should be implemented fully into the recording strategy, and what role it might fulfill.

Digital photogrammetry is found to provide datasets that contain more and better information than more conventional recording methods, such as drawing, photography and laser scanning. In this thesis, I specifically argue that photogrammetry produces data sets containing a less abstracted representation of the real world; a trait that may prove very useful during the post-excavation phase, and highly beneficial when communicating with the wider public. The data sets I present can also valuable in multidisciplinary research and as a tool to mediate discoveries and archaeological contexts for future researchers. The thesis provides strong arguments for implementing digital photogrammetry as a recording method of archaeological cave sites. A functional, “best-practice” photogrammetric workflow was therefore made; both to tackle particular challenges at Blombos Cave, but also to provide advice for others, of how to best approach cave environments.

III NORWEGIAN ABSTRACT

I denne oppgaven undersøker jeg hvordan digital fotogrammetri best kan benyttes til å dokumentere en hulelokalitet. Den Sør-Afrikanske mellomsteinalder-lokaliteten Blombos Cave (BBC) er brukt som test-objekt. Takket være moderne prosessorkraft og kraftige, intuitive programvarer har fotogrammetri blitt populær innen arkeologisk feltarbeid, særlig under godt belyste forhold. Mørke, trange og til tider skjøre hulelokaliteter kan forøvrig by på utfordringer, også for fotogrammetri. Der mange dokumentasjonsmetoder kun evner å dokumentere samtidige fenomener, benytter fotogrammetri allerede eksisterende data (fotografier) til å generere tredimensjonale modeller. Hvorvidt fotoarkivet tilhørende BBC kan brukes til å generere ny spatial informasjon om utgravde kontekster, utforskes som et sekundært tema i denne oppgaven. Foreløpig har lite informasjon angående hvordan slike utfordringer best kan løses blitt publisert, og dette er noe jeg ønsker å forbedre gjennom denne oppgaven. En vellykket strategi for hvordan digital fotogrammetri kan benyttes til dokumentasjon av en hulelokalitet og dens omliggende landskap, samt produsere ny spatial data ved bruk av arkivbilder, blir utviklet og presentert gjennom denne oppgaven.

For å kunne fastslå den romlige kvaliteten av den fotogrammetriske dataen, sammenliknes den med et datasett som ble skapt ved bruk av laserskanning. Resultatet viser at fotogrammetri evner å oppnå liknende spatial nøyaktighet. For å kunne fastslå hvorvidt fotogrammetri bør innføres ved BBC, ser jeg nærmere på spatiale og visuelle dokumentasjonsmetoder som allerede blir benyttet ved lokaliteten. Metodiske begrensninger og teoretiske utfordringer ved informasjonen hver metode skaper blir også diskutert. Det slåes fast at digital fotogrammetri er godt skikket til å generere et datasett som er mindre selektivt og subjektivt, enn de øvrige metodene, og vil potensielt kunne overta noen dokumentasjonsoppgaver ved BBC.

Basert på resultatene som presenteres i oppgaven, argumenteres det for at fotogrammetrisk data har potensiale til å være svært nyttig i arkeologiske feltstudier, og med tilrettelegging gjelder dette også hulelokaliteter. Eksempler på potensiell, multidisiplinær bruk innen arkeologi, men også som formidlings og konserveringsverktøy trekkes frem for å underbygge denne argumentasjonen.

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VI Glossary

CPU	Central Processing Unit – The primary processing unit of a computer.
DSLR	Digital Single Lens Reflex camera – A digital camera using mirrors an
DEM	Digital Elevation Model - A digital model or 3d representation of a terrain containing information of the surface elevation.
EXIF data	Exchangeable Image File Format – A standard for specifying the format of images, which containing information regarding camera model, focal length, lens, ISO value etc.
GIS	Geographical Information System – Refers to a computer software or hardware developed to collect, manipulate, analyse, display and store geographical and spatial information.
GPU	Graphics Processing Unit – A processing unit specially designed to handle computer graphics and image processing.
JPEG	Joint Photographic Experts Group - A popular file format used to store compression image.
LSA	Later Stone Age – Refers to a period of African prehistory between 22 000 – 2000BP
MSA	Middle Stone Age - Refers to a period of African prehistory between 250 000- 22 000BP
Mesh	In computer 3d modelling mesh or polygon mesh is made up of vertices, edges and faces which make up the surface of an object.
Accuracy	The spatial position of a single point is measured and then re-measured multiple times. The measurements taken can be considered accurate if the mean of the measurements is close to the true value of the point, even if the spread is wide.
Photogrammetry	A method of obtaining 3dimentional measurements for a set of 2 or more images taken of an object or area from different angles.
Point cloud	When multiple XYZ coordinate points are visually presented, they form a point cloud. Such point clouds often represent the surface of an area or object.
Precision	The spatial position of a single point is measured and then re-measured multiple times. The measurements taken can be considered precise if the spread between the measurements is low, even if the mean is not close to the true position of the point.
TIFF	Tagged Image File Format – A file format used to store images with the ability for lossless compression.
TLS	Terrestrial Laser Scanning – A ground-based laser scanner, commonly just referred to as laser scanner.
RS	Remote Sensing – A method which measures a phenomenon without direct contact.
Orthographic Image	Unlike the perspective view of a conventional photograph which depicts a surface plane form a fixed positon an orthographic image depicts a surface at a right angle from the surface plane in the same way as a geographical map.

VII CONTENTS

1. INTRODUCTION

1.1. Aims and Research Questions

Digital photogrammetry is a method of remote sensing used to record spatial and visual data and has become popular within the field of archaeology. In just the past few years a series of studies and theories on the subject has been published (Fisher et al. 2015, Koutsoudis et al. 2013, De Reu et al. 2013) yet only a few publications have focused on cave contexts in particular (Grussenmeyer et al. 2012, Lerma et al. 2010, Núñez et al. 2013). These publications demonstrate how photogrammetry can be used to record smaller parts of a cave interior or how the method can be used to create a photorealistic texture for surface scans created with laser scanning.

In this thesis, I show how digital photogrammetry can be applied to an archaeological cave excavation as a standalone method, regarding recording and use of data. Also, I show how a new photogrammetric recording can be combined with images from the projects image archive to obtain visual and spatial information in a way that was previously not available. The idea is that this type of information has the potential to improve the understanding of material and recording stemming from past excavation seasons. The case study for this project is Blombos Cave (BBC), a South African cave site that was occupied during the Later Stone Age (LSA) and Middle Stone Age (MSA) (Henshilwood, D'Errico, et al. 2001).

The aim of my project is to discover how digital photogrammetry would work in a setting with which it is not associated and with conditions more challenging than are encountered at an open-air archaeological site. In addition to tackling the technical aspects of applying this method, equal importance is given to the evaluation of its archaeological relevance. Five goals were set for my project, each aimed at providing a solution for a different aspect of the overall question of my project - the how and why digital photogrammetry should be applied at Blombos Cave.

1) Develop a workflow for the specific conditions of a cave context/sites, specifically in:
   a) Low light setting
   b) Limited and confined space
   c) Complex geometry
2) Give “best practice” advice for the use of digital photogrammetry in these settings to provide a basis for future use of photogrammetry at BBC and similar sites.

3) Investigate if images for previous excavations can be combined with intentionally recorded images to obtain new spatial and visual data.

4) Evaluate and compare the photogrammetric workflow and results with other techniques used at BBC to determine the relevance and future role photogrammetry might have as part of a standardised recording structure at BBC.

5) Investigating the archaeological relevance for photogrammetry at an MSA Cave site such as BBC by determining potential areas of use and the quality of the information it provides.

The last goal is arguably the most important. Archaeological relevance is here defined as the ability of the new method to produce field data faster or to generate data of higher quality and novel character. I will, therefore, discuss the potential of the data I produce by drawing on examples of how such or similar forms of data have already been used. I will not go into the potential applications in depth as this is beyond the scope of this thesis.

1.2. Spatial extent and analytical scope

There are three main reasons why BBC was chosen as a case study for my thesis. First, limited data was available on the subject of recording similar environments, and thus BBC is an interesting and useful site to study. Second, the cave's relatively small size meant that a photogrammetric recording project was manageable within the time and scope of a master thesis. Third, the excavations at BBC had been carried out over many seasons meaning that there was sufficient material to work with and on which to perform comparisons.

1.3. What is photogrammetry?

Photogrammetry is the science of extracting true geometric measurement from still images. The word is made up of the three Greek words; "phot" meaning light, 'gramma' which may either refer to a letter or something drawn and 'metrein' which is the noun for the measure (Schenk 2005). To explain how photogrammetry works, our eyes may serve as an analogy. They are set slightly apart and therefore provide the brain with a pair of slightly different images caused by the two different angles from which they observe. With the help of this "offset", we get depth perception and can estimate the distance between ourselves and what we see and also the distance things we see. This principle, known as "stereoscopic viewing", is the key to getting three-dimensional information in photogrammetry. In photogrammetry, the eyes are replaced by images that originate from different camera positions but capture the same area. With two or more images we are then able to calculate the position of one or more points appearing within the images (Linder 2009: 1 - 2, Fussell 1982).

1.4. Thesis structure

- In this **chapter (1)** I presented the aims, scope and motivation for my project and outlined the general principles behind photogrammetry.
- In **chapter 2** I discuss a more in-depth background to photogrammetry in general and in archaeology specifically.
- In **chapter 3** I provide the theoretical framework for my thesis by clarifying the role and challenges of modern archaeology and archaeological documentation, outlining the emergence of modern documentation and discussing four examples of documentation with similar roles to photogrammetry.
- In **chapter 4** there is a general site description of Blombos Cave, where basic site information such as geographic location, stratigraphic sequence, excavation methodology and published archaeological material is presented.
- In c**hapter 5** I explain the technical and practical aspects of photogrammetry and how a recording strategy and workflow was developed and employed. I then go on to explain how the recorded data was processed into an end product.
- In **chapter 6** I present the results of my data collection and processing through a brief description and visual examples. I also evaluate the spatial quality of the data by comparing it a point cloud created using a laser scanner.
- In **chapter 7** I demonstrate how archive images from previous excavation seasons can be processed and combined with the results presented in chapter 6 to provide a new set of spatial data which is then presented
- In **chapter 8** I evaluate and discuss the results' individual and combined significance.
- **Chapter 9** I present my concluding remarks

During this project, a large amount of data was accumulated. Some of these are located in the appendix.

2. BACKGROUND TO PHOTOGRAMMETRY AND ITS USE IN ARCHAEOLOGY

To better understand how digital photogrammetry is used in archaeology, I briefly outline its development and its early use in archaeology. I then look at some concrete examples of how it has already been applied to archaeological sites similar to Blombos Cave.

2.1. Photogrammetry – a general background

The principles that photogrammetry rely on have long been known. Leonardo Da Vinci demonstrated how true spatial information could be deduced from perspective drawing given that certain information was available (Booker 1963, 222). Not long after the development of photography, by Daguerre and Niepce in 1839 (Schenk 2005), it was suggested that it would be possible to acquire measurements from this new invention. This was first attempted by Colonel Aimé Laussedat who successfully applied the principle on both photographs and drawings (Laussedat 1899). Figure 1 was created by Laussedat to show how two drawings are used to create a plan by matching points between them. As a result of his pioneering work he is often referred to as the “father of photogrammetry” (DeLoach et al. 2000, Schenk 2005). In these early phases, photogrammetry was most extensively used and developed in military settings as a means of mapping (Laussedat 1899).

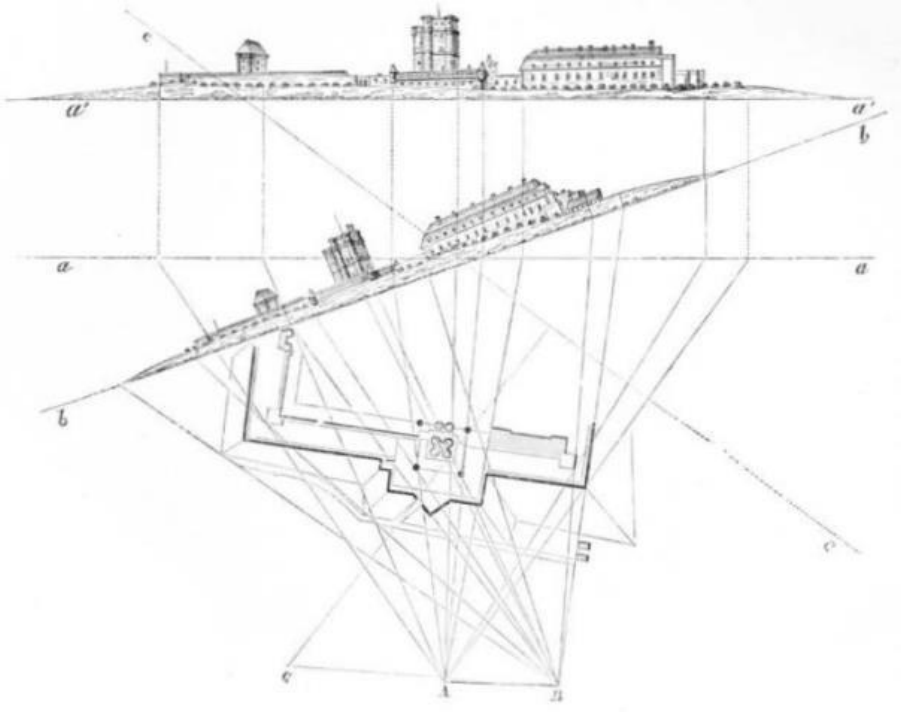


Figure 1: Early example of photogrammetric principles used to create a plan from drawings (Laussedat 1899, 28)

2.1.1. *Analogue Photogrammetry*

The early phases of photogrammetry, often referred to as analogue photogrammetry, relied on complex machinery requiring a photogrammetric operator to carry out all the operations and calculations mechanically and manually (Linder 2009). This was time and labour consuming work requiring specialists with a firm understanding of the principles. By the 19th century tests already showed that the method proved to be time and cost efficient compared to contemporary counterparts (Laussedat 1899).

2.1.2. *Analytical Photogrammetry*

With the invention of the computer in the 1950s and 1960s, it was then suggested that the orientation of a camera could be calculated using mathematical formulas calculated by the computer (Schenk 2005). A human operator was still required to analyse and plot points in the images using what is known as an “analytical plotter”. This method is known as analytical photogrammetry (Linder 2009).

2.1.3. *Digital Photogrammetry*

The current state of photogrammetry is referred to as digital photogrammetry or soft photogrammetry (Maalouli 2007). It uses digital images instead of analogue photographs, either captured by a digital camera or scanned from analogue originals. The majority of the image processing is now done automatically by software solutions employing what is known as ‘computer based vision’ to automatically identify, select and match points used to orient images in a relatively short amount of time (Brock et al. 2002). As the position of more and more points is calculated, they form what is known as a point cloud (Figure 2) similar to that created by a laser scanner (Koutsoudis et al. 2013). Contrary to laser scanning, digital photogrammetry does not require specialised equipment beyond what is in general use at most modern excavations. Rather, it mainly relies on the standard digital single-lens reflex (DSLR) camera but can have the value of its data improved with the support of a total station or GPS (Global Positioning System) (Parkinson et al. 1995) which are both instruments used to record the spatial position of points. These points can then, in turn, be used for geographical referencing, allowing for correct scaling and geographical positioning of the photogrammetric data (Agisoft 2014). Modern software solutions such as PhotoModeler Scanner, Photoscan, 123D Catch etc. have significantly aided with understanding and successfully employing photogrammetry in a way that makes sense to the archaeologist. In the next part, I demonstrate this.

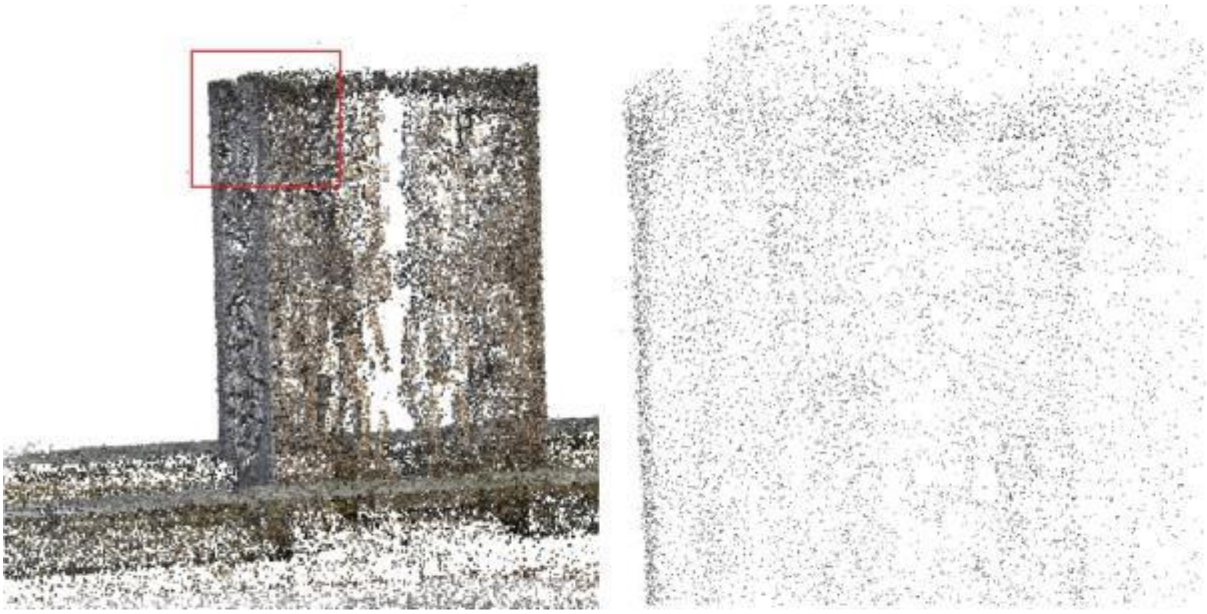


Figure 2: Point cloud created using the photogrammetric software. Total view left and closer view on the right (Images captured for Agisoft Photoscan).

2.2. Photogrammetry in archaeology

The earliest application of photogrammetry in an archaeological context took place during the 1874-75 expedition in the Persepolis ruins (Laussedat 1899). Up until the time of digital photogrammetry and even further on, the appearance of "low cost" automated solutions photogrammetry was primarily used for mapping and elevation models. The cost was one of the reasons preventing the archaeological community from employing photogrammetry. Even though this technique was cheaper than its counterparts, and had been for some time (Laussedat 1899), it was still too costly for most excavations as the analytical and analogue equipment needed to process the images was expensive and required a professional operator (Fussell 1982). As technology developed and the process became digitised the method started to be applied to different archaeological scenarios, besides general mapping. Cooper et al. (1994) explored the potential of photogrammetry when between 1989 and 1993 they recorded the tomb of Christ in Jerusalem. The project was a collaboration between archaeologists, historians, and photogrammetrists and resulted in a model of the tomb.

Recently, the personal computer, digital SLR cameras and relatively intuitive low-cost software solutions have allowed archaeologists to apply photogrammetric recording. Digital photogrammetry is now used in a wide range of archaeological settings; such as open air rescue excavations (Kjellman 2012), artefact recording (Koutsoudis et al. 2013), rock art recording (Lerma et al. 2013, Domingo et al. 2013, Rabitz 2012), the recording of cultural heritage structures (Koutsoudis et al. 2014) and submerged sites (Van Damme 2015, Diamanti et al. 2015). As a method that has now become accepted and adapted within the field of archaeology, there are numerous papers discussing its ease of use and cost efficiency compared to other methods of spatial surface recording (Kjellman 2012, Spring et al. 2014, Sanz et al. 2010, De Reu et al. 2013).

2.2.1. Photogrammetry and 3D recording in cave contexts

A core focus of my thesis is the application of digital photogrammetry in a cave setting. The spatial recording of these environments relies mainly on terrestrial laser scanning (TLS) (Leonov et al. 2014, Haaland 2012, Rüther et al. 2009). In cases where photogrammetry has been used (El-Hakim et al. 2004, Grussenmeyer et al. 2012, Grussenmeyer et al. 2010, Lerma et al. 2010, González-Aguilera et al. 2009) it is in combination with TLS. Digital photogrammetry then serves as a method of acquiring texture for the data collected by the laser scanner and not as an independent method.

An early example of spatial cave recording using photogrammetry is the 1994 recording of the Cosquer Cave in France. Cosquer Cave has a submerged entrance and thus required a team of divers and photogrammetrists to record its outline. TLS recording was also applied and combined with the photogrammetric data. The project showed that the data produced by photogrammetry had a lower degree of accuracy than that created using TLS. Also, the photogrammetric recording was a more tedious process because analogue images had to be developed after each recording day to maintain an overview of the recorded area (Thibault 2001). A more recent example, used on a larger scale in combination with TLS and a spatial imaging system, is the plotting of the Bronze Age Les Fraux Cave in France. In this project, the various methods were combined in a complementary way. One of the main focuses of digital photogrammetry, in this case, was to create a texture that could be applied to the TLS data (Grussenmeyer et al. 2012, Grussenmeyer et al. 2010). A further example is the recording of two caves in northern Spain, Las Caldas and Peña de Candamo. Here the large scale recording was done using TLS and close range photogrammetry used to record and provide texture for the rock art in the cave (González-Aguilera et al. 2009).

3. THEORETICAL FRAMEWORK OF ARCHEOLOGICAL DOCUMENTATION

3.1. Introduction – The role of archaeology

Archaeology is the study of the human past, from our origins up to the present. This is done primarily through uncovering and analysing the remains left behind by our ancestors, but also by looking at their contemporary environment and other aspects that might have shaped these early humans. The aim of archaeology is not just to understand how and when people lived but also why they lived the way they did. We do not just seek to identify what behavioural patterns can be identified by the material remains, but also how and why those patterns came to be (Renfrew et al. 2008, Scarre 2005). While personal interest and curiosity is the starting point for many archaeologists archaeology, today the profession also involves providing the public with a better understanding of the human past. This role is not just idealistically motivated but is related to the fact that modern archaeological research is often financed by the public and that many modern societies have deemed cultural heritage as something belonging to everyone and not a privileged few. As a result, it has become clear that modern archaeologists have to be able to communicate what they are doing and their discoveries to the public (McGimsey et al. 1977b, Renfrew et al. 2008).

The time between an archaeological excavation and the publication of material may be very long. Also, only a very small part of all the excavated material is ever seen by the public, most commonly through museums and popular science documentaries and publication. This is a problem because it may lead to common and negative misconceptions such as that “too many pointless excavations are taking place.” Such misconceptions are not just a problem affecting the public support archaeological excavations often need, but also the protection of cultural heritage. Human activity is the biggest threat to archaeological sites today. An example is the construction of cities and roads on land with cultural remains. Another example comes in the form of individuals failing to recognise that they have come across an archaeological artefact or site and intentionally or unintentionally damage or destroy it.

To prove its relevance archaeology does not only need to present discoveries but also explain the way in which the information has been acquired. Successfully mediating archaeological discoveries and their connection to archaeological sites has the potential to cultivate public interest and support. In addition to reaching out to the public archaeologists also have a duty towards their fellow scholars and scholars in other disciplines to publish their research and results. Academic peer outreach is, of course, important as it allows other members of the scientific community to study the results themselves and reinterpret material and in this way expand and improve our understanding of the past.

3.2. Challenges of archaeological field documentation

The primary source of information and knowledge, that archaeology brings to the public and shares within its field, stems from archaeological sites and excavations. It can, however, be argued that an archaeological site does not contain information but is in fact simply a composition of sand, dirt, rocks and the occasional artefact that have accumulated over time through different site formation processes. It is rather through excavation, interpretation, and documentation that information is produced. What this, in turn, means is that the information obtained from a site is greatly dependent on the interpreting archaeologist(s), their understanding of the material, the excavation strategy and recording methods (Roskams 2001: 35). In other words, physical material (the site) is turned into archaeological data through excavation, recording, and analysis which in turned is used to create an understanding of how a site came to be. The final analysis of the recovered materials will take place in the laboratory, and it is here that some of the greatest finds are made. Careful and well thought-out analytical and interpretive techniques are thus paramount.

Based on this argument it is clear that archaeological excavations have the potential to generate a lot of different data and this data will be coloured by the people and method that created it. It is also clear that the data collected from a site will not be an all-encompassing record of all the information that was uncovered at the site. Rather is will inevitably be a subjective selection of the potential information that could have been generated. Attached to this information comes an uncertainty as to what has been excluded and how correctly the data represents the real world. Depending on how it was obtained the archaeological data will in one way or another be a distorted representation of the actual site. Understanding how different recording methods process and abstract the real world is, therefore, important (Figure 3). The way in which a recording method distorts the real world can be divided into three layers (L2, L3, L4,). The first being the way in which for example a feature is conceived and understood (L2). This is followed by how and what the method records and how this information is presented (L4). The final layer regards the way in which active choices made during the recording process infer the recorders personal analysis (L4) (Longley 2005:129). In addition, comes the distortion caused by different site formation processes that have taken place over time since the site was first created (L1)

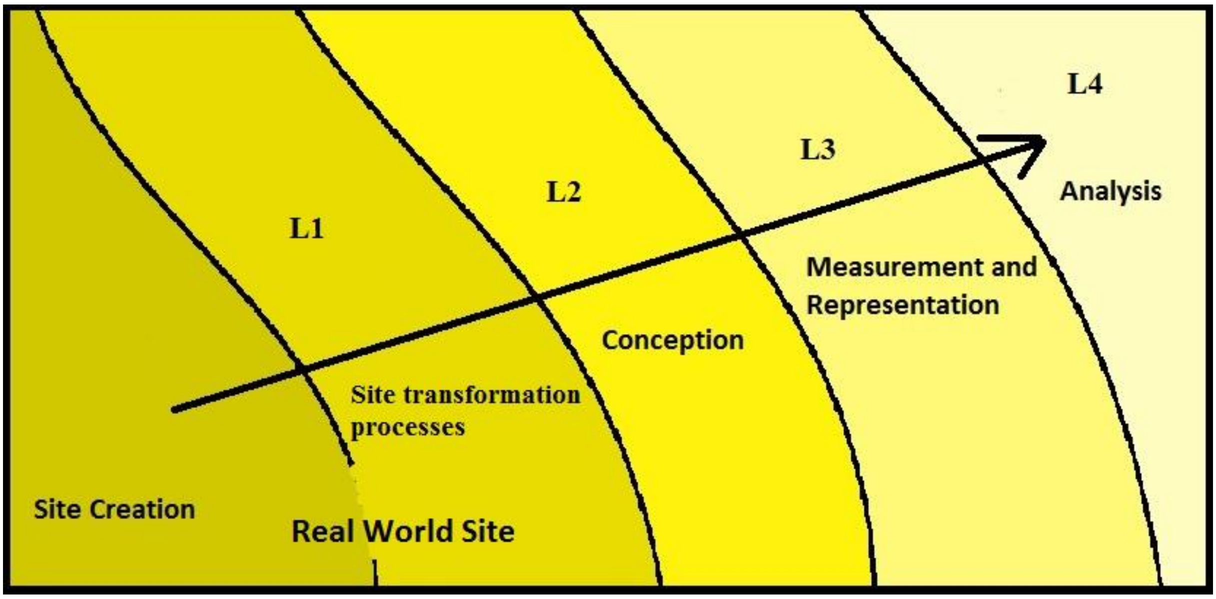


Figure 3: Visual representation of the different layers of distortion (L1, L2, L3, L4) separating the site as it was when it was created and how it is represented in the archaeological record. The initial distortion is a result of the transformation processes occurring over time altering a site from its original state to the state it has during excavation (L1). The remaining layers represent the abstraction caused by the recorders conception (L2), how data is measured and represented (L3) and the level of analysis inferred by the recorder (L4). The figure is adapted from Longley 2005 (128).

Today archaeological excavations are often part of interdisciplinary collaborations including social sciences, physics, geology, biology, etc. Such collaborations have the potential to allow for more solid theories and a greater understanding as they provide a huge range of different information with different resolutions and relying on various proxies. As a result, modern archaeological research projects need to have an overarching research goal used to develop a suitable strategy meant to ensure that the necessary data is produced (Renfrew et al. 2008). Archaeological research and analyses are to a large degree carried out over long periods after excavations have finished. In addition, much of the cross-disciplinary research is often performed by individuals who have spent a limited amount of time at the site (Roskams 2001:37-39). As time passes the memory of how the site was and the memory of things that happened during an excavation will deteriorate, and the researchers understanding of the site becomes more dependent on recorded data. The ability to create a solid interpretation or theory is, therefore, dependent on the data quality and correct understanding of how different recording methods abstract and distort the real world to shape the recorded data (Figure 3). While artefacts are mobile and can be extracted from a site, features, sections, and layers are immobile and are often destroyed as part of the excavation process. This means that while the artefacts can be studied at a later stage, any study of the immobile elements will rely on the site recordings (Renfrew et al. 2008: 115).

The recording performed as part of modern research projects is aimed at collecting data necessary to answer specific research questions. While this might be the primary intention behind the application and execution of a recording method, the documented data will often serve secondary functions. For example, if a site is re-excavated by new archaeologists their understanding of the site will be shaped by what the previous archaeologists considered important enough to document and how distorted or abstracted documentation is. This is also an important factor that comes into play when new questions are addressed using old excavation material. In some cases previously recorded material may be too distorted to be safely relied upon, and new excavations become necessary (Roskams 2001).

3.3. Introduction to the development of archaeological documentation

An archaeological artefact on its own may have limited value when attempting to understand the past; rather it needs to be seen in connection with the context in which it was recovered (Carver 2009). Another equally accepted fact is the destructive nature of archaeology, by which is meant that the excavation of a site both gives us information and destroys the site (Lucas 2001b: 40). The importance of context and the finality of excavation have of course not always been a cause of concern as it is today. During the greater part of the 19th-century archaeological material and sites were largely the interest of collectors and antiquity dealers whose greatest concern was value, aesthetics and how exotic the artefact is (Lucas 2001a, 4-5).

A contrast to this is the work of General Pitt Rivers who lead systematic excavations with thorough documentation, including detailed topographic plans (Pitt-Rivers 1887). He has since been revered as the “father of field archaeology” (Lucas 2001a, 5 and 19). Pitt Rivers argued that the archaeologists’ primary objective is to document as thoroughly as possible while attempting to remain as objective as possible (Pitt-Rivers 1887, xvii). In this way, the valuable information uncovered during a good excavation would be preserved for the future (Lucas 2001a:20). If Pitt Rivers is credited with having created modern field archaeology, then Flinders Petrie is credited with producing one of the first field manuals “Methods and Aims in Archaeology” (Petrie 1904, Lucas 2001a). This meticulous work includes chapters on everything from the organisation and handling of workers and excavators to recording, packing and ethics. As with Pitt Rivers, Petrie greatly emphasised the importance of systematic excavation and recording and the important relation between artefact and context (Petrie 1904, 50).

> *"The unpardonable crime in archaeology is destroying evidence which can never be recovered, and every discovery does destroy evidence unless it is intelligently recorded. Our museums are ghastly charnel-houses of murdered evidence…" (Petrie 1904, 44).*

On the subject of recording he describes the correct use of the tools of his time: the divided rod, measuring tape, box-sextant, theodolite, plane table, prismatic compass, and the camera (Petrie 1904, 54-55 and 73). An important point made by Petrie is that no matter how thorough a recording takes place it is still limited by the recorders observation, more often than not he finds what he is looking for, rather than discovering that which he did not know existed (Petrie 1904, 1). Since then different opinions and approaches on the matter of archaeological excavation and recording have been presented, developed and challenged. As methods evolve and develop the archaeologist is faced with the challenge of deciding the best level of resolution at which to excavate, study and record his or her site. The extremes at each end being either too up close to see the bigger picture or too far away and thus overlooking the important details (Kidder et al. 1962, 137-138).

As part of the evolving methods of documentation, new technologies are being adopted and adapted for archaeological use. When it comes to spatial and visual recording some examples are the total station (Wheatley et al. 2002), laser scanning (Rüther et al. 2009), structured light scanning (McPherron et al. 2009, Roman et al. 2010) and Reflectance Transformation Imaging (Díaz-Guardamino et al. 2015). The method I will be testing in this thesis, digital photogrammetry, is one such method that is becoming popular amongst archaeologists, but whose origins date to the mid-19th century (Fussell 1982, 157).

3.4. Methods of surface documentation

An important part of archaeological documentation concerns the recording of space and surfaces. To record this, archaeologists use a range of different methods and tools. These work in different ways and, while often able to record the same areas, may provide very different results. I present four different methods used to record archaeological surfaces and space by describing the way they work, what type of data they provide and how this data is affected by the different layers of distortion. The selection reflects methods that are currently being used at BBC and will form part of a methodical comparison evaluating what role photogrammetry might have at BBC (chapter 8).

3.4.1. Drawing

Drawing was one of the first recording methods employed by archaeologists and is to a varying degree still being used. During an archaeological excavation, drawing will often be used to record section stratigraphy, layers and features (L2) and come in the form of either a technical drawing or a sketch (L3). Technical drawings are spatially correct two-dimensional representations created using careful measurements while sketches are normally quick, imprecise and stylised drawings serving as metadata for field notes. Both forms of drawing techniques will in many cases contain information describing the surface and composition of recorded objects in the form of a legend. A defining feature of drawing is that is a highly analytical method of documentation (L4). The archaeologist has complete control over what is being recorded. This has the advantage of better showing important elements of the feature that is being recorded. The advantage is double-edged, however, because important information might be overlooked. Compared to digital documentation drawing has the advantage of not being reliant on electronic equipment which may be subject to failure under harsh conditions.

3.4.2. Photography

To varying degrees, photography has taken over the roles of drawing in many archaeological excavations, such as recording section stratigraphy, features, and layers. An advantage of photography is its ability to capture more information in a shorter span of time that drawing. If used correctly and under reasonable conditions, a modern camera can capture a high level of detail both in terms of resolution and colour. Modern digital cameras also allow the recorder to instantly review images and make adjustments. Photography is often deemed a more objective form of documentation than drawing as it captures everything in its view and not just what has been selected by the recorder (L2). While perhaps less analytical than drawing there are many subjective choices that come in to play when creating a photographic record. These include the decision of at which stages photography should be performed, what should be included in the image (scale, surroundings etc.) and the angle and distance an object should be photographed from. In addition to the subjective factors affecting photography, there are also technical aspects (L3) set by the recording device which shapes the result. These affect how much information the camera can record and how an image is distorted. An example of the former is the image sensor which determines the camera's ability to handle different types of light, the resolution of the image and to correctly separate colours. The camera optics is an example of the latter as it distorts the shape of everything in the image to a varying degree. Because of this images are normally only used to obtain visual information and at best a rough spatial estimate.

3.4.3. *Laser scanning*

LiDAR (light detection and ranging), often referred to as laser scanning, is a method of remote sensing, meaning that it measures a phenomenon without direct content. The method uses a laser to obtain, visualise, and analyse three-dimensional data points of archaeological objects (Brock et al. 2002, White 2013, Mlekuž 2013). LiDAR is an active method as it induces a phenomenon and measures the reaction. This allows it to work regardless of lighting conditions. The method works by firing a laser pulse that is reflected back to a sensor array upon hitting an object. With the information of the sensor array's exact position at the time it emitted the laser and received the reflection, the position of the object reflecting the laser is calculated (Crutchley et al. 2009: 3-4, White 2013: 176-178). A laser scanner may record the position of between tens of thousands and millions of individual points per second. Together these points form a point cloud which represents the surface of a scanned object. Ground-based laser scanners are referred to as terrestrial laser scanners (TLS). These are highly accurate, the scanner used at BBC, for example, is capable of recording a surface with an accuracy of 3mm at distances of 30m and bellow (www.trimble.com).

A TLS' ability to correctly recreate the surface of a recorded object is primarily affected by two factors. A constant factor is the limitations of the recording device itself, its accuracy, precision, range, etc. and a varying factor is how well the device is set up by its operator (L3). I would argue that the point cloud created using a laser scanner has a limited analytical distortion as the method mechanically scans the entire surface designated by the recorder. The proper analysis of the point cloud first takes place after the recording is finished. The data are unavoidably covered by the natural layer of distortion caused by the recorder's perception (L2) affecting the decision (L4) on when and where to perform the scan. It does, however, have the potential to inadvertently record information the recorder might have overlooked or failed to understand. The point cloud, while a spatially accurate representation, will in many cases not contain any colour information. This means that identifying for example different layers in a section profile will be impossible (L3).

3.4.4. Total station (Spatial single point recording)

A total station relies on the same principle as a Laser Scanner, by measuring the return time of a laser pulse. The total station is however not designed to scan surfaces in high resolution but rather to measure the position of single points. How correctly these measurements are determined by the same two factors as a TLS. The primary uses of total stations tend to be spatial plotting of finds, samples and other forms of single point spatial recording. The recording provides XYZ coordinates of a recorded position. Just as with the drawing practice, the archaeologist actively chooses what to record and how to label the plotted positions and as such its recorded data are subjective. Consequently, the recorded data is greatly distorted by the archaeologist's perception (L2) and selective choices (L4). The method provides highly accurate data however the description of what each point represents may vary greatly (L3).

3.5. Concluding remarks

How and what kind of information is collected by different methods of recording has a great effect on the information that is produced and preserved when an archaeological site is excavated. Modern archaeology often relies on cross-disciplinary collaborations. This means that it can be an advantage if the recording methods employed provide intuitive data which may be relevant and is easy to use for multiple members of the research team.

Intuitive documentation also has the potential to serve secondary roles outside the scientific community. Here some forms of archaeological recording may provide data that can be used to help with mediation as part of for example outreach programs and museum exhibitions.

No form of recording is all-encompassing and devoid of the recorders opinion and understanding. However, the degree of distortion between the real world and a set of recorded data greatly affects it's potential to be used in different forms of analysis and determines how prosperity may understand a site. Properly understanding how different factors affect different forms of documentation is, therefore, important to determine, how it can be used and consequently its potential value.

4. SITE AND MATERIAL

In this chapter I describe the background of BBC, the archaeological material uncovered and the excavation methodology currently followed.

4.1. Location

Blombos Cave (BBC) is located on South Africa's southern Cape coast, 300 km east of Cape Town. The site lies within the Blombosfontein Nature Reserve roughly 100m from the (Indian Ocean) shoreline in a steep incline 35 meters above sea-level. The cave has a south facing opening and was formed by wave action cutting into the calcified sediments of the Mio-Pliocene Wankoe Formation (Henshilwood, D'Errico, et al. 2001). The cave is relatively small and confined, having a floor area of 55 square meters behind the drip line and a roof height of roughly 1 – 1.5m from the upper layer before excavations commenced in 1991. It is presently between 2.5 and 2.7 meters from "floor" to celling in the excavated areas. In addition to the preserved deposits behind the drip line, an additional 18 square meters outside the cave is held in place by large boulders (Henshilwood et al. 2001, Henshilwood 2008).

4.2. Excavation History

Initial investigation of the site was undertaken by Christopher Henshilwood between 1991 and 1992. BBC, at that time, referred to as GSF 8 (Garcia State Forest, Site 8) was part of a greater study for Henshilwood's doctoral thesis "Holocene archaeology of the coastal Garcia State Forest, southern Cape, South Africa" (Henshilwood 1995). When first discovered the cave opening was nearly completely covered by dune sand and 20cm of aeolian sand covered the upper Later Stone Age (c. 2 - .3 kilo anno, ka) layers. The aeolian sand cover indicated that the LSA layers had not been disturbed since the time of their final deposition roughly 300 years ago. The early excavation was focused on the LSA layers, and BBC (GSF 8) was one of a total of 9 archaeological sites being studied. In 1997 excavations restarted at the site, now renamed Blombos Cave and these are continuing. The focus of the excavations is currently the Middle Stone Age (MSA) layers (c. 100-72 ka). (Henshilwood, Sealy, et al. 2001, Henshilwood 2008, Henshilwood, D'Errico, et al. 2001, Henshilwood et al. 2002, Henshilwood et al. 2004, Jacobs et al. 2006a, Henshilwood et al. 2009, Mourre et al. 2010, Henshilwood, d'Errico, et al. 2011).

4.3. Stratigraphy and Dating

The LSA deposits are divided into three main occupational periods (L1, L2 and L3) and are separated from the MSA deposits by a sterile aeolian sand unit, referred to as "DUN" or Hiatus, with a thickness of between 5 and 50 cm. The LSA Deposits have been dated to 2000-290 BP using radiocarbon dating (Henshilwood 2008). Within the MSA layers, four main occupation periods have been identified (M1, Upper M2, Lower M2 and M3) which in turn have multiple finer sub lenses (Figure 4) (Henshilwood 2005, Henshilwood, Dubreuil, et al. 2011). Multiple methods have been employed to date the MSA levels including Electro-spin Resonance (ESR), Uranium-Thorium series (U/Th), thermoluminescence (TL) and optically stimulated luminescence (OSL) (Henshilwood, d'Errico, et al. 2011, Jacobs et al. 2006b, Henshilwood et al. 2002, Jacobs, Duller, et al. 2003, Jones 2001, Jacobs, Wintle, et al. 2003). The M1 phase has been dated to 74±5 ka and 78±6 ka, and 72.7±3.1 ka and 76.8±3.1 ka, using the TL and OSL respectively (Jacobs, Wintle, et al. 2003, Jacobs, Duller, et al. 2003, Jacobs et al. 2006a, Tribolo et al. 2006). OSL has dated the sterile dune sand, DUN, to 68±4 ka, 69±5 ka, and 70±5 ka. The M2 phase has been dated to 81±4 ka and 82±4 ka using OSL (Henshilwood, d'Errico, et al. 2011, Henshilwood et al. 2002). The various dates give BBC a suggested occupational period between c. 300 years to 101 ka with an occupational hiatus between 70 ka and 2 ka caused by the cave opening being sealed by dune sand (Henshilwood 2005, Jacobs et al. 2006a)

4.4. Archaeological finds from Blombos Cave

The conditions for preservation of material and stratigraphic integrity have been very good at BBC. Three factors have played a part in facilitating these conditions. The first is the aeolian dune sand which created a protective sand layer covering the deposits during periods when the site was not occupied. The second is the groundwater, rich in calcium carbonate, seeping from the cave roof through the sediments creating an alkaline environment. The third is the natural protection a cave offers.

4.4.1. Ochre Pieces

Over 8000 pieces of ochre has been uncovered for the MSA levels at BBC, of which more than 1500 are longer than 10mm. Many of these show signs of intentional use and processing. The most interesting parts of the ochre material are the two internationally engraved pieces (77-72 ka) published in 2002 (Henshilwood et al.) and the additional 13 engraved pieces (72-

101 ka) published in 2009 (Henshilwood et al.). These engravings suggests some of the earliest forms of symbolic behaviour known (Henshilwood et al. 2009).

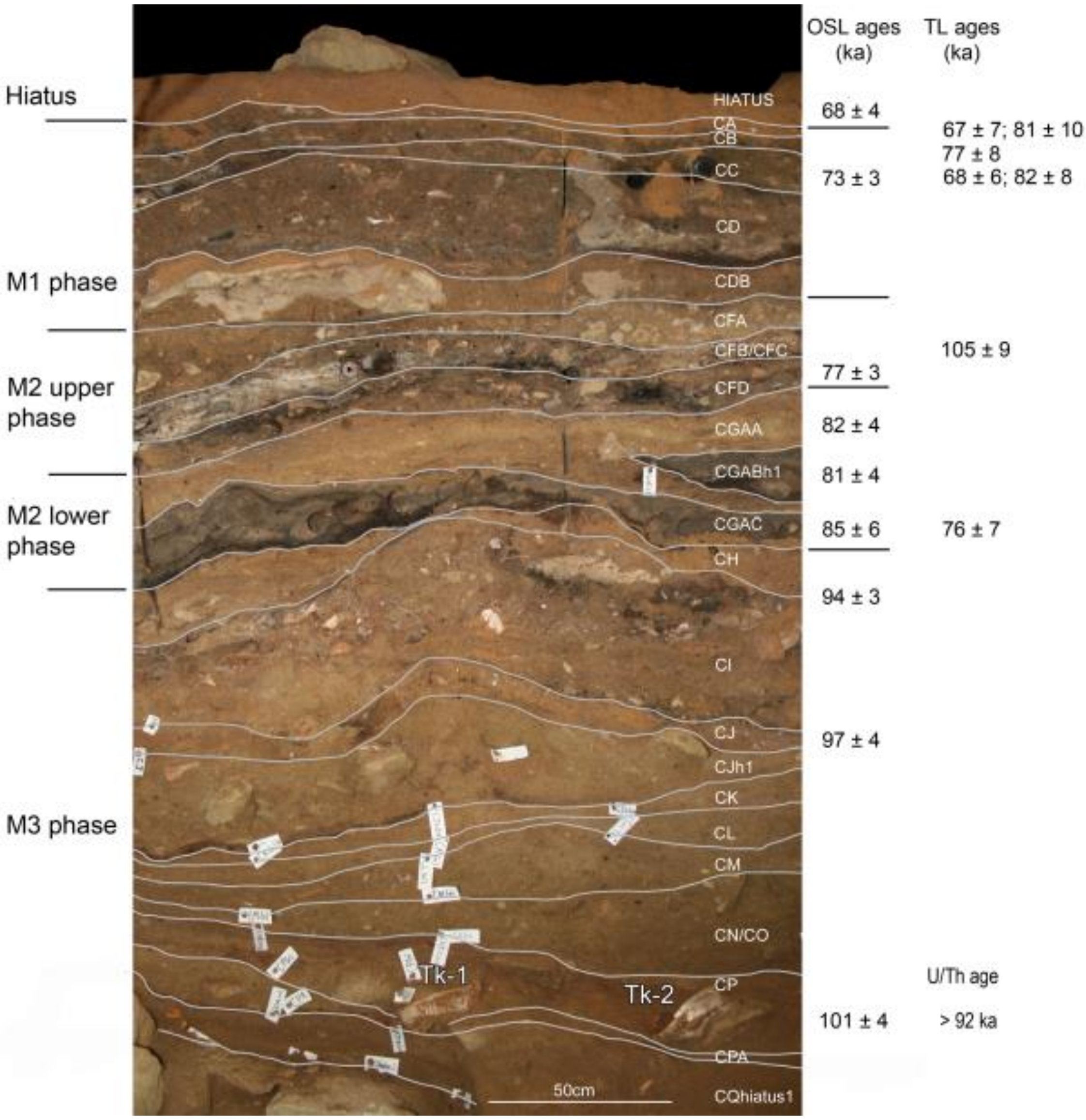


Figure 4. Part of BBC's south section. The numerous stratigraphic units have been outlined and labelled, and the corresponding phase (left) and estimated dates (right) are listed on the side (Henshilwood, d'Errico, et al. 2011)

4.4.2. Ochre-Processing Workshop

An ochre processing workshop dated to 100ka was discovered in 2008. The workshop contained two *Haliotis midae* shells containing a liquefied ochre mix. Bone, charcoal, ochre, grindstones and hammerstones next to the shells with the ochre mix residue are a part of the workshop. This material has been interpreted as an ochre processing toolkit. The toolkit was found *in situ* and covered by dune sand suggesting that it was abandoned shortly after use

(Henshilwood, d'Errico, et al. 2011). The purpose of the processed ochre mixture is not known and open for interpretation.

4.4.3. *Still Bay Points*

The top the M1 and upper part of M2 phase have yielded bifacial, leaf-shaped points of a distinct type which are restricted to southern Africa's Still Bay techno-tradition (Henshilwood, Sealy, et al. 2001, Villa et al. 2009, Mourre et al. 2010). Studies have shown that around half of these points appear to have been heat-treated before they were finished using pressure flaking techniques (Mourre et al. 2010). The bifacial points appear to have served as spear points and multi-purpose tools (Lombard 2007, Villa et al. 2009).

4.4.4. *Bone Tools*

Over 100 bone tools have been recovered from the LSA and MSA layers, including awls and bone points. Of the 57 stemming from the Still Bay units (Haaland 2012), 40 have currently been published (Henshilwood et al. 1997, Henshilwood, D'Errico, et al. 2001, Henshilwood, Sealy, et al. 2001, d'Errico et al. 2007). The bone awls were primarily made from long-bone shaft fragments and sharpened using scrapers. It has been suggested that some of these points may have been used to pierce shell beads and soft material (Henshilwood, D'Errico, et al. 2001, d'Errico et al. 2005). Some of the bone points that may have been hafted and used as projectile points were polished after the scraping process. As the polished surface appear to give no apparent practical benefit, it may be that the polishing was performed to improve the tools aesthetic quality, perhaps adding to its value (Henshilwood, Dubreuil, et al. 2011). In addition to the bone tools a bone fragment with eight parallel lines has also been recovered from the Still Bay layers. Microscopic analysis has concluded that the incisions are not a result of butchery but rather intentional engravings made using a stone tool. The engraved pattern on the bone tools resembles that found on the engraved ochre pieces (D'Errico et al. 2001).

4.4.5. *Shell beads*

Over 70 *Nassarius kraussianus* shell beads have been recovered from the upper part of the M2 phase and the M1 phase at BBC (Henshilwood et al. 2004, Vanhaeren et al. 2013, d'Errico et al. 2005). The beads primarily stem from the M1 phase and all occur within the Still Bay layers. They appear to have been intentionally pierced by what has been suggested to be bone points. Microscopic analysis of the use-wear found on the beads has been compared with modern experiments and show that the beads had been strung together and potentially worn or attached to clothing (d'Errico et al. 2005). The different groups of beads found within the cave are found to have use-wear unique within a single group suggesting different ways, or styles, of stringing and attaching the beads (Vanhaeren et al. 2013).

4.4.6. Behavioural interpretation of Blombos Cave Middle Stone Age assemblage

The key finds mentioned here, the engraved ochre, toolkit and *Nassarius kraussianus* shell beads are all considered to be convincing, early signs of modern human behaviour. The complexity and multitude of components making up the toolkit suggest an ability for planning and preparation (Henshilwood, d'Errico, et al. 2011) and the use of jewelry and creation of abstract patterns suggest the emergence of symbolic behaviour (Henshilwood et al. 2009, d'Errico et al. 2005)

4.5. General excavation and recording strategy

The method/strategy of excavation and recording employed at BBC has developed quite significantly since the first excavations took place in 1992. To see how photogrammetry will fit into the recording system at BBC, the methods already employed are presented here.

4.5.1. Coordinate system

During the initial excavations at BBC, an alphanumerical square meter grid system was established. The system aligned with the cave's North-South axis where the cave opening had been defined as South. The coordinate system started at A1 and had values increasing in the South and East direction. The squares are named after their northwestern corner and are in turn subdivided into half meter quadrants with alphabetic names a,b,c,d. As part of Haaland's Master's dissertation (2012), a new and secondary numerical coordinate system was developed. It overlays the old system (Figure 5) and was used as part of an intra-site spatial analyses (Haaland 2012). In the new system X and Y have been given the arbitrary values 50 and 100 while Z refers to the altitude above sea-level. From the creation of this new coordinate system, all spatial recording in the field has been using it (Haaland 2012).

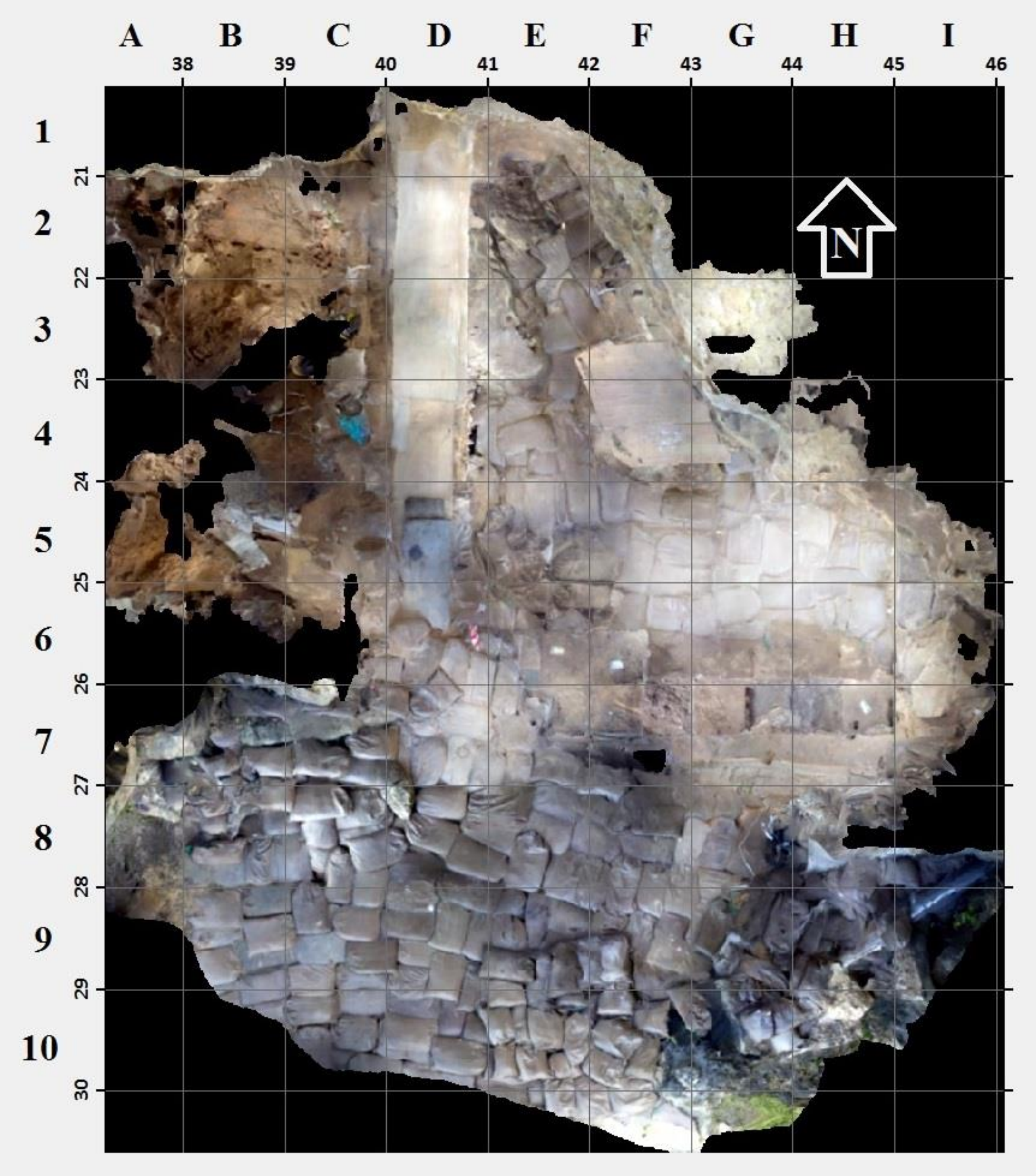


Figure 5. Sitemap of Blombos Cave.

4.5.2. Excavation methodology

Excavation has from the beginning primarily relied on trowel and brush and follows the natural stratigraphy of the deposits. The work is done quadrant by quadrant with stratigraphic units being defined by texture, colour, composition, thickness and content and subsequently labelled as units or subunits. Layer thickness varies between 2 and 30 cm. Identified layers are given alphabetically ordered names (CA, CB, CD, CC) starting from the top and advancing through the alphabet as the excavation progresses downwards (Figure 4). Layers that are perceived to have greater contextual similarities are given a third letter, to indicate their relationship to the parent unit (e.g. CFA, CFB/CFC, CFD).

4.5.3. Finds recording

During excavation,archaeological material is collected and labeled with reference to its respective quadrant and layer. Finds of significant interest are also spatially recorded within the numerical coordinate system using the Trimble VX Spatial Station (total station). The spatial station has an accuracy of +/- 2mm and a precision of 1/1000 cm (see glossary for definition). The general categories of finds regarded as having significant interest include lithics over 2cm, ostrich eggshell, ochre, identifiable bones and other artefacts of special interest. These finds are then individually bagged and labelled with a unique specimen number and provenance data. Non-plotted material from each quadrant, such as sediments and deposits are sieved through 3mm and 1.5mm mesh and labelled as coarse fraction and fine fraction respectively. This material is then retained for further sorting and analysis.

4.5.4. Surface recording

Each stratigraphic unit's surface is topographically recorded on a quadrant level. This is done by first scanning the quadrant surface recording 500 spatial points using the Trimble VX Spatial Station which creates a 3D point cloud. Secondly, 4 markers are placed on the surface and spatially recorded before it is photographed (Nikon D4 DSLR). The point clouds can then later be combined and used to create a surface model on which the photographs can be draped. This will then result in the digital recreation of the entire unit surface from the time this form of recording was started (2011). In 2011 a Trimble CX 3D Laser Scanner, a ground-based or terrestrial laser scanner (TLS), was used to perform high-resolution surface scans from 4 different positions within and outside the cave. The resulting 4 point clouds were combined into a complete point cloud model covering both the interior and exterior containing a total of 20 million points. The TLS data was used to create a plan of the cave interior at various levels in addition to contour lines of the cave exterior. In turn, this data was further processed to create a plan view of the cave outline (Haaland 2012). In chapter 6 I use this point cloud as a reference to evaluate the accuracy of the photogrammetric recording I performed.

5. METHODS: TECHNICAL AND PRACTICAL APPROACH

In this part, the theoretical background and practical execution of close range photogrammetric recording and processing are presented. This will give a basic understanding of how the recording is executed, the factors affecting the recording (Figure 3) and how conventional images are used to create three-dimensional models. The workflow of digital photogrammetry can be divided into two main stages. The first is the recording, which is explained below, and the second is image processing which is illustrated and described in Figure 7.

5.1. Establishing a photogrammetric recording workflow

Photogrammetric recording relies on one main tool: the camera. Almost any modern camera can be used. However, the camera's quality and specifications directly affect your recorded photographic material which subsequently determines the quality and nature of your result. Some of the most important camera specifications to be considered are:

1. **Image resolution:** The image resolution directly determines the level of detail contained within the image and in turn the amount of detail made available for the software solution to recreate a recorded object.
2. **Dynamic Range:** The camera's (camera sensors) ability to differentiate between the different nuances in colour. This determines the amount of information available, of objects with a very monotone colour palette.
3. **Lens distortion:** The way an image is distorted by the camera's optics, in turn, affect how a photographed object is represented in the image.

The next important consideration should be recording strategy. Depending on what is being recorded, varying strategies for image capture should be used (Figure 6). As mentioned photogrammetry relies on observing how things appear from different angles, important elements to be kept in mind are, therefore:

4. **Camera movement**: Images need to be captured for different camera positions, the camera should not be panned.
5. **Maintaining good overlap**: for the images to be able to work together a 60-80 percent overlap is recommended.
6. **Persistent scene/object**: No changes should be made to the object or area during the recording process, the object needs to remain consistent

7. **Avoid reflective surfaces**: A reflective surface causes an object to have a different appearance depending on the position it is viewed from or the position of elements it is reflecting.
8. **Sharpness and exposure**: Unfocused or blurry images give an incorrect representation meaning misinformation, the same can be the case with incorrect exposure.

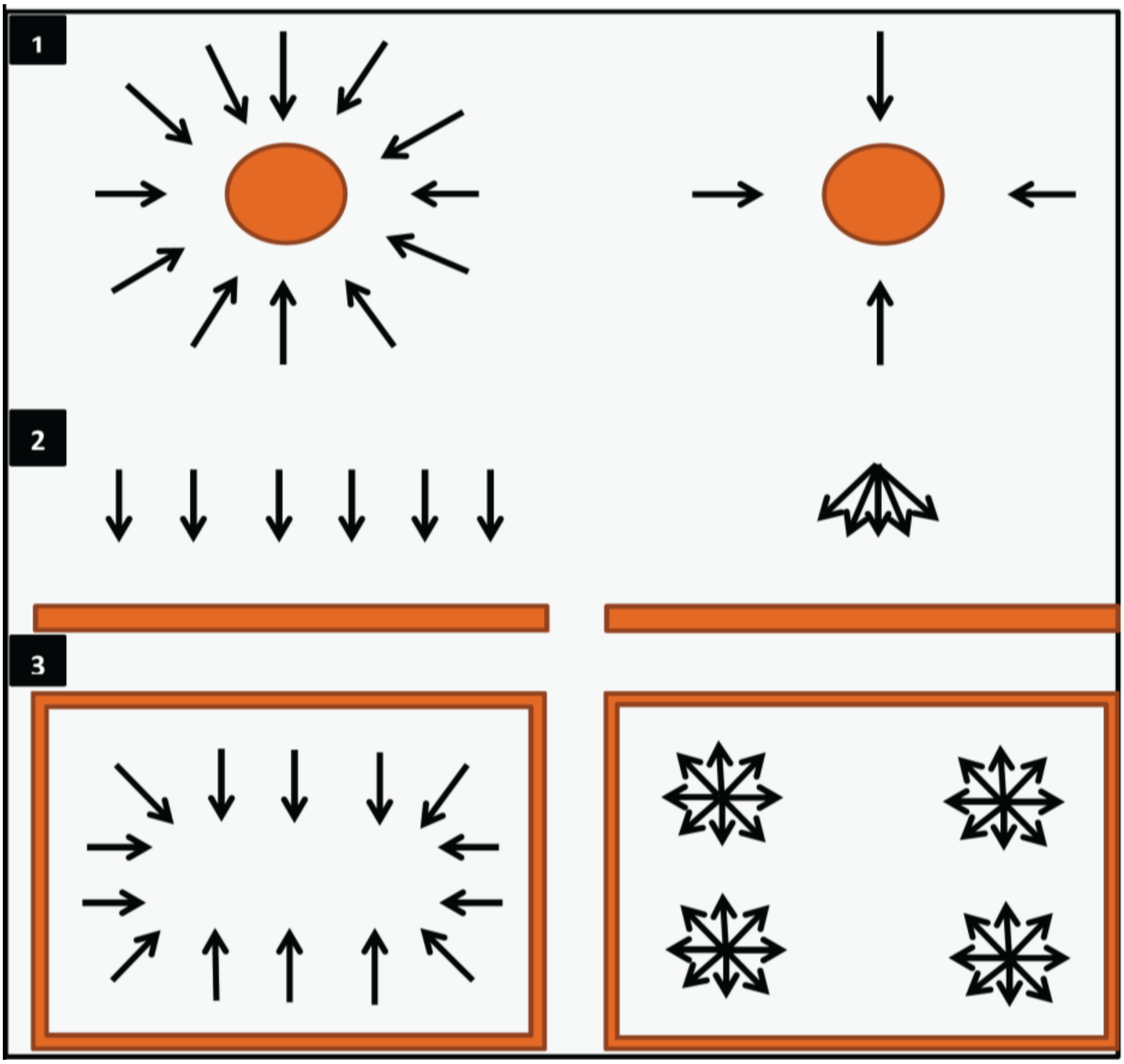
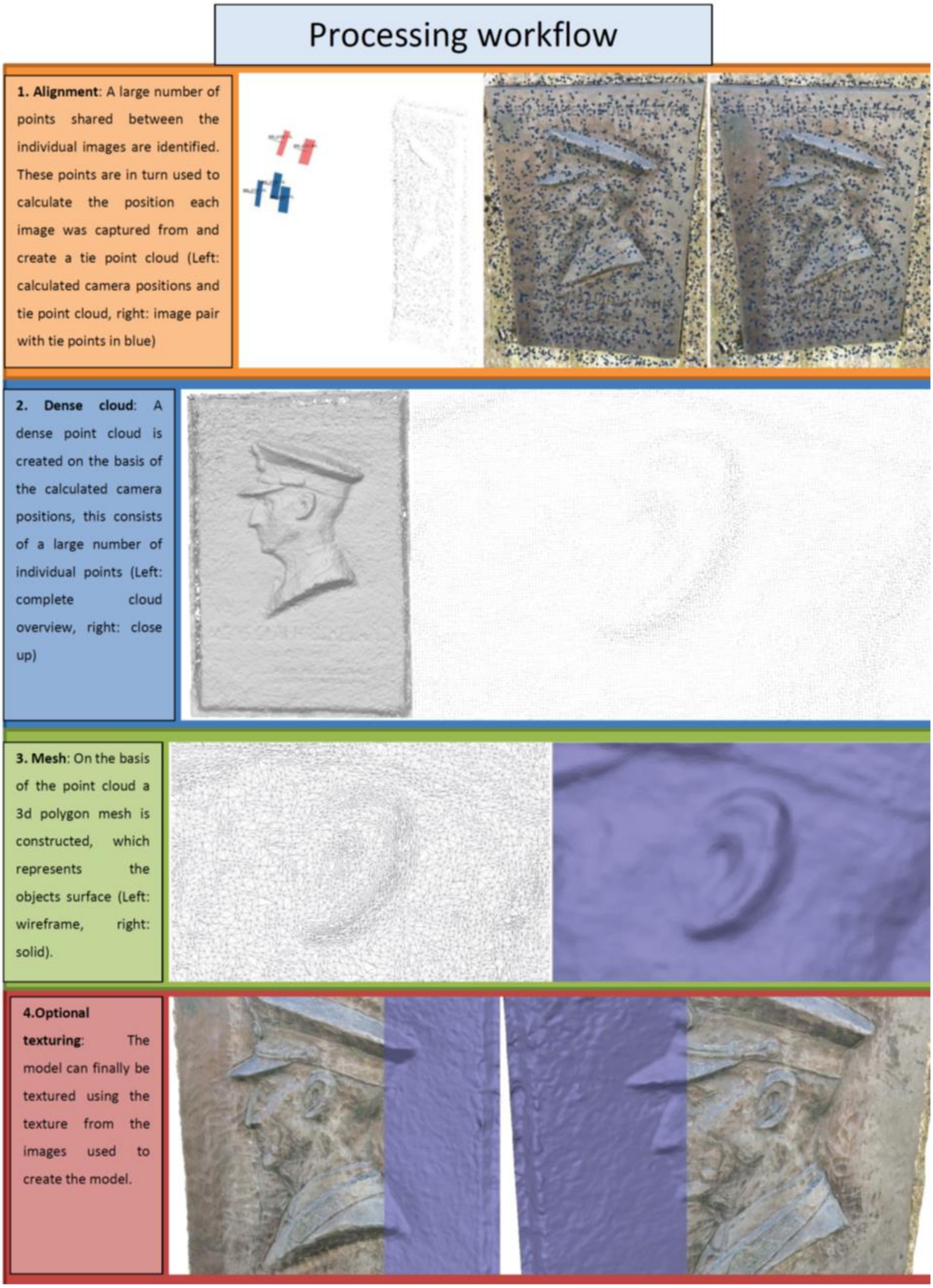


Figure 6. Illustration of recording strategy for freestanding object (1), façade (2) and enclosed surroundings (3). Left side shows correct execution, right side illustrates insufficient overlap (1) and incorrect camera positioning (2 and 3). Adapted from (Agisoft 2014, 5-6).



Processing workflow

1. Alignment: A large number of points shared between the individual images are identified. These points are in turn used to calculate the position each image was captured from and create a tie point cloud (Left: calculated camera positions and tie point cloud, right: image pair with tie points in blue)

2. Dense cloud: A dense point cloud is created on the basis of the calculated camera positions, this consists of a large number of individual points (Left: complete cloud overview, right: close up)

3. Mesh: On the basis of the point cloud a 3d polygon mesh is constructed, which represents the objects surface (Left: wireframe, right: solid).

4.Optional texturing: The model can finally be textured using the texture from the images used to create the model.

Figure 7.Graphical figure illustrating the 3 steps of surface reconstruction and the optional fourth step of texture reconstruction (all images captured from within Photoscan).

5.2. Software evaluation and pre-field tests

5.2.1. Pre-field preparations

The time between when I had selected a topic for this thesis and the start of the 2013 field season was limited. Here, I briefly elaborate on the process of selecting a software solution for this project. I then describe the pre-field preparations that helped develop a workflow strategy that would be followed and adapted during the field recording. All equipment used during this project is listed in Table 2

5.2.2. Software considerations

Initially different software solutions were considered (Table 1), from which two were selected for testing and evaluation. The selection was based on three criteria that had to be met (listed below) also article reviews (Bjørnstad et al. 2012, Green et al. 2014), recommendations, descriptions (provided by the solutions) and prior personal experience were taken into account.

- The first criterion was that the software worked on a field computer with no internet connection. This meant that several solutions, such as Autodesk's 123DCatch (http://www.123dapp.com/catch) and ARC 3D web service (http://www.arc3d.be/) which rely on online processing, had to be excluded.
- The second criterion was that the solution needed to be highly automated, meaning that it could carry out large amounts of data processing unsupervised thus freeing up the recorders time. This was both important for the short field season and the subsequent post seasonal processing that would be carried out in Bergen.
- The third criterion was that the software needed to be easy to understand and master. This was important as the time leading up to the field season was limited, and it was necessary to become proficient in the use of the chosen software within this period.

These two last criteria meant that solutions requiring data to be processed and transferred to several different programs, thus requiring a larger degree of micromanaging would not be viable choices. Bundler/PMVS2 (Kersten et al. 2012) and VisualSFM (Wu 2011) were not evaluated further for this reason.

I performed in-depth testing of two viable software programmes, PhotoModeler's Scanner (http://photomodeler.com) and Agisoft's Photoscan (http://www.agisoft.com/). These solutions appeared to fulfil my criteria and were recommended for archaeological recording with good results (Rabitz 2012, Kjellman 2012, De Reu et al. 2014, De Reu et al. 2013).

Solution	Free/Cost	Degree of automation	Large degree of adjustable parameters	All in one solution	Computer/web based Processing
Photoscan Professional Edition	549 USD (free updates)	Full/partial	Yes	Yes	Computer
PhotoModeler Scanner	2495 USD (update 795 USD)	Full/partial	Yes	Yes	Computer
123D Catch	Free	Full	No	Yes	Web
VisualSFM	Free	No	No	No	Computer
ARC3D	Free	No	No	Yes	Web

Table 1: Different software solutions were initially evaluated before a decision was made on which solution would be used in this project. The table shows the criterion that was used to perform the initial selection.

The next step in the evaluation process was software testing. Several test cases in Bergen were photographically recorded and used as a basis for the software evaluation. These included two building façades and two statues. When presented with the same datasets the programs provided significantly different results. PhotoModeller Scanner was in several cases unable to successfully generate complete 3D models whereas PhotoScan could. When presented with data for a flat surface, such as a building façade, both solutions appeared to be more or less equally successful. The problems were encountered when an uneven or round surface was recorded such as that of the two recorded statues. In these cases, PhotoModeller Scanner was unable to orient properly and match all the images. In addition to being superior when it came to data processing, PhotoScan also had a more intuitive layout and allowed for a higher degree of automated processing. As a result, Agisofts PhotoScan was deemed the best choice and acquired.

5.2.3. Testing equipment and workflow

Once a software solution had been selected and obtained the field preparations went over to the second phase; equipment configuration and recording strategy. As opposed to the basic recording strategies, point, shoot, move, repeat (Figure 8), used when documenting the scenes in Bergen, BBC required the development of a new strategy.

Figure 8: Example of the basic recording strategy used, during the trial and testing period. The blue squares indicate the position an image was taken form. Below is a selection of the images used to create the model above demonstrating sufficient overlap.

The two main challenges when working in a cave setting were predicted to be light conditions and freedom of movement. To solve these challenges, two possible strategies were considered. The first would be to use a tripod in which case the camera would remain stable allowing the exposure time needed in a dark cave environment. The second would be to use a flash configuration allowing the camera to be handheld for greater mobility and rate of photo acquisition. Initially, there was some concern regarding both configurations. I predicted that the first configuration would be time-consuming and restrict freedom of movement. I was concerned that the second setup would result in an inconsistent scene caused by shadows created by the flash. This would, in turn, impair the photogrammetric software from being able to read and connect the images.

5.2.4. Testing in Stavenes tunnel

The configuration testing was done in the opening of an abandoned railway tunnel at Stavenes, outside Bergen. The location was chosen as it was considered to have similar lighting conditions to BBC.

The tests showed that both configurations were able to tackle the lighting challenge. As predicted a tripod setup did not require additional light, but it was time-consuming as it required the camera/tripod to be moved and adjusted for each photo. Also, the shutter time, often exceeding 30 seconds, had to be added to the time per image equation.

The flash configuration, consisting of one mounted flash and one external handheld flash, proved to be very promising. Because of the very high shutter speed photos could be captured in quick succession without having to move and adjust the camera for each shot. Also, it turned out that the software was able to tackle the changes in light conditions created by the flash. One drawback of this setup was that it required a second person to move the external flash. The main problem with the flash configuration was the batteries used to power the flash. The tests showed that to be able to capture a large image set it would be necessary to have multiple fresh batteries available. As both configurations produced data that could be successfully processed by PhotoScan the second and third predicted challenge, limited freedom of movement and time were considered. At Stavenes this had not been a problem as I was able to move freely around. However, drawing on the experience of working with the tripod and considering the fragile and cramped nature of the BBC site as well as the limited timespan that would be available to perform the recording, the tripod configuration was deemed least likely to succeed.

5.3. Implementing photogrammetric workflow during the 2013 BBC field season

5.3.1. Technical equipment available

For the 2013 field season images were captured mainly using a Nikon D4 DSLR with a Nikon 24-70mm lens and a Nikon 60mm fixed lens. Also, the camera configuration was modified to include three external flashes and a ring mounted micro flash system. The higher amount of external flashes was used to avoid shadows better. Soft boxes were also used to reduce the sharp and hard light of the flashes. Geographical reference points were recorded using the Trimble VX Spatial Station acquired in 2011. The reference points were marked using red plastic stickers or with plastic crosses. Alternatively, some reference positions were not marked. Instead, the spatial station’s red laser marker or prism staff was used to designate an area, and a picture was captured for later reference (Figure 1: Appendix). A useful feature of PhotoScan is that it provides coded markers which can be printed out and placed in the field to mark geographical reference points. The coded markers can then be automatically detected by the software solution when they appear in an image set. I had not had the sufficient time to become acquainted with how these work when the season started and did therefore not take advantage of this feature.

As a precautionary measure, a laptop computer (Table 2) was brought to the base camp to review the collected image data as the photogrammetric recording progressed and made necessary adjustments to the recording equipment and strategy. Electrical power at the laboratory was limited to a generator. Data evaluation could therefore only be performed by running low precision data generation of smaller groups of images. Towards the end of the season, it became apparent that and insufficient time and power had been delegated to properly test the image sets. This meant that all the sets were not properly evaluated. This would result in an incomplete recording of parts of the cave which was only discovered after the season was over.

Equipment	Model
Camera	Nikon D4
Lens	AF-S NIKKOR 24-70mm f/2.8G ED AF-S Micro NIKKOR 60mm f/2.8G ED
Flash	Nikon R1 Wireless Close-Up Speedlight System Nikon SB-900 flash Nikon SB-800 Nikon SD-80DX
Total station	Trimble VX Spatial Station
HP™ Elitebook 8570w field processing computer	Windows 7 64-bit RAM: 32GB RAM CPU: Intel Core i7 3840 (4-core CPU @ 2.8GHZ) GPU: Nvidia Quadro K2000 – 2GB 256 GB SSD
HP ™ Zbook 17 Lab Computer	Windows 7 64-bit RAM: 32GB RAM CPU: Intel Core i7 GPU: Nvidia Quadro K3000 4GB
Dell ™ Precession T7610 lab computer	Windows 7 64-bit RAM: 128GB RAM CPU: Intel® Xeon® E5-2687W v2 (8-core CPU @ 3.40 GHz) GPU: Nvidia GTX Titan Black – 6GB 256 GB SSD

Table 2. Equipment used during this project.

5.4. Data collection procedures during a normal field day

The 2013 BBC field season ran from 22nd November to 7th December. Apart from my goal of performing large scale photogrammetric recording, multiple other projects and activities were taking place at the site. This included filming for a documentary, photographing and interviewing for an article, micromorphological sampling, extraction of dating samples, geological sampling as well as the traditional excavation. This primarily presented a challenge as the cave is quite small. The solution became to work around the other activities. This meant that recording could be done in areas where excavation was not taking place, at other times recording took place during lunch or in some cases the recording could only be performed after work hours or during the weekend. Another issue that limited how freely the recording could take place was the fact that the D4 camera was also used for conventional photographic recording during excavation.

5.5. Recording of the cave site

5.5.1. Photogrammetric data sets

It quickly became apparent just how much bigger the dataset would become than anything I had attempted earlier. It was, therefore, important to maintain an overview of the acquired and missing data to avoid recording the same areas twice or producing incomplete data sets.

Based on the experience from the pre-seasonal testing (section 0) a basic recording strategy was established. The strategy primarily concerned how the cave would be divided up between different recording sessions (Figure 9), and defined the movement pattern which the recorder would follow, to ensure sufficient image overlap and total area coverage. It was expected that any complex and detailed strategy would have to be discarded or greatly altered in the process of practically executing it; all planning documents were therefore only made with simple drawings, ad-hoc in the field.

The main point of the strategy was to attempt to collect data from the cave ceiling first and use this as an upside down foundation for the rest of the model. The reasoning behind this was that the ceiling was deemed to be the most time consistent part of the cave, meaning that it would change the least during the field season. It was also deemed to be the most consistent feature of the cave over time meaning that it was more or less the same as it had been during the first excavations and would remain so in the future. Once I had scanned and processed this part, other areas of the cave could be combined and attached when time was made available for them to be recorded.

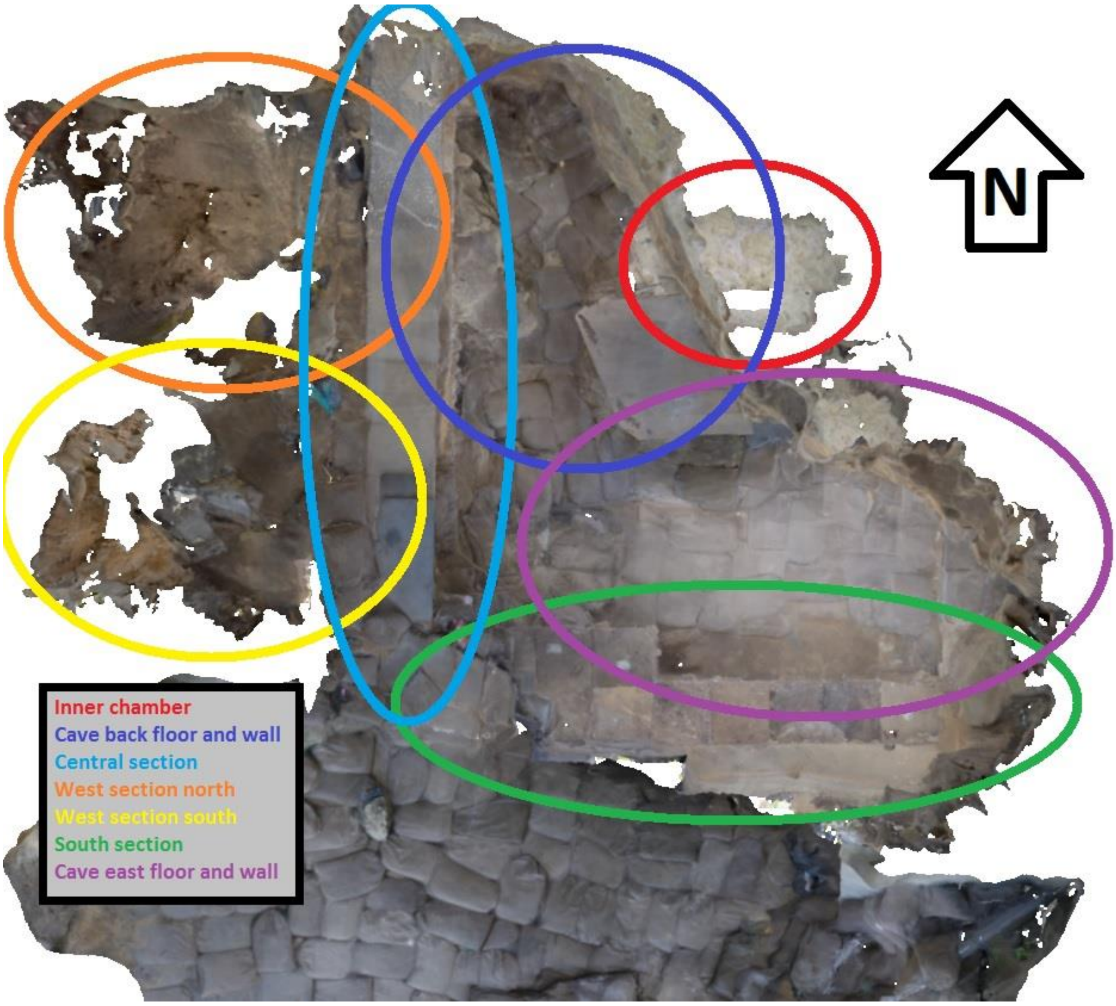


Figure 9. During the recording process, the cave was divided into multiple smaller parts which were recorded separately. Each of the separate parts overlapped with its neighbours to ensure complete cave coverage. This illustration does not include all recording areas.

5.5.2. Light conditions within the cave

Poor and uneven lighting conditions were one of the biggest challenges throughout the recording process. As opposed to performing photogrammetric recording in an open environment where little or nothing is obstructing the sun, very limited natural light enters BBC. A flash configuration had therefore been chosen to tackle this challenge. This configuration included two macro flash units mounted to the lenses and three external flashes.

For the flash setup to function, it was important to be constantly aware of how the area captured within the image frame was covered by the mounted and external light sources. Misplaced flashes would, for example, cause areas in the front or background to become over or under exposed, and what might work from one angle, would often not work from another. To tackle this potential problem, two people needed to cooperate; one person would be managing the external flashes, and the other would operate the camera, capturing and reviewing the image data as the recording progressed.

In some areas of the cave, such as the Inner Chamber and the two western chambers the light was so poor that the camera was unable to focus. To solve this issue an additional light source in the form of either a flashlight or a lamp was used to illuminate an area to focus on (Figure 10). The light from these sources was quite weak and did not affect the images greatly. It should be noted that all images were captured in both Nikon's own uncompressed (raw) format (.nef) (http://www.nikonusa.com) and a compressed raster format (.jpg) (http://jpeg.org). The .jpg images were used to do in field testing to verify successful recording. PhotoScan is not compatible with .nef, therefore these images were not used before they could be converted to a readable format (.tif) during the post seasonal processing (section 5.9) capturing in a raw format greatly improves the possibilities of photo editing over compressed image format, it also means that more information can be made available for the photogrammetric solution. Capturing images in a raw format were, therefore, crucial to ensure the best possible dataset for photogrammetric processing

Figure 10: The inner chamber was so dark that an additional light source was required for the camera to be able to focus.

5.5.3. Tackling confined space within cave interior

The second big challenge with the BBC recording was space and the limited freedom of movement caused by the nature of the site. This issue was primarily dealt with in three ways:

1) **Fragile site**: It was not possible to stand and climb in all areas of the site without damaging, or running the risk of damaging the archaeological material.
2) **Extremely narrow areas**: Some areas could only be covered from a single angle such as the side caverns which were long and narrow and did not offer the recorder nor his equipment the necessary space to move around.
3) **Equipment limitations:** The flash ring, an essential part of the camera configuration, limited the maximum angle of the lens to roughly 30mm. A wider angle led to parts of the ring covering the view (Figure 12).

In an open area, this last issue would not have been such a big problem as the camera could simply have been moved further away from the object. This was not possible, however, and so more images had to be captured to cover the same area. Maintaining your bearings as you try to capture images of a surface in a systematic matter becomes difficult when working through the camera viewfinder at short distances. In the most extreme cases such as the inner chamber, it was in fact not even possible to use the analogue or the digital viewfinder at times. To tackle this challenge, it became important to keep a mental map of the area you were working on and concentrate on one part at the time and reviewing the captured images at regular intervals to determine that the data was of satisfactory quality and that they overlapped.

The most difficult part of recording the inner chamber was to capture images that would successfully connect the chamber to the rest of the cave. The very tight opening into the chamber (40 cm) causes most camera angles to either only cover the interior of the chamber or the exterior. Also, the camera did not have the capacity to properly focus on both the interior and exterior at the same time, which meant that the chamber or interior would always be out of focus when both parts appeared in the same picture. In an attempt to solve this issue, different sets of images were captured in the hope that one or more would provide the overlap needed to align the chamber interior with the rest of the cave interior (Figure 11).

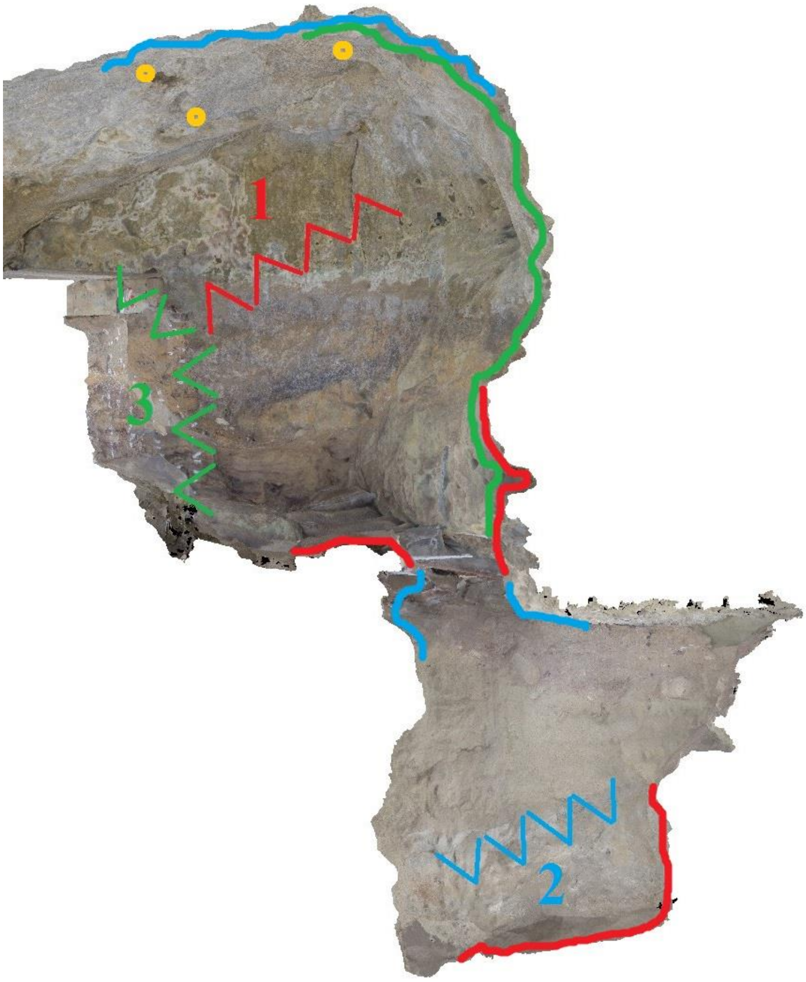


Figure 11: Stylized depiction of the recording strategy used to collect the data that would connect the inner chamber and the main cave interior. The two opposite facing image-sets covering both the inner and main chamber (1 and 2) were intended to work in combination with images collected following the standard recording strategy (3). In this way the different image sets would be stitched together. The second set of images (2) covered parts of the cave ceiling with geographical reference markers (yellow), which would aid in the correct alignment of camera positions (5.10)

The first was taken from the main chamber and consisted of images covering both the immediate area around the opening of the inner chamber and parts of the floor and wall visible from this angle. The second set was done in the opposite way, from the inner chamber and out. These images covered parts of the ceiling of both the inner chamber and the cave. This set was especially valuable as the area of the cave ceiling it was covered contained three of the spatial reference markers. The final set of images covered the cave wall and ceiling above the chamber's opening and overlapped with the two other image sets. The camera focus for the first and second image set was gradually cycled between near and far to contain a sharp coverage of both chambers. Many of the images in these two set where captured with a high aperture which meant a larger depth of field but less sharp images.

Data from the extremely confined parts of the cave were among the most important to process on the field laptop once back at the base camp because there was some uncertainty about whether the coverage would be sufficient.

Figure 12: The micro flash system used in the recording of BBC is mounted on the camera lenses using a ring attachment. This attachment limited the angle of the lens to 30mm. At wider angles such as the 24mm example seen here, it covers part of the view.

5.6. Sediment Washout on sloping cave talus

The first recording started on the 25th of November with the recording of an area were part of the archaeological material is being eroded by water, hence referred to as the washout (Figure 13 and Figure 14). A simple recording strategy was followed to document this area in which a total of 215 images were captured. A set of 15 geographical reference markers in the form of plastic crosses were placed across the area. I then circled the feature taking images from different positions and angles as I moved. Starting from one side, I then moved across the area in a zig-zag pattern photographing with the camera facing down, allowing for the capture a series of top-down images with high overlap.

5.7. The cave exterior

The exterior of BBC was recorded in two sessions between the 5th and 6th of December taking a combined time of about 3 hours to capture 753 images. Traditionally, large open areas such as the BBC exterior would be recorded from a top-down view using such tools as a pole, UAV (unmanned aerial vehicle commonly referred to as drone) or kite (Verhoeven et al. 2013, Linder 2009). The natural conditions of the BBC exterior make it difficult to apply such tools, however. Winds can prove to be too powerful and unstable for even larger drones, which was experienced by the documentary camera team. The steep cliffs leading down to the sea and unstable terrain meant that using a kite with a camera rig was also not possible. For the same reason, a tall photo pole would also have proven difficult and potentially dangerous.

Similarly to recording the BBC interior, limited freedom of movement was the main challenge when recording the BBC exterior. This is because the landscape is dominated by steep cliffs with loose rocks, sand, and brush. In practice, it meant that the images had to be taken from positions which could be reached safely and where the view was not obscured by vegetation. I was therefore forced to adjust the strategy away from PhotoScan's recommended recording strategy (Agisoft 2014) (Figure 6) to something which visually appears similar to the exact opposite (Figure 13).

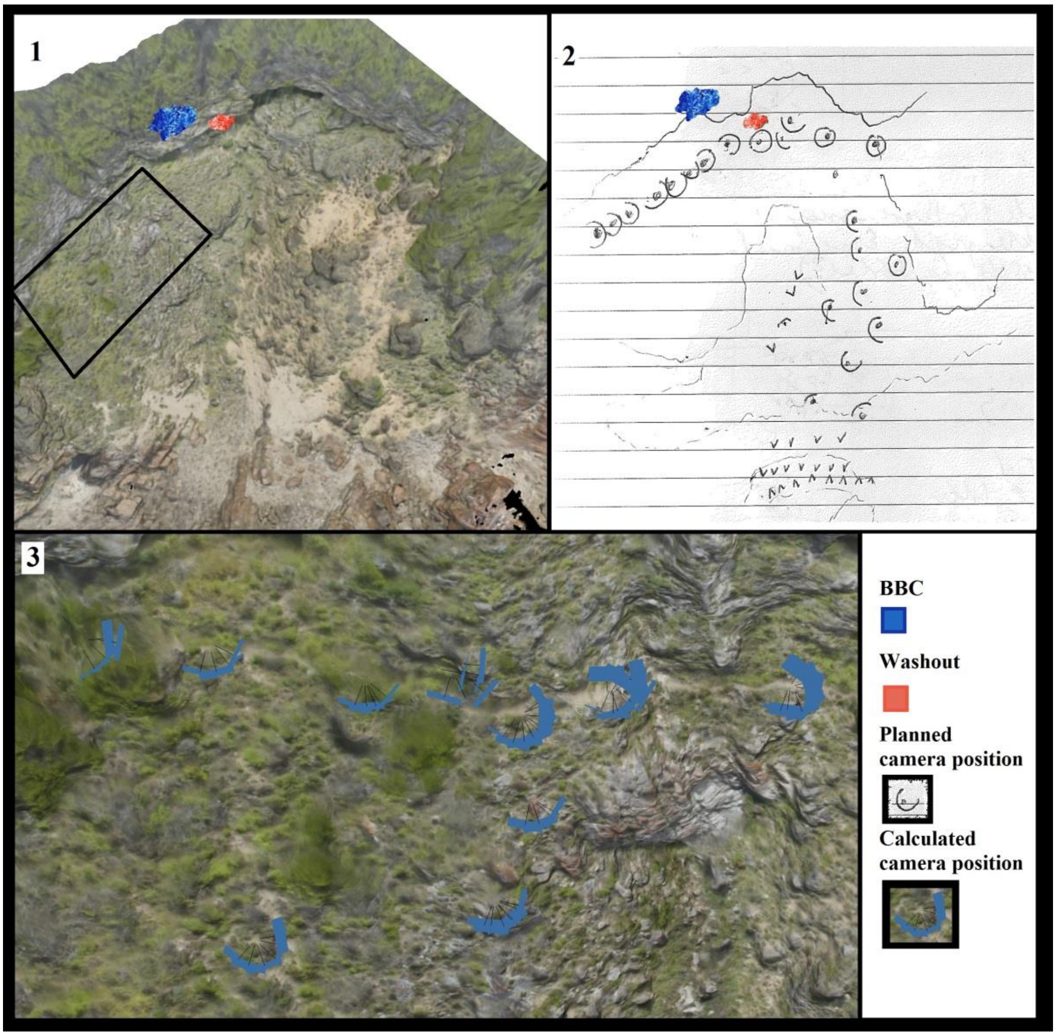


Figure 13. To record the steep landscape surrounding BBC (1), a recording strategy was developed (2) which differed from the standard recommendations (Figure 6). Vegetation and uneven terrain meant that care had to be taken when traversing the landscape and a limited number of positions with the necessary view that could be reached. This meant that multiple images had to be taken from each of these positions (3).

The idea behind this alternate recording strategy was that the images from the different recording positions would not be matching with images from their group, but rather with images from the other groups (Figure 13 part 3). In turn, this would create a steady overlap of the whole exterior with each part covered from various angles. Naturally, the limited freedom of movement caused by the difficult terrain resulted in some areas not being recorded or being poorly covered. However, the time, terrain and the equipment available meant that this was inevitable.

5.8. Collecting spatial data

To geographically reference the photogrammetric data, multiple reference markers had to be recorded (section 1: Appendix). For the BBC interior, several easily recognisable features were spatially recorded using the Trimble Station. Also, 1cm round, red stickers were attached to the cave ceiling in various places and then spatially recorded to increase the amount of geographical reference points. In total 14 points were recorded on the inside of BBC. For the recording of the washout 15 small plastic crosses (Figure 24) were placed across the area and then recorded using the Trimble VX Spatial Station. A quick drawing of the washout with marker placement was made as a guide to help during data processing (Figure 14).

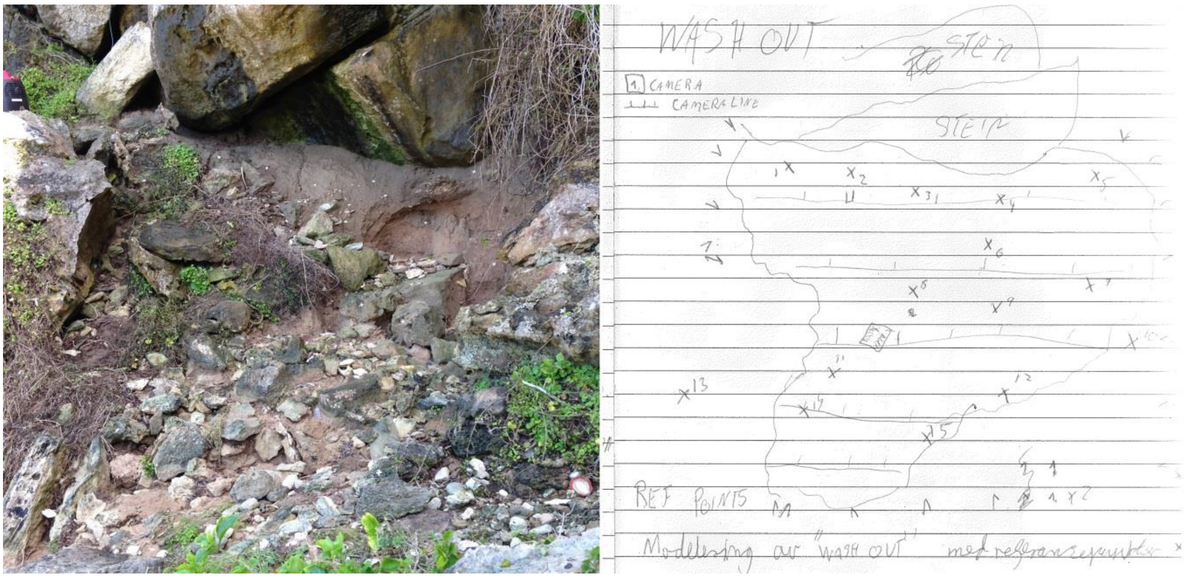


Figure 14. The Washout outside BBC (left) was geographically referenced using 15 plastic crosses. They were placed across the area and spatially recorded before taking pictures. To help correctly identify the markers later, a simple drawing was made (right). It indicated the position and label of each marker.

When recording geographical reference points for the exterior, images were taken with the prism staff in each position to later help identify the reference positions (Figure 15). During the spatial referencing of the exterior model, identifying the position of all the geographical reference points proved to be difficult. The problem was caused by the fact that several reference images taken did not include enough recognizable features from the landscape. In retrospect, large reference markers should have been placed or painted across the exterior and used to indicate georeferenced markers. This practice has been executed with success on other projects before (Verhoeven et al. 2012, Muñoz-Nieto et al. 2014).

To ensure success, the number of geographical reference points that were recorded was higher than what was deemed necessary. This was done as it was predicted that not all the points would be usable or correct and that this would only be discovered once we had returned from the field.

Figure 15. Images were captured using a smartphone to help document the position of the reference points recorded across landscape surrounding BBC (1, 2, 3, 4). These images were used as a reference to help identify and mark the reference positions within photogrammetric image set that covered the BBC exterior landscape (5, 6, 7). In this example 2, 3, and 4 represent 5, 6 and 7 respectively. Several of the other reference positions, including 1, proved impossible to locate in the photogrammetric image set.

5.9. Data processing and analysis

The post seasonal processing of photographic and geographical data was mainly conducted at the University of Bergen (UiB). In this chapter I describe how the work was carried out by looking at the way data was prepared, processed within the software solution and what results were produced. Initially, a mid-range laptop computer was used (Table 1). The specifications of this computer limited the way I was able to work with the data. To better work with the large amount of data, a powerful desktop computer was acquired containing a powerful CPU and GPU and most importantly a large amount of RAM (Table 3). This new computer only became available once I had already been working with the data for some time. This chapter therefore also describes how the limitation of the initial laboratory laptop was tackled.

5.9.1. Pre-processing preparation

Before the photogrammetric processing of the images, the image data was sorted, reviewed, edited and converted into a file format that could be read by Photoscan. The BBC interior recording had produced more than 1150 images. This number exceeds the capacity of the initial lab laptop computer available at UiB (Table 2) due to the large RAM requirement needed to produce an adequate point model detail (Table 3). The solution was to sort the images into smaller groups (<300) by the area of the cave they covered. During this sorting process, images were also roughly reviewed, and the worst data was removed. This included blurred and unfocused images, very over- or under-exposed images, and images that were too obscured by interfering elements (excavators' equipment, etc.).

Photos	**20 - 50**	**100**	**200**	**500**
Lowest quality	100 MB- 300 MB	150 MB - 450 MB	300 MB - 1 GB	1 GB - 3 GB
Low quality	500 MB - 1.5 GB	750 MB - 2.2 GB	1.5 GB - 4.5 GB	4 GB - 12 GB
Medium quality	2 GB - 6 GB	3 GB - 9 GB	6 GB - 18 GB	15 GB - 45 GB
High quality	8 GB - 24 GB	12 GB - 36 GB	24 GB - 72 GB	60 GB - 180 GB
Ultra-high quality	32 GB - 96 GB	48 GB - 144 GB	96 GB - 288 GB	240 GB - 720 GB

Table 3: Estimated RAM requirements depending on total amount of images and quality setting. This estimate is based on 12mp images (http://www.agisoft.com/downloads/system-requirements/).

5.9.2. Initial Editing

Once sorted, the images were imported into an editing program (Photoshop). The main form of editing concerned the adjustment of exposure. Highlights (overexposure) and showdowns (underexposure) were adjusted to bring out a more consistent colour within the image itself and across the entire dataset (Figure 16). This was deemed necessary as images covering the same area in some cases had very different exposure or light. It was believed that if such inconsistencies were too high, it would lead to poorer or unsuccessful image alignment causing "noise" or incomplete data. A secondary reason for the image editing was to improve the final model texture.

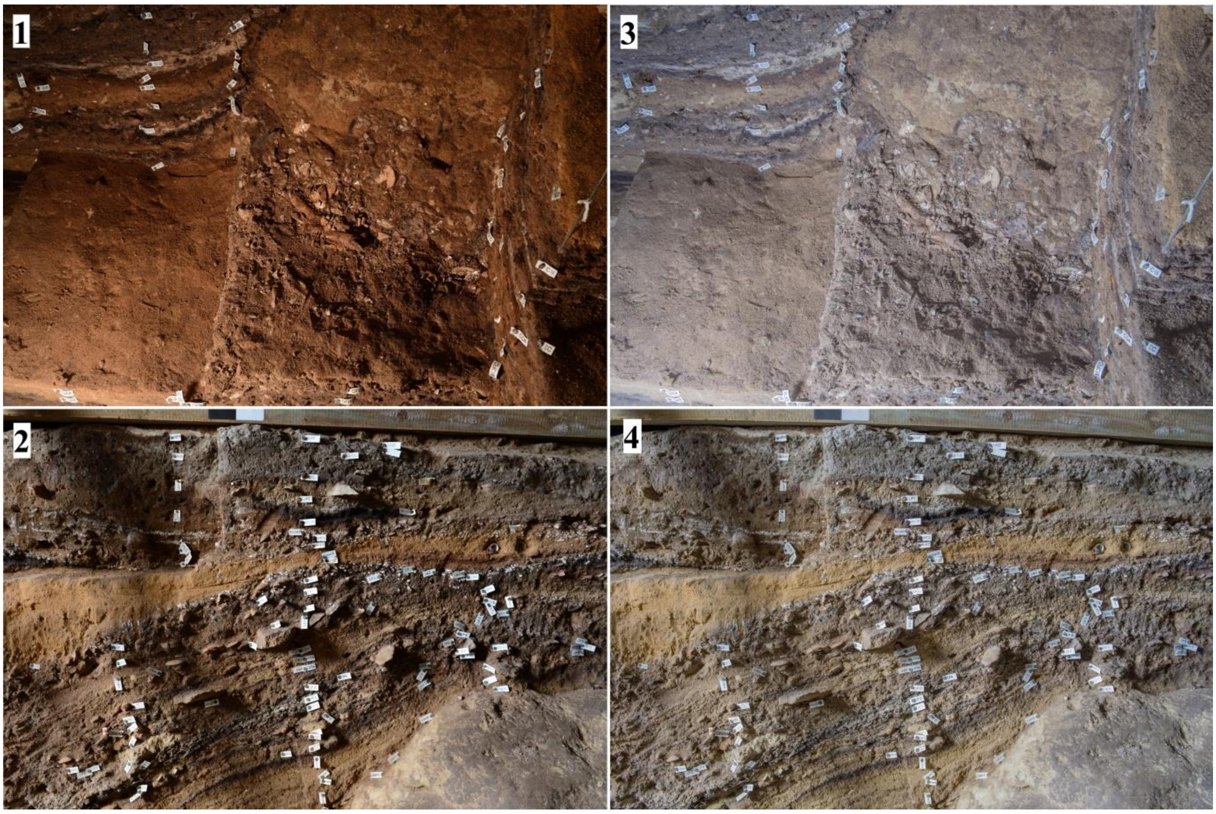


Figure 16. Before the images being imported into Photoscan colour editing was performed in Photoshop to create consistency across the entire image set, and to remove shadows. The two examples above (1, 2) show how colour is edited and shadows are removed (3. 4).

Several factors would require that an image needed editing:

- The battery of one or more of the various flashes gradually becoming depleted without one of the two operators noticing. This would cause the flash to become less powerful or not to go off when the picture was taken, as it was not yet fully charged. A result of this was typically under exposure for the entire or parts of the image.
- Another re-occurring problem was shadows and highlights which for the most part were caused by the positioning of the flashes. For example, it was at times not possible

to angle the light sources in a way that gave an even light distribution across the entire scene. This would give an uneven exposure from for example front and background.

- An uneven exposure caused by the camera operator progressing outside of the area covered by the current flash placements (Figure 16). The degree and quality of the editing were made possible because the images were available in a raw format (.nef).

Once the necessary editing had been completed the images were converted to .tiff, an uncompressed raster image format readable by PhotoScan. No correction for lens distortion was applied during the editing phase as PhotoScan uses the images metadata, camera and lenses model, and camera settings, etc., to calculate and compensate for this during processing. (Agisoft 2014).

5.10. Photogrammetric Image Processing

At PhotoScans current build (1.2.3.2331) the process from images to a finished textured surface model has four stages: alignment, dense cloud construction, mesh construction and texture generation (Figure 7). A brief description of the four stages with elaboration on areas where editing is exceeding the basic steps was performed to ensure a good result is given below. A full list of processing parameters is provided in section 1 of the appendix. It is important to understand how the data is created to have a better understanding of what data is created and consequently how it can be used. For a more in-depth understanding of the process and adjustable parameters, one can refer to the Agisoft Photoscan Pro User manual (Agisoft 2014).

5.10.1. Alignment

The first stage of the image processing is image alignment. Here the software solution searches the images for a predefined number of points. These points are then in turn used to match and tie the images together and calculate the camera positions. These tie points from a sparse point cloud that was at times manually edited to improve the positioning of the cameras. As the BBC recording was carried out over the course of several days it was inevitable that there would be differences between the images such as moved equipment, people caught in the corner of the frame (Figure 17) and so on. Such inconsistencies can produce an unwanted result in the final data. Where necessary masking was, therefore, applied using the solution’s masking tool. When masking has been applied to an image, the solution can be set to ignore these areas during processing. It should be noted that masking can be a time-consuming task. Therefore, the recorder should strive to ensure that the recorded data will need a minimum amount of editing during the processing phase.

Figure 17. Some of the images I captured contained unintended elements that were not consistent throughout the recording. These elements, here outlined in read, had to be masked to avoid miscalculations and incorrect model texture. In the two lower images masking has been applied and is represented by the greyed out area with a thin white border. In the upper image, the masking process is not completed.

5.10.2. Dense Cloud Construction

Once satisfied with the alignment of the images the software is set to generate what is referred to as a dense cloud. The systematic calculation of the spatial position of a large number of points shared between images is determined by the camera positions estimated during the alignment phase. The quality of the dense cloud construction can be adjusted and affects the amount of detail and geometric accuracy that will be produced. In "practical terms" the quality adjustment determines if the images will be processed in their original resolution or how much they should be downscaled. The settings directly affect the processing time and number of points calculated (Table 1: Appendix). It was, therefore, important to consider what the purpose of the data production would be and what capacity, in terms of hardware, was available to handle the data.

5.10.3. Mesh Construction

The third stage aims to recreate the surface of the scanned object in the form of a 3D polygon mesh (Figure 7). This mesh makes up the solid surface of the final product and is created using the dense point cloud. The resolution of the mesh and the amount of polygons can be defined by the user. The mesh construction is the most memory demanding stage of the modelling process (Table 3) and was the reason why the modelling initially had to be carried out in smaller pieces due to the restriction imposed by initial lab computer. Displaying an interactive high-resolution polygon mesh can be very demanding on the computer's hardware. To avoid such potential issues, the resolution of the cave interior was set to 5 million faces.

5.10.4. Texture Construction

The final stage of model reconstruction is building texture. The solution generates a texture for the solid mesh surface on the basis of the images. To ensure a high-quality texture in terms of sharpness and correct representation, several of the images had to be disabled before the generation started. Disabled images included images with a lot of inconsistent and disturbing elements and poor focus or blur. The resolution of the texture was set to 16000x16000 pixels to ensure that the model would not be to demining on the comuper hardware. As shown above, each stage of model generation relies on the data produced during the previous stage. This is an important point as it affects how deviations and errors are transferred and alter the final product. In general what this means is that the distortion between the real cave and the presented data grows for each stage in the processing (Figure 3). To ensure the generated model most closely resembles the actual cave it is, therefore, important to strive for optimal results at each step of the process.

The modelling of BBC and its exterior was redone on several occasions during this project. The main occurrence came with the acquisition of the more powerful desktop computer (Table 2). This allowed the entire dataset to be processed as one (chunk), which meant that the cave model did not become a tapestry of several smaller parts, but rather a single solid piece. In turn, this meant that the modelling process could be set to run automatically, testing out various settings and configurations to improve upon the results. These different processing runs were performed with minimal need of user intervention. All software settings for the final model generation are provided in section 1 of the appendix.

5.11. Accuracy and spatial referencing

The three recorded case studies were all geographically referenced in accordance with different strategies as demanded by their nature. A description of the methods I used and the estimated accuracy provided by the software solution follows.

5.11.1. Blombos Cave

The markers used to indicate the geo-reference points for the BBC interior were not coded and could consequently not be automatically detected by the software. The reference positions instead had to be designated manually within the solution. Potentially this could have been done by going through the 1150 images one by one, searching for the points and marking them where they appeared. This would, however, have been problematic for several reasons. First of all, it would have been time-consuming to find the various points and secondly identifying which specific point was indicated by a marker would also be difficult as the cave surface can appear quite homogenous by visual inspection (Figure 1: Appendix). To reduce the amount of time spent on manual input an alternative solution/workflow was followed:

1) First, the alignment process was run through once on low settings. This results in the quick calculation of the position and relation between the images.

2) A marker could then be placed in two images, and the solution would calculate and suggest its position within the remaining images it appeared in.

3) The estimated positions could then be reviewed and corrected where necessary in a relatively short amount of time.

4) The field notes were then used to correctly identify and name each marker before importing the correct coordinates.

5) The images were then realigned and processed at a higher setting and resulted in a greater level of accuracy.

Once the second alignment had completed, the space point cloud was edited, removing incorrect tie points to optimise the camera alignment. The result gave an estimated error, which is distance between input coordinates and estimated position, of 1.06 cm (Table 2: Appendix)

5.11.2. The Washout

The washout was by far the smallest of the 3 case studies both in physical size and in terms of recorded data. Consequently, it was also the easiest to geo-reference, something that was executed much in the same way as the cave interior. The following workflow was used:

1) The Image set was first aligned on a low setting.

2) Markers were then imported and could be “placed” within the images in reference to field notes. As soon as a marker has been placed in 2 images, the software would calculate its estimated position which could then quickly be confirmed or readjusted.

3) The image data was then reprocessed to achieve a more accurate result.

The calculated mean error of spatial markers was calculated to 0.6cm (Table 3: Appendix).

5.11.3. The exterior

The exterior geo-reference points were created by recording the position of distinct features in the landscape. Images of the features (Figure 15) and field notes were recorded to later be able to correctly indicate them during the geographical referencing part of the process. This proved to be impossible for most of the markers, however. Instead, an alternative strategy was employed:

1) Several of the images used to generate the BBC model added to the set of images covering the exterior and landscape. A set of identical images were included in the cave interior model and the exterior landscape model.

2) Once both models were processed, the exterior model was aligned with the geographically referenced interior model, on the basis of the shared images. In this way bringing the exterior model into the BBC numerical coordinate system.

3) The exterior markers were then imported into the indirectly referenced exterior model project. Using the marks coordinates, Photoscan visualises the markers position in relation to the model and estimates their position within the exterior images.

4) The images were then visually inspected, and the estimated positions of the reference markers were confirmed or readjusted in accordance with the field notes and images.

5) With eleven reference markers manually positioned within the exterior image set, the model was reprocessed.

The result showed that the geographical reference markers had an average deviation of 21.4cm (Table 4: Appendix).

6. RESULTS

In this part, I describe and present the results of the image processing described in chapter 5. First I elaborate on the types of data that can and has been exported and then illustrate in the form of a series of figures. These are discussed in chapter 7. Finally, I explain how the data's spatial accuracy was evaluated using an external software solution. The image processing resulted in three geographically referenced high resolution textured surface models: BBC interior (3D Model 1: Appendix), BBC exterior (Figure 23 and 3D Model 2: Appendix) and BBC washout (Figure 24 and 3D Model 3: Appendix). These 3D models were used to produce orthographic images (Figure 20, Figure 21, Figure 22, Figure 23, Figure 24), digital elevation models (DEM) (Figure 24) and contour lines.

The figures are generated on the basis of a model with 2.5 - 6 million faces. It is possible to generate models with a significantly higher resolution using the images I recorded. Such models would contain a larger amount of topographical detail and texture information (Figure 18). For the purpose this thesis, however, it was deemed unnecessary and impractical to create such high-resolution models. The reason being that higher resolution models would be too demanding on the computer hardware and that the detail of such high-resolution models cannot be displayed through a thesis, but instead require specialised software and hardware.

Because all data is spatially referenced within the local BBC coordinate system, no additional steps had to be taken when importing the data into a GIS solution (see glossary) such as ArcMap 10.1 used here. Bellow follows illustrative examples and explanation of the end results of the 2013 recording and examples of how the data can be combined in a GIS software. These results are discussed further in chapter 8.

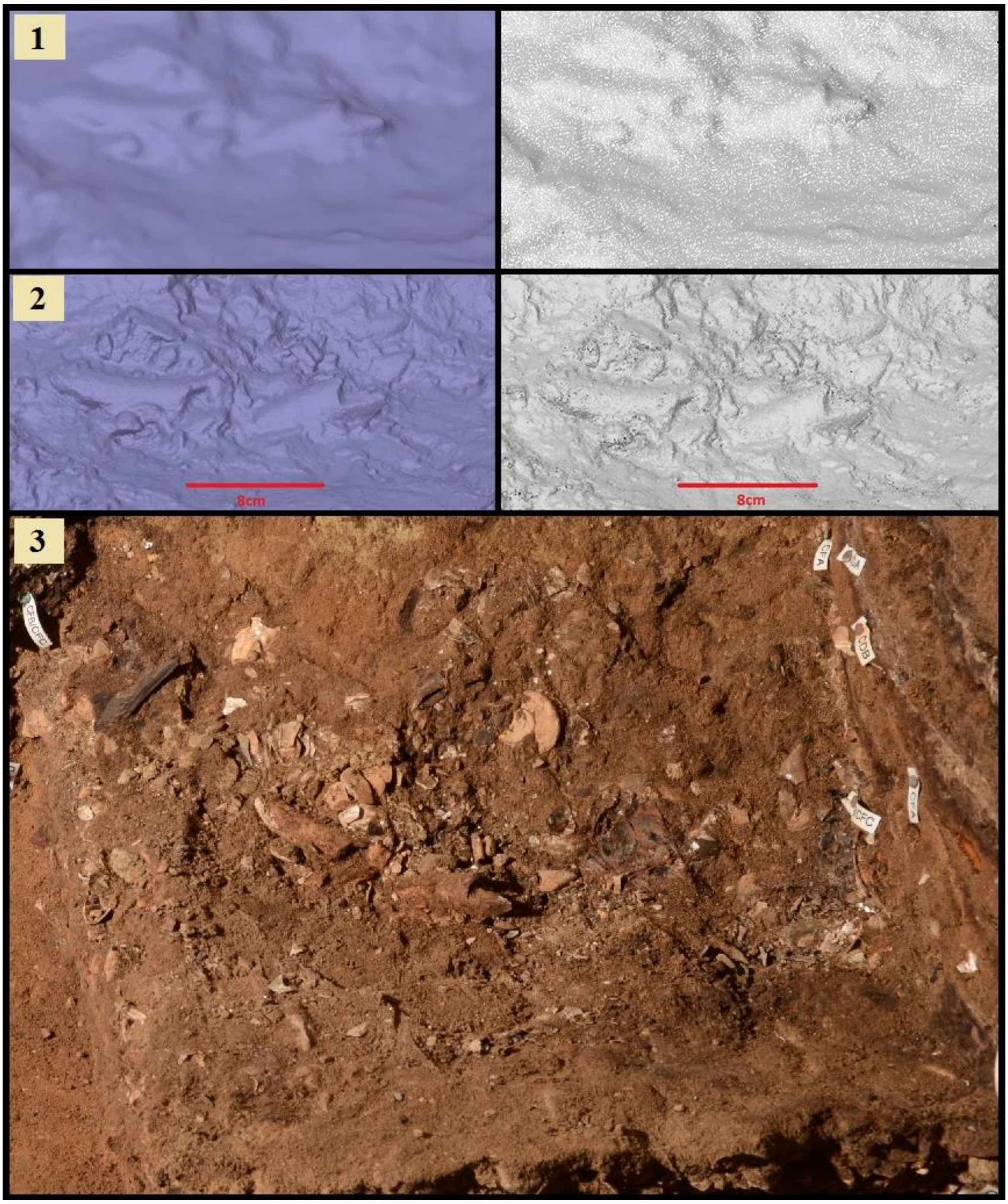


Figure 18: Photoscan lest one select different level of resolution when generating models. This determines the level of detail that is extracted from the images and consequently the detail quality of the model. The examples here illustrate the level of detail my images can prove at a medium (1) and high (2) setting. The example comes from in-situ faunal remains located at quadrant F7b of the south section at BBC (3).

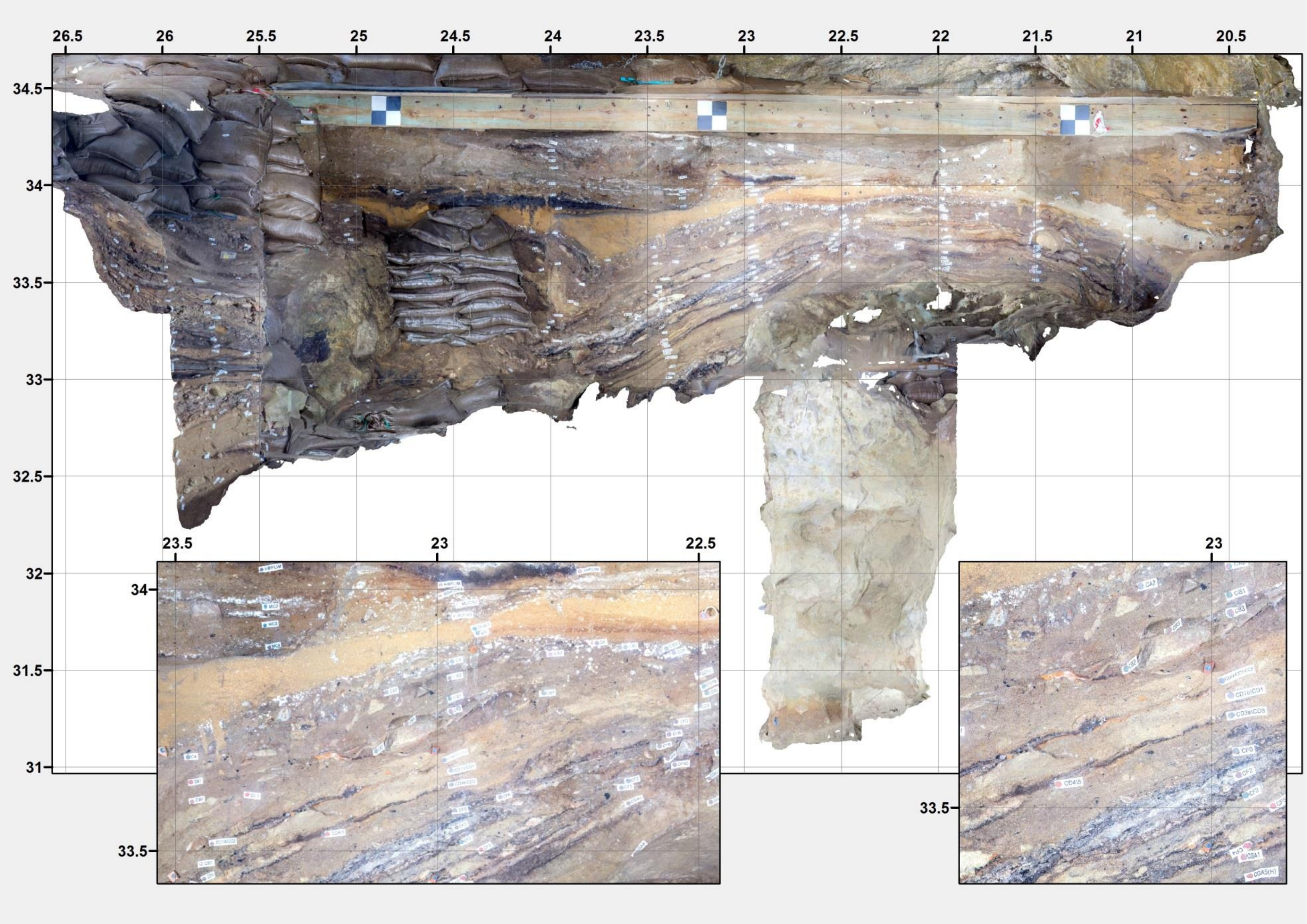


Figure 19. Orthographic image of the west section, inner chamber and parts of the south section at BBC viewed form the east. The image was created by removing the east part the cave model. The detail examples below illustrate the high level of detail available across the entire image and which cannot be fully appreciated in this example.

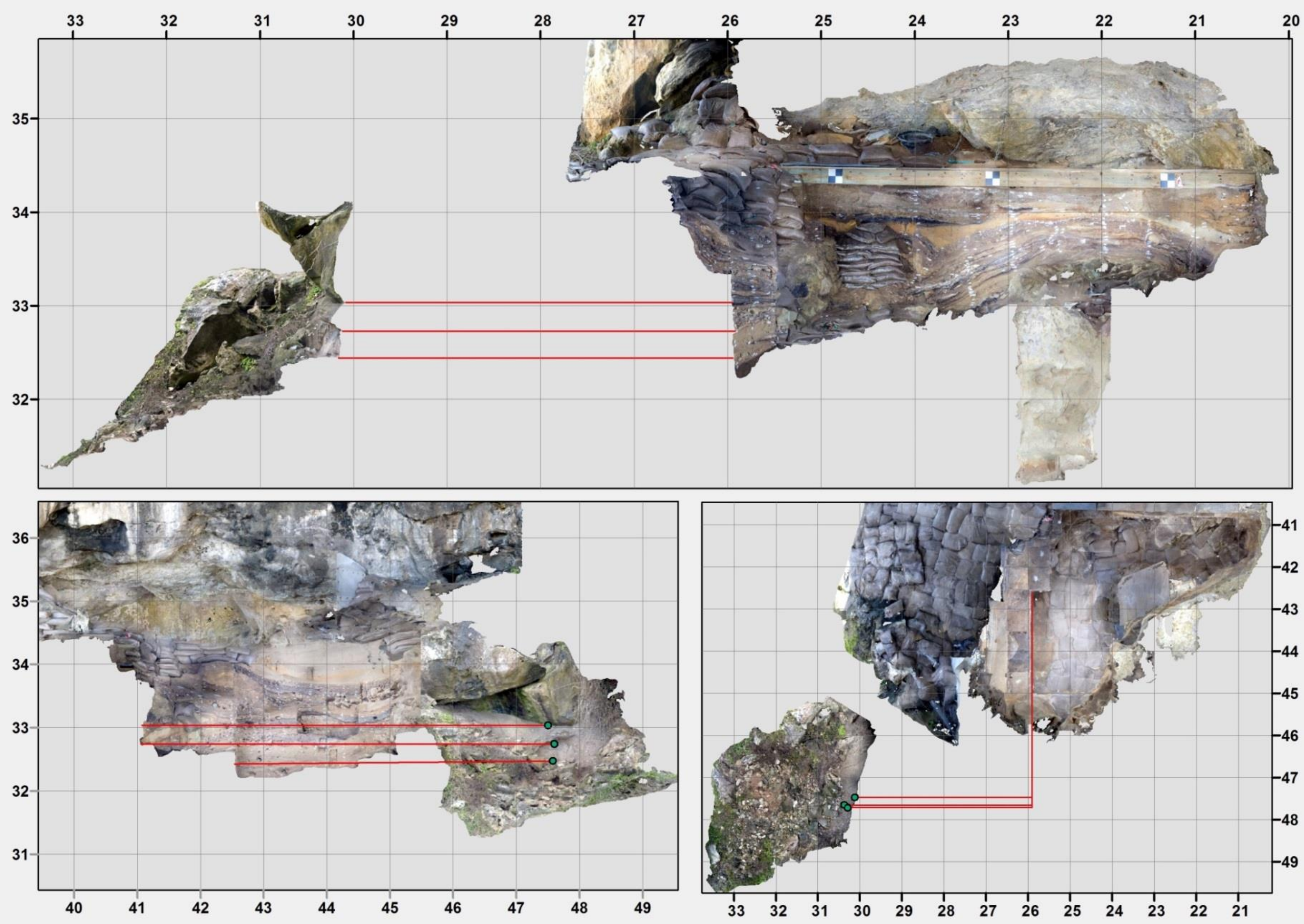


Figure 20: BBC interior and BBC Washout: orthographic illustration of the spatial relation between the BBC interior and washout from an east (top), south (bottom left) and top down (bottom right) perspective.

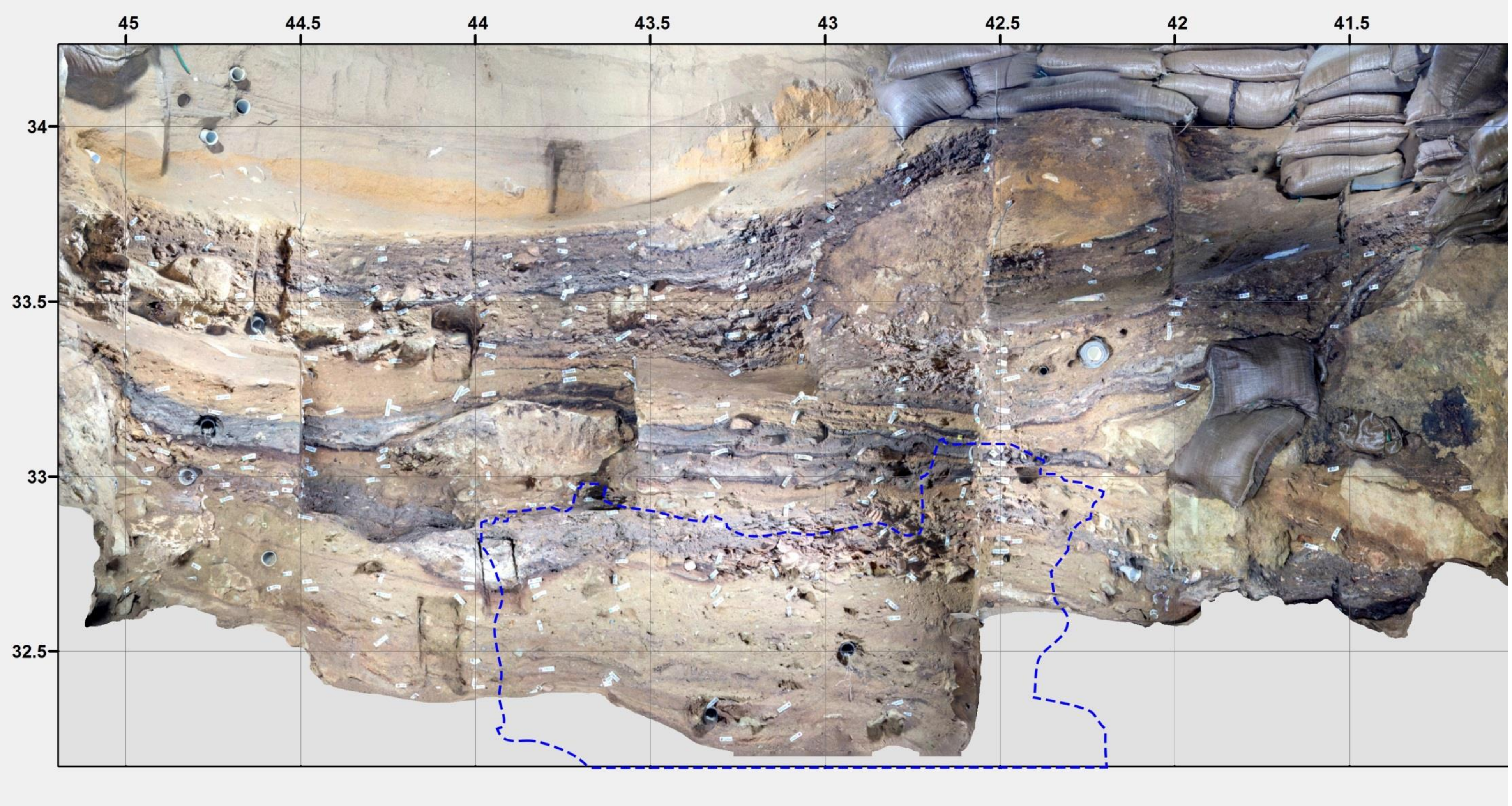


Figure 21: BBC South section; Orthographic image of the south interior section viewed from the north. The blue outline marks the inner chamber (Figure 22) outline.

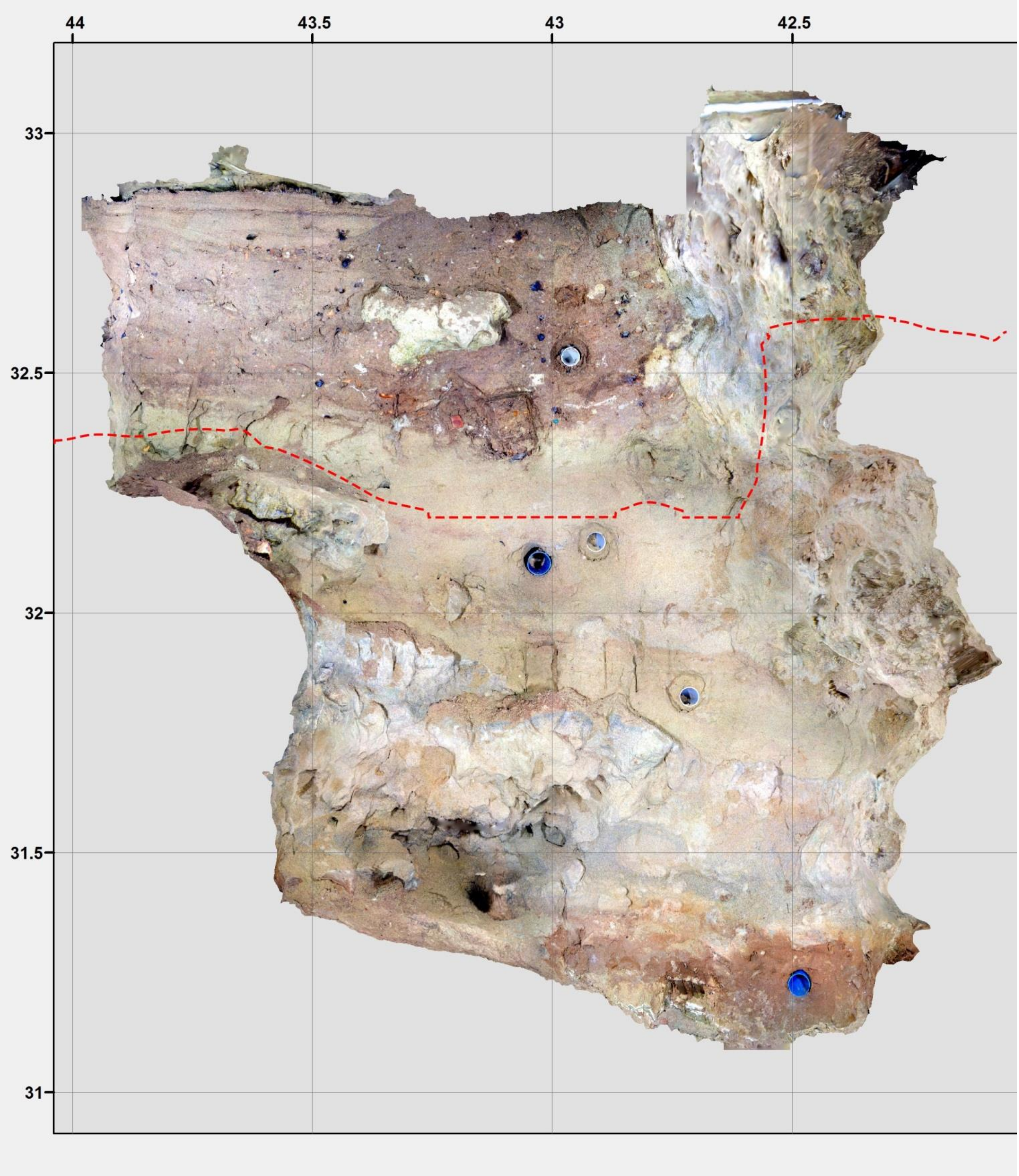


Figure 22: BBC inner chamber; orthographic image of the south side of the BBC inner chamber. The BBC South section (Figure 21) is marked by the red dashed line.

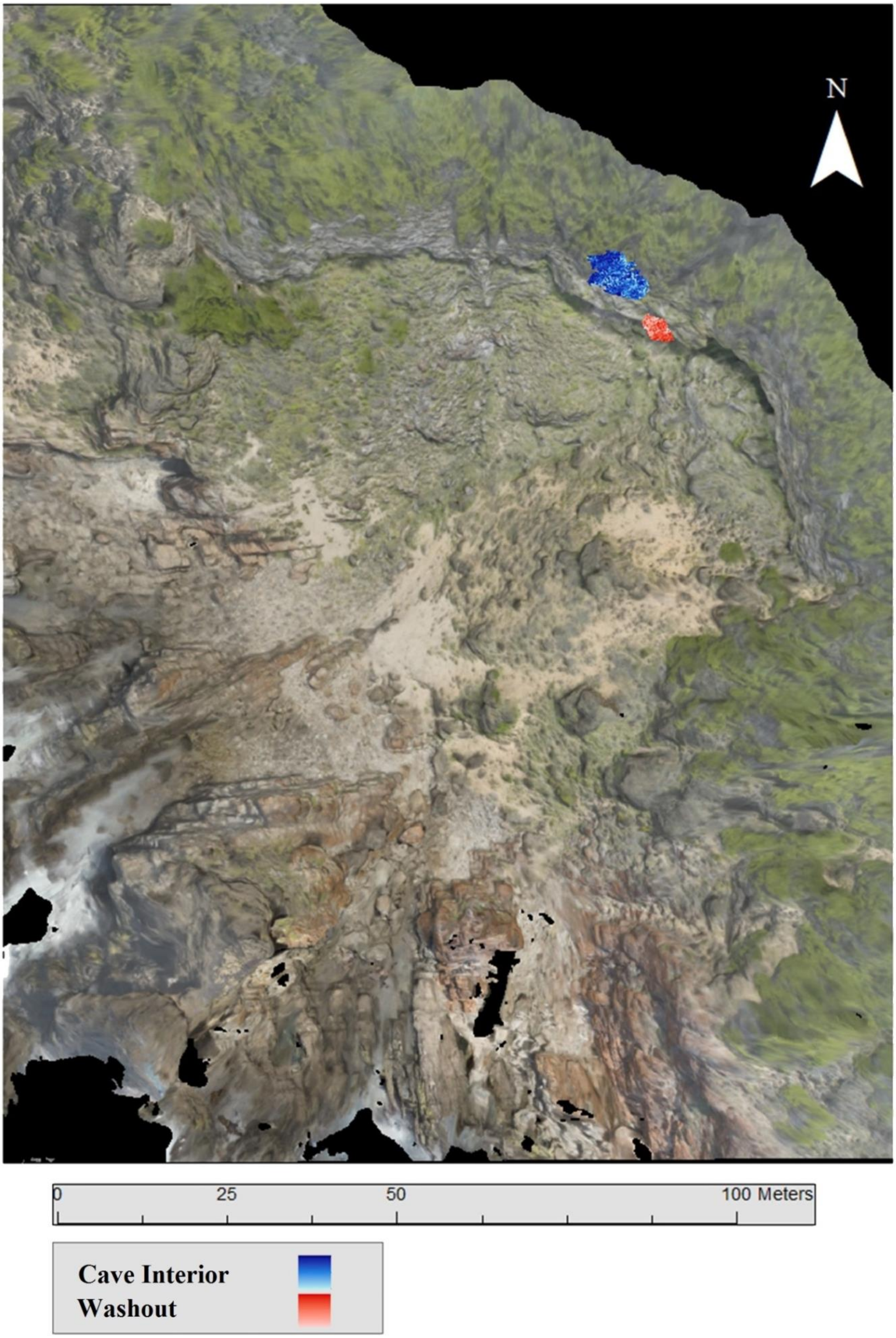


Figure 23: BBC Exterior; orthographic top down image of BBC exterior with BBC interior (blue) and washout (red) superimposed. The arrow indicates north within the local coordinate system and not actual north.

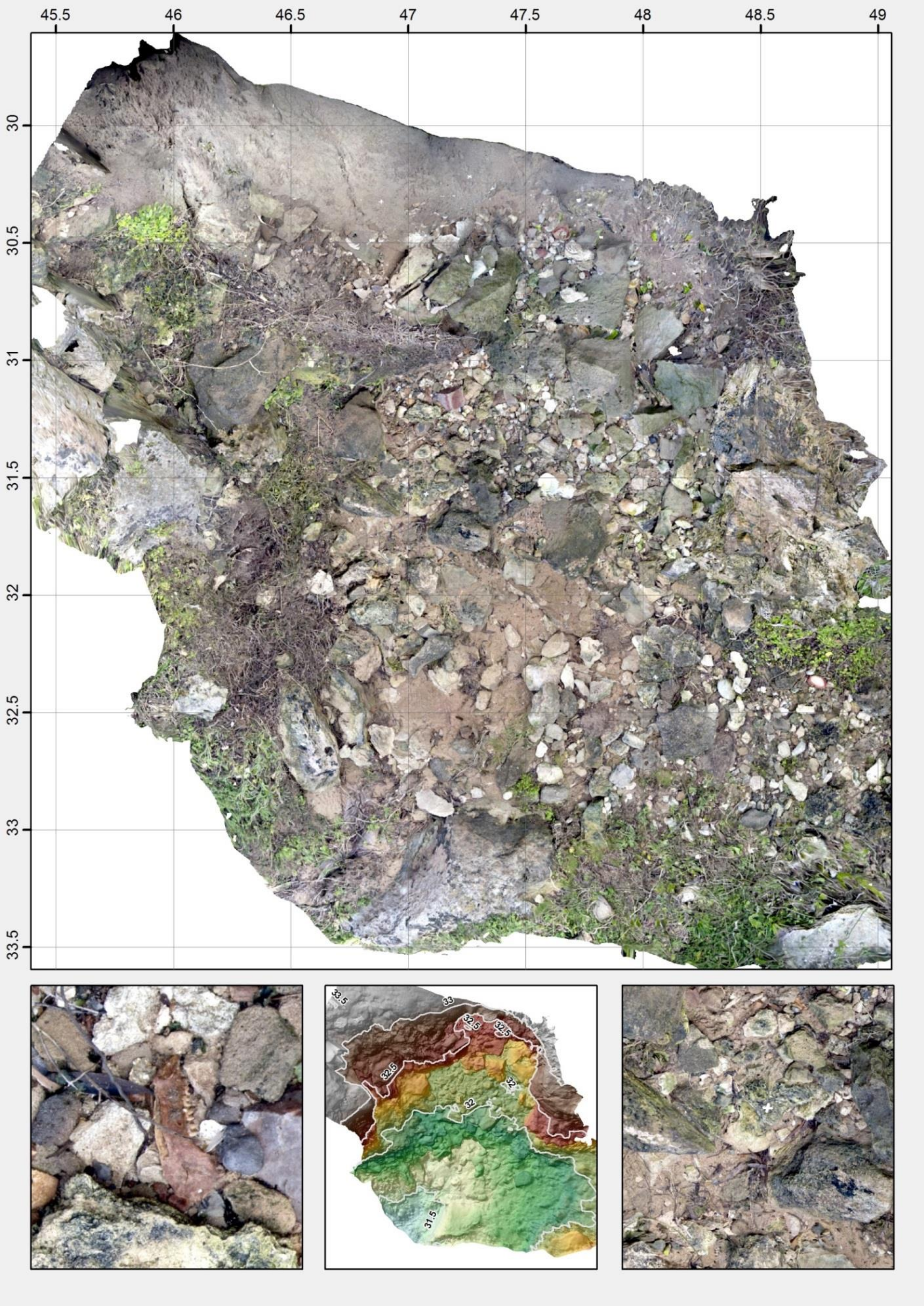


Figure 24: BBC Washout overview and detail; orthographic overview of the washout located southeast of the cave interior (above), final remains (lower left), hill shade map with contour lines (lower middle) and detailed image of one of the markers used to reference spatially the data.

6.1. Data Accuracy – Comparing results with Terrestrial Laser Scanning.

Here I describe a spatial comparison between the digital photogrammetry (DPG) data and the data recorded by the terrestrial laser scanner (TLS) in 2011. This is done to evaluate whether or not the DPG data is precise enough to substitute any future laser scanning of the BBC interior and to acquire a third party estimate of the data generated with Photoscan. During the entire recording process, a visual inspection had served as the only form of quality control. Once the data had been processed and geographically referenced post-season the first indication of actual spatial precision became available (section 5.11). Photoscan provides an estimated deviation between the reference point's actual position and their estimated position. The error mean was 1.06cm with a range of 1.58cm (Table 2: Appendix). The low error margin indicated a successful recording in terms of spatial accuracy. However, relying only on 14 control points and an error margin calculated by the same software solution that produced the data itself is not sufficient to properly evaluate the result.

To get secondary and higher resolution comparison, I decided to perform a comparison between my data and the 2011 TLS data using the TLS data as a reference. The point cloud from the TLS and DPG was compared using the open source solution CloudCompare (CC) (http://www.danielgm.net/cc/). The process of comparing the two datasets was done as follows:

1) A section of the photogrammetric point cloud encompassing the northeastern part of the cave wall and ceiling was exported as a .txt file; it contained just less than 14.2 million points (Figure 25). A full cave point cloud to point cloud comparison could not be performed as many areas of the cave had been altered between 2011 and 2013. The cave wall and ceiling were chosen as the subject for this comparison because it has remained unaltered since excavations first took place at BBC.
2) The two point clouds were imported into CC and a cloud to cloud (C2C) comparison was performed. The C2C comparison estimates the distance between individual points in the reference point cloud and nearest point in the compared point cloud. The comparison gave a standard deviation of 2.05 cm, a mean of 1.25 cm (
3) Figure 28) and a range of 31 cm. Only 4.5% of the calculated values had an absolute distance exceeding 3 cm. The cause of these higher values was attributed to several holes in the reference point cloud (Figure 26) caused by the scanning station's field of view.
4) CC was set to exclude points with a greater distance than 3 cm as all these points originated in areas that were not included in the TLS data. Adjusting for the holes in the

TLS point cloud resulted in a mean equal to 0.89 cm and a standard deviation of 0.43 cm (Figure 28 and Figure 27).

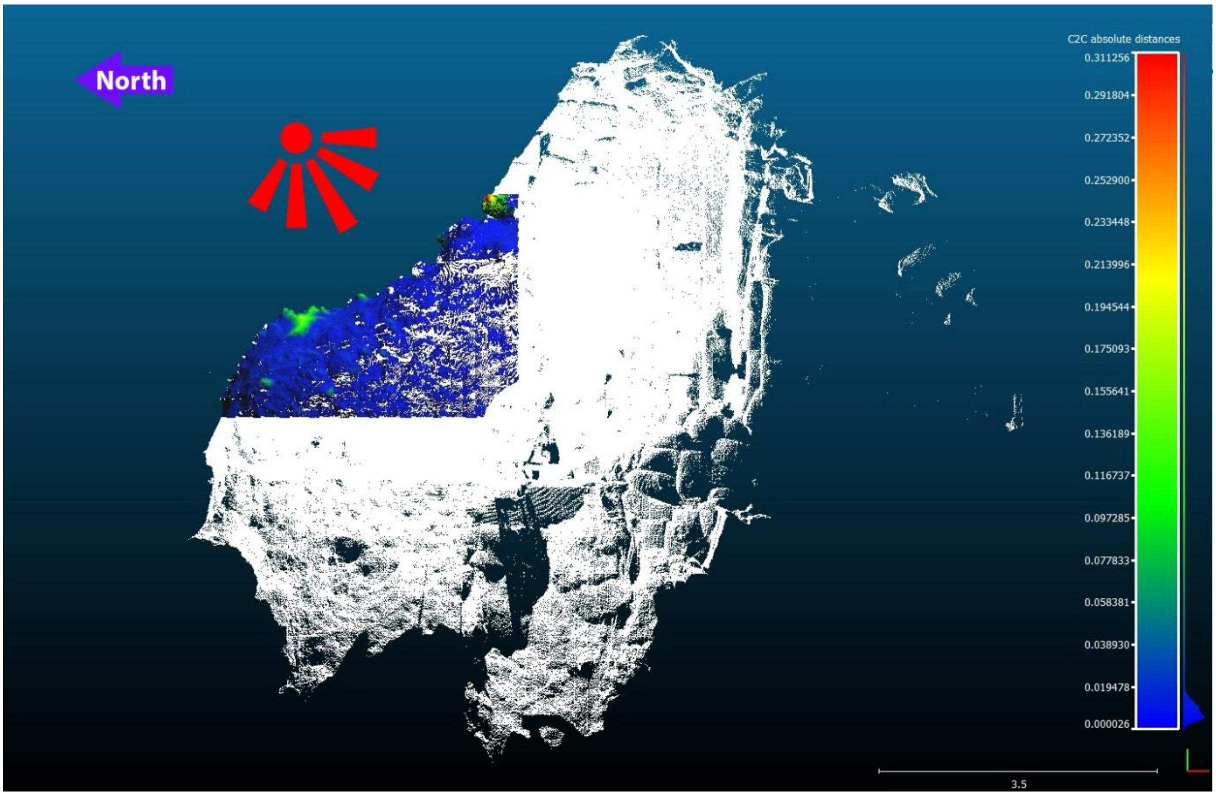


Figure 25: The comparison between TLS (white) and photogrammetric (colour) point cloud was performed on the north east area of the cave wall and ceiling. The initial comparison resulted in distances calculated up to 31 cm. These values correspond with gaps in the TLS point cloud visible from the north east in Figure 26 and Figure 27 (figure adapted from CloudCompare).

When comparing two point clouds that have been recorded and spatially referenced with different equipment, there might be a slight parallel misalignment. This misalignment is caused by the inaccuracy that occurs when spatial recording equipment is set up. It, in turn, manifests as a shared impression in all recorded measurements. Before performing the comparison between two point clouds Cloud Compare, therefore, has the option to optimize the alignment between the two clouds. I chose not to do this in order to evaluate TSL and photogrammetry as independent methods of recording. What this means is that the spatial position of the TSL points is based on the station's orientation during setup in the field while the PG points spatial position were based on the total station setup orientation and the reference marker placement within Photoscan. Both methods of spatially referencing data have a technical and human component affecting the precision of the recording. The sub-centimetre difference between the two point clouds is therefore arguably within the range that can be attributed to the way the data has been spatially referenced. The exterior landscape data was also compared to the TSL data using the same strategy (Section 2: Appendix). The results showed that the standard deviation was lower (7.2cm) than the mean error of the geographical reference markers (21.4cm) used to spatially reference the exterior photogrammetric model. The photogrammetric scan of the landscape covered a greater area around BBC than the TLS (Figure 46). The reference markers furthest from the cave had the highest error margin. This might be the reason why the cloud to cloud comparison of the landscape point clouds calculated a lower spatial deviation than the geographical reference markers suggested.

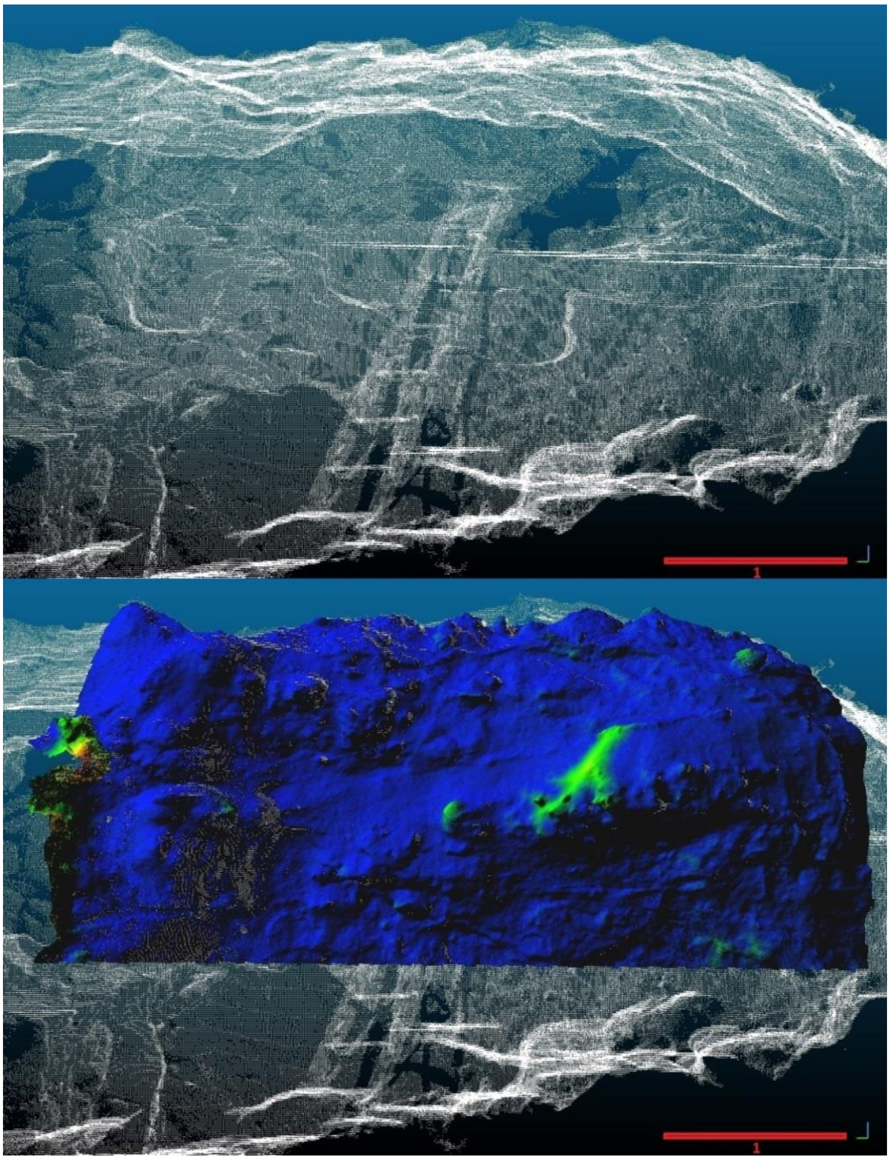


Figure 26. The TLS point cloud (white) was incomplete, containing several gaps in the cave surface (seen above). These holes corresponded with the areas of the DPG point cloud (colour) which deviated most from the TLS point cloud, here represented in green and red (bellow).

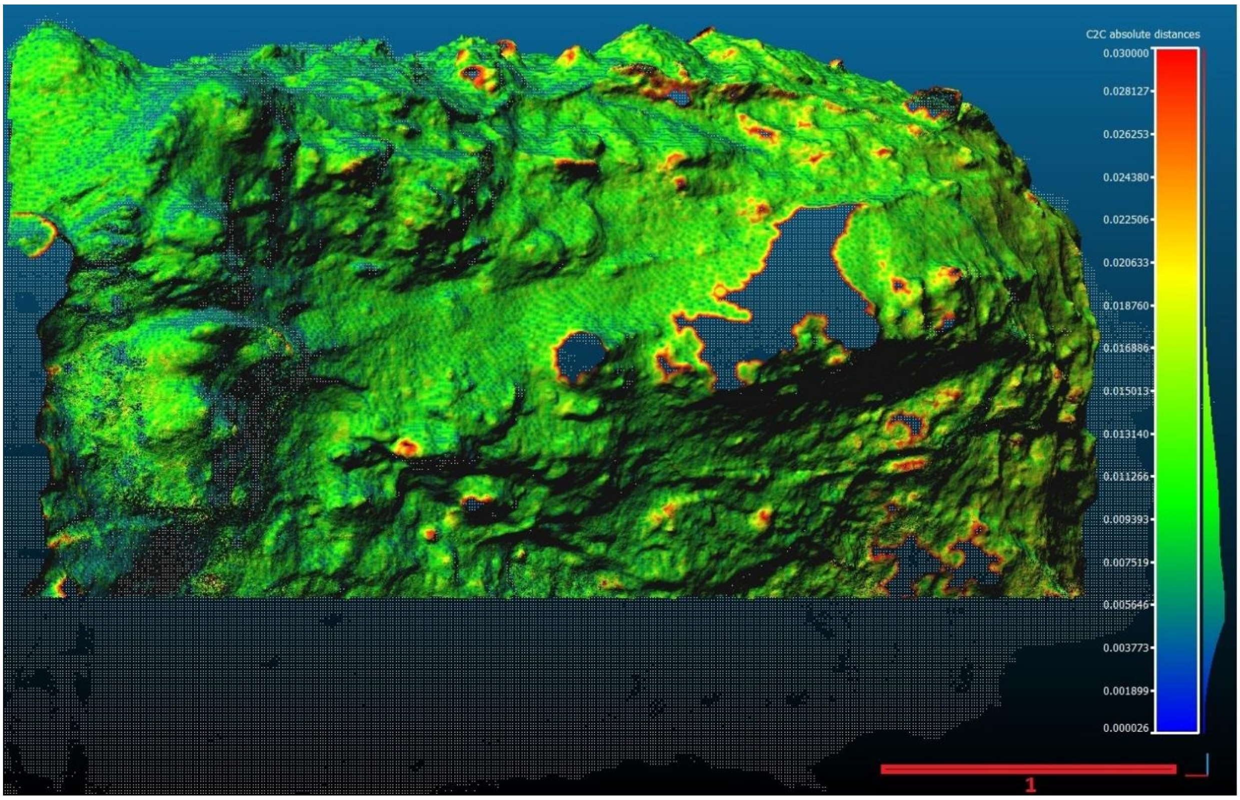


Figure 27. To compensate for the holes in the TLS point cloud (white) CloudCompare was set to disregard values above 3cm. The result confirmed that the higher values of deviation stemmed from the holes (colour).

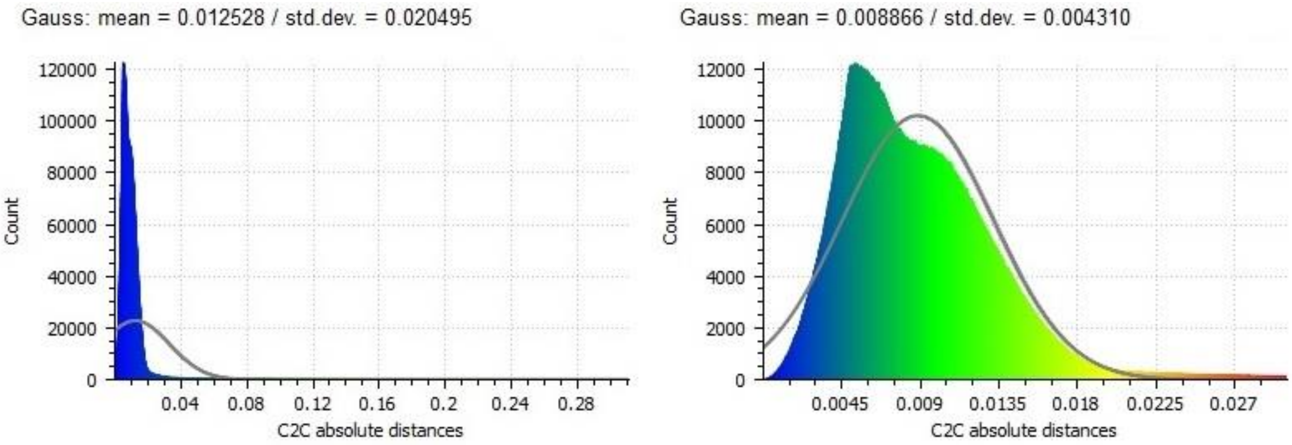


Figure 28. The initial cloud to cloud comparison (C2C) gave a standard deviation exceeding 2cm (left). The higher values were attributed to gaps in the laser scan point cloud. To correct for this values exceeding 3 cm were excluded. This resulted in a significantly lower standard deviation of 0.4cm (right).

7. OLD BBC PHOTOGRAPHIC MATERIAL

During excavations at BBC, a large number of photographs were taken as part of the recording process. One of my project goals was to see what potential spatial data could be created and acquired from the BBC image archive. Here I first briefly explain the reason for working on the archive data and then how the process was carried out. The results are presented at the end in the form of orthographic section profile images and a gradual 3D perspective build-up of the reconstructed profiles within the current (2013) BBC Cave.

The spatial recording strategy at BBC has changed over time to gradually encompass a broad variety of features and elements and a higher level of precision, in addition to a new coordinate system (chapter 4). As a result, some forms of spatial data are only available from the areas of the cave that has been excavated in more recent seasons. These gaps in the data record are what I hoped to fill.

Using archive photos for photogrammetric purposes is not a new concept. My focus is on the potential this can have for BBC in particular, and the explanation of the workflow I employed. I wanted to produce a set of data that could work seamlessly with all modern data that has been spatially recorded within the numerical coordinate system. It would then be possible to obtain spatial and visual information on the stratigraphy, as well as the position of larger objects and structures, such as rock falls and hearths that had not been thoroughly recorded during excavation. Generating the 3d models within the photogrammetric software solution primarily follows the same strategy a described in chapter 5, and I will therefore primarily highlight elements unique to working with archive data.

7.1. Data acquisition – Archive Review

During the excavation seasons pre-dating 2002, analogue cameras were used for photographic recording. This meant that while the later collections were digital and could be reviewed from any location, I had to travel to Cape Town to review and collect images from the analogue collection.

1) The BBC image archive was reviewed, and image-sets with potential for photogrammetric processing were collected (Table 4). These sets comprised of multiple overlapping images of a consistent or largely unchanged area.
2) Data-sets stemming from analogue images were digitalized using a CanoScan FS4000US scanner and exported as .tif files.

7.2. Pre-processing – Image editing

Once I had collected the images, they were largely processed in the same way as those I had captured myself (section 5.10). The archive images had not been captured with photogrammetry in mind, and it was, therefore, necessary to take some alternative steps to achieve a good result. A significantly higher degree of masking had to be performed using once images were imported into PhotoScan. Many of the images I used were captured at different stages of excavation which meant that the surface I was trying to reconstruct would still be covered by sediments or protected by sandbags (Figure 29).

Figure 29: Example of images where masking (greyed area with white border) was applied to cover incomplete excavation (left), and elements which covered the area of interest and did not remain consistent within an image set (centre and left).

7.3. Processing – Model generation

To improve the camera alignment, the tie point cloud was reviewed and edited by removing incorrect points. The camera positions could then be optimized (Figure 30), a process in which the estimated camera positions are refined in accordance with the edited tie point cloud. For those datasets containing the lowest quality images or an insufficient amount of overlap, manual marking of shared features was performed to guide the alignment process. This action was primarily performed on the images from 2000 which stemmed from analogue images that in some cases were overexposed or blurred (Figure 31).

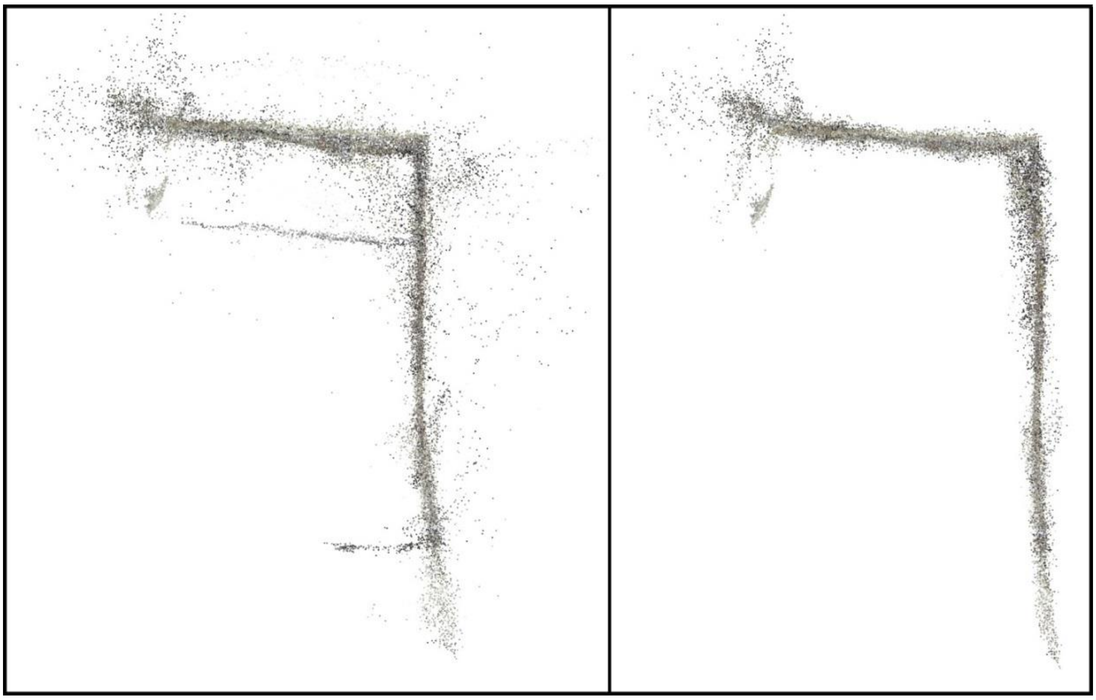


Figure 30. A point cloud before (left) and after (right). Incorrect tie points have been removed, and the cloud has been readjusted. Note how the optimized point cloud has straightened up in the lower right area. This example is the section profile H4c-H6a and H6d – F6d from 2000.

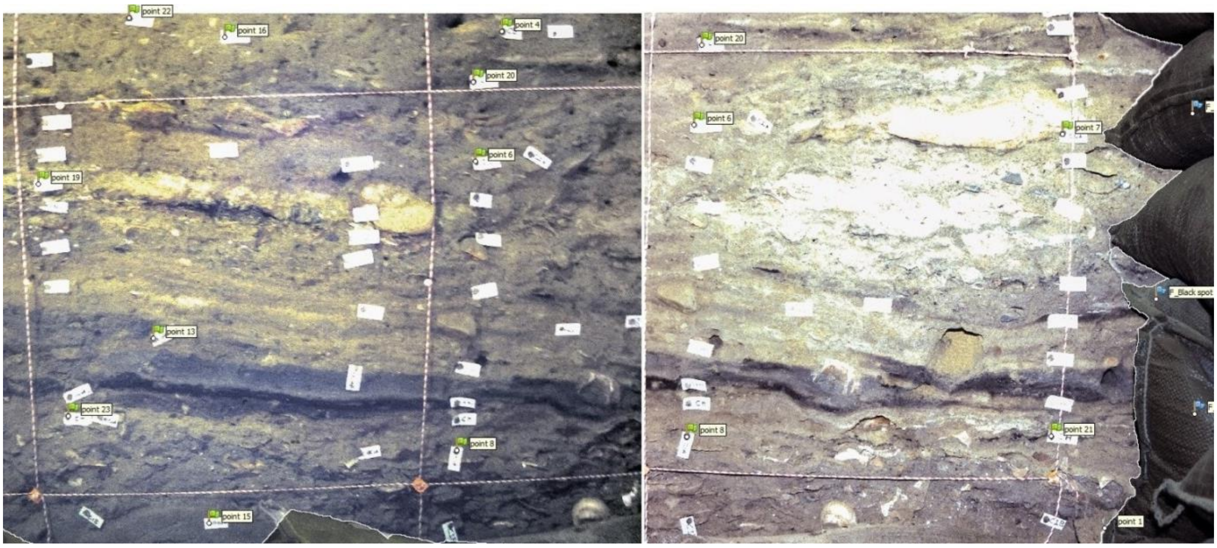


Figure 31. Manual marking of shared features (green flags) had to be performed in order to guide the software solution during the alignment process. This was primarily the case for the slides captured in 2000 which in many cases had poor overlap, exposure and focus. The shared features I marked were mostly nails used to pin layer labels.

7.4. Spatially referencing data

All archive models were spatially referenced directly or indirectly on the basis of coordinate points extracted from the 2013 models (chapter 5-0). Any spatial error present in the 2013 model has been transferred to the archive data. The following workflow was:

1) A minimum of four markers were placed on features appearing within a respective archive model and the 2013 model. Such features were primarily part of the cave wall, however, in some instances, markers were also placed on the label nails, stratigraphic features and material (Figure 32).

2) Estimated marker positions were exported from the 2013 model and imported to their respective archive models, effectively providing the archive model with a spatial position and orientation.

3) Archive datasets were combined with 2013 data, and a visual inspection was performed to determine if the alignment had been successful.

4) Where needed, additional reference markers were added to improve spatial positioning of the archive data (Figure 33). Reference markers were in the case of the 2000 data extracted from other archive datasets (2008 and 2011).

5) In some cases, the archive data was improved by reprocessing the data once spatial markers with coordinates had been added.

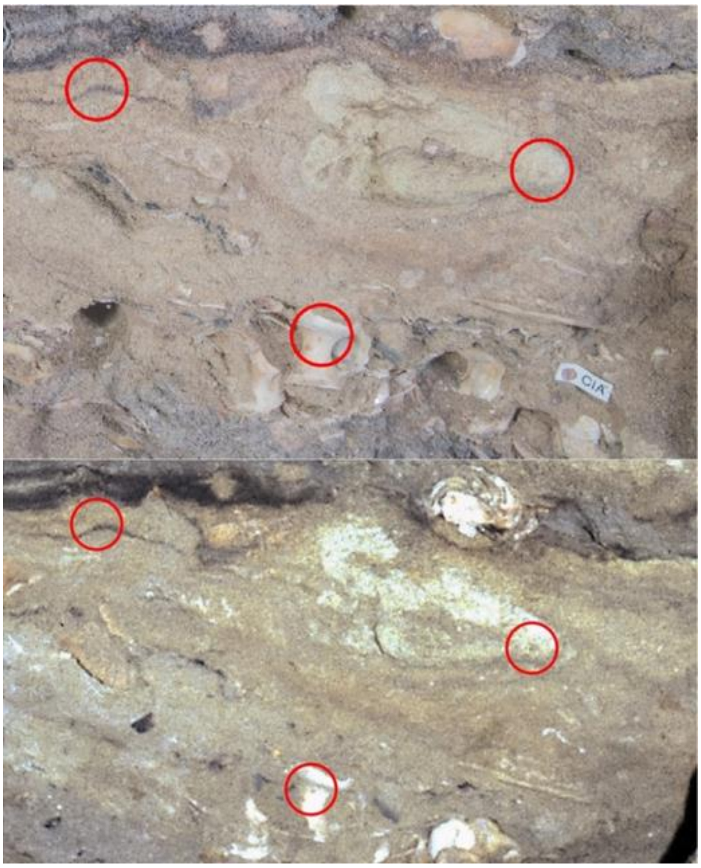


Figure 32. Example of features shared between the modern data (2013) above and archive data (2000) below. The example stems from the section profile of F6d. These 3 reference markers worked in combination with markers taken from other parts of the model. In no case was a model spatially aligned using only markers from such a close vicinity.

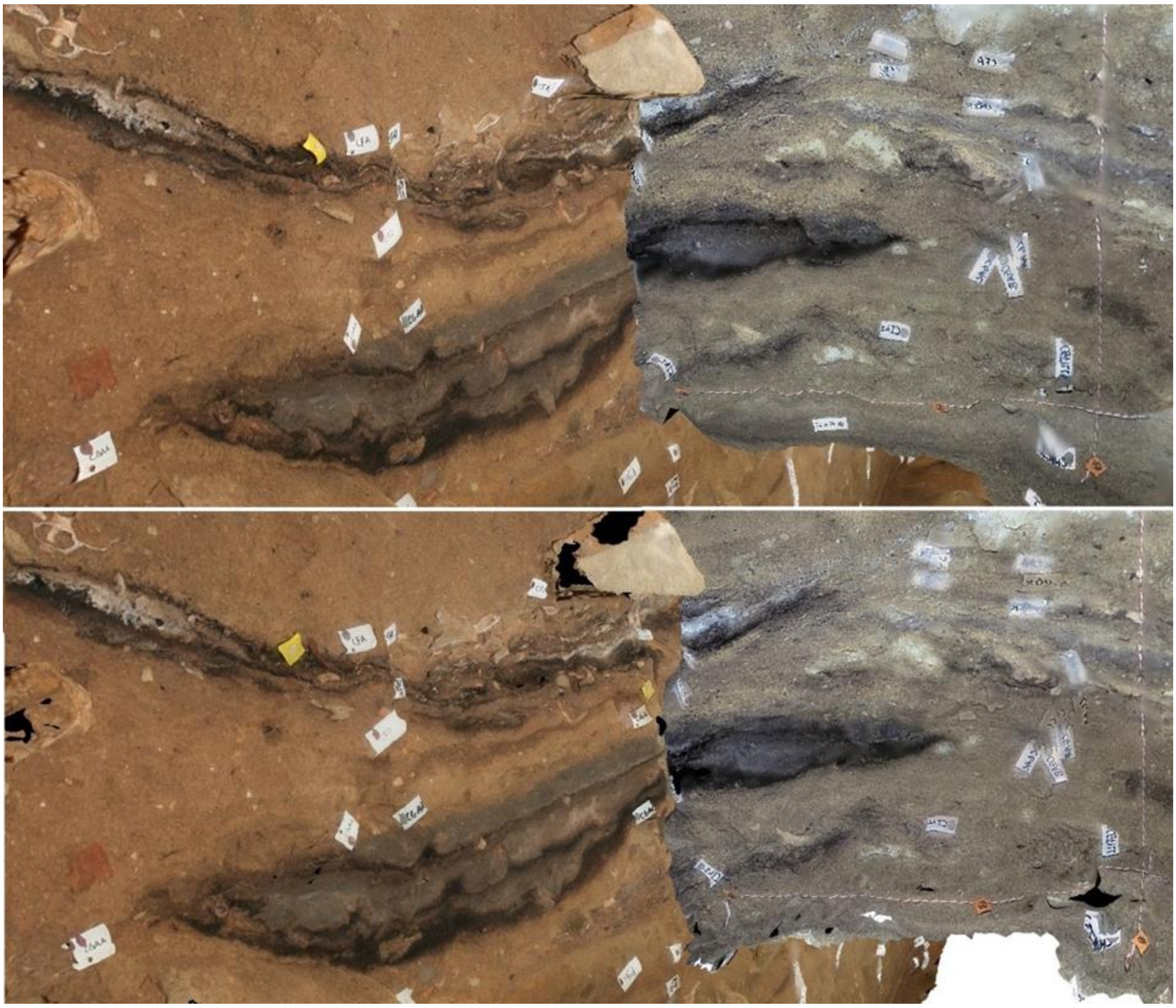


Figure 33. Visual assessment was used to determine if the archive models had been correctly aligned within the BBC coordinate system. In cases where this was detected (above) the reference markers were reviewed and either improved or removed. Also new markers were added. Once this was done the model's position was readjusted (below).

7.5. Result

Following the workflow above, 7 section profiles and one quadrant layer were successfully recreated as spatially referenced 3D models (Figure 34, Figure 35). These 3D models were, in turn, used to create orthographical images of the sections (Figure 38, Figure 39, Figure 37, Figure 40, Figure 41, Figure 42, Figure 43). Spatial positions and outlines of features that are part of these reconstructions can now be measured and extracted. The spatial accuracy of the reconstructed models varied individually and was affected by the quality of the image data (resolution, sharpness, overlap and angle coverage) and the precision with which the position of reference markers could be identified (Table 4). As the newer images were of higher quality, they resulted in more accurate and higher resolution models. Any study carried out on this new data I have created and presented here considers the limitation set by the spatial precision of each.

Profile/ Section	**Year**	**Image count**	**Reference markers: direct/indirect/ from image alignment**	**Estimated accuracy (Control point average)**	**Control measurement (Detected deviation per meter)**
H4d – H6b	2000	27	0/5/0	0.52cm	
E6d - H6d + H4c - H6a	2000	86	13/2.0/28	1.58 cm	E6d - H6d: 1cm H4c - H6a: 0.3cm
I5b - I6b	2002	25	5/0/0	0.26cm	
I5a - I6a	2005	44	6/0/0	0.86cm	
F6d – I6d (South profile)	2008	44	8/4/0	0.66cm	
F7a – H7b, H6c, H6c-I6b	2010 2011	366	5/0/0	0.13cm	

Table 4. Generated archive models with information regarding data set, method of spatial referencing and estimated accuracy. In the case of the 2000 models, a string grid system had been overlain on top of the profile at 0.5m quadrants. Control measurements were taken along these lines and showed a deviation varying between +3mm and + 3cm.

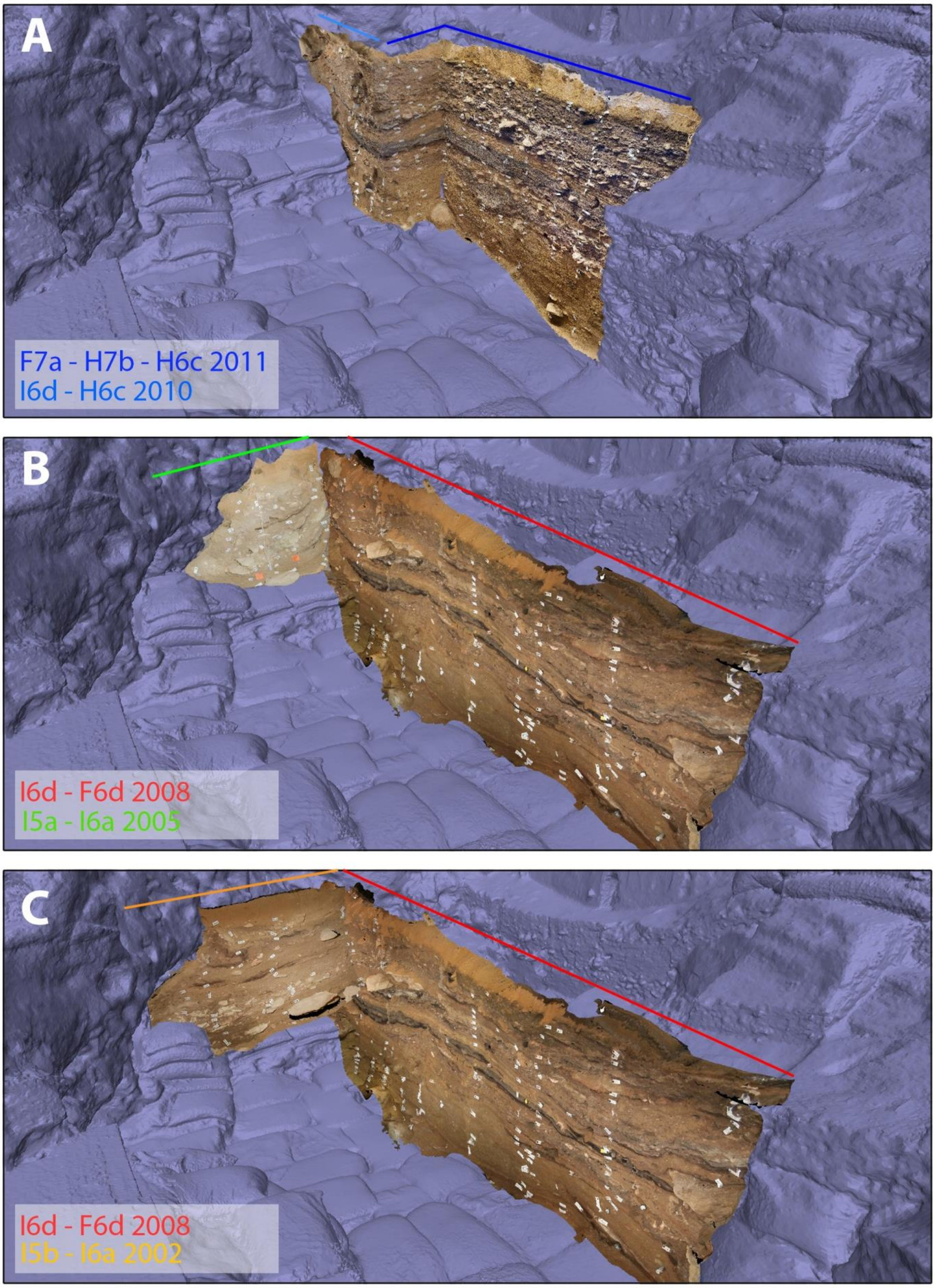


Figure 34. Oblique view of the sections created from archive images. The section profiles are displayed in combination with an un-textured 2013 model and show a step by step (ABC) reconstruction of the cave stratigraphy from 2011 (A), 2008 and 2005 (B) and 2002 (C).

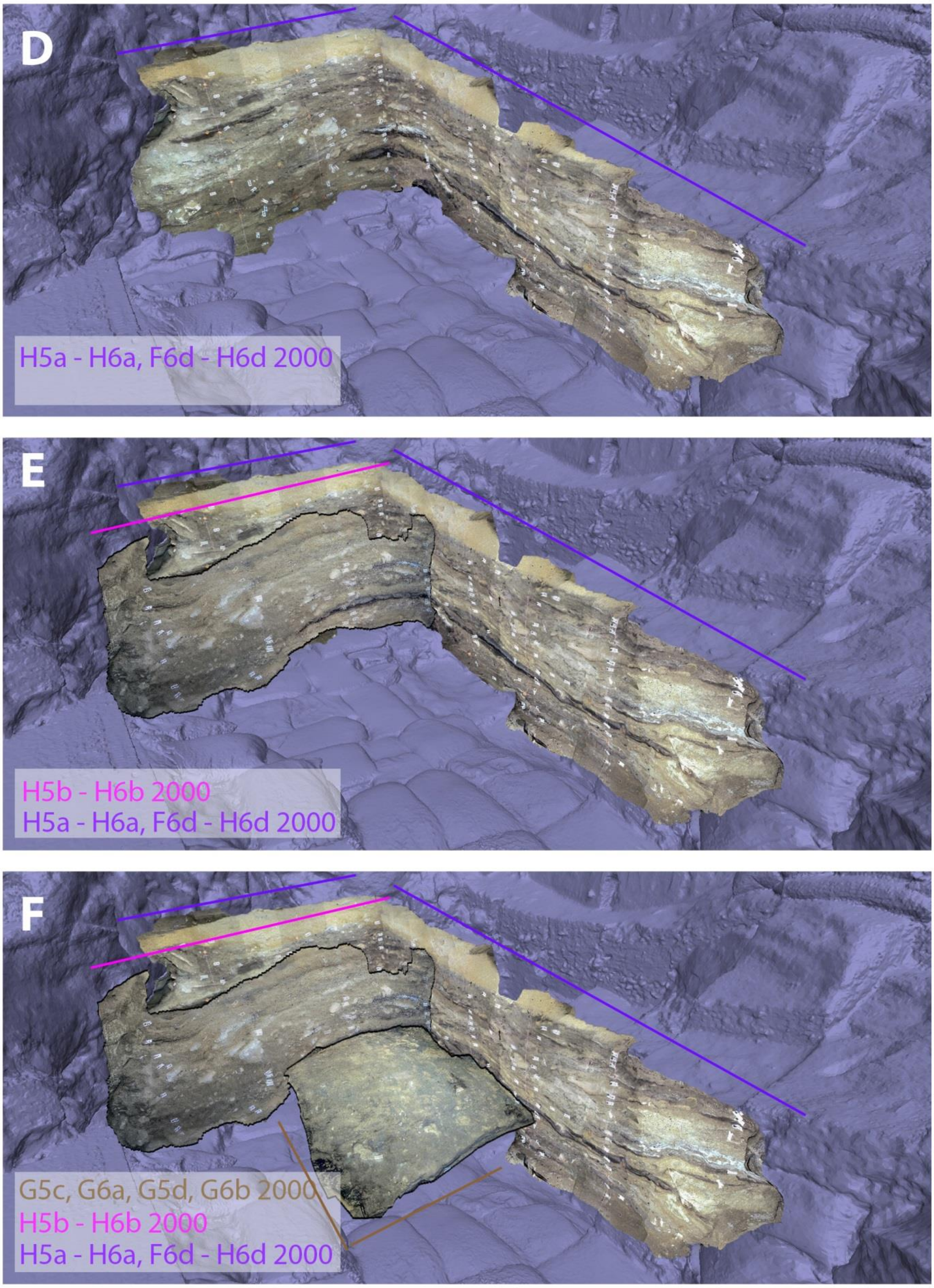


Figure 35: Oblique view of the sections created from archive images. The section profiles are displayed in combination with an un-textured 2013 model and show a step by step (D, E. F) reconstruction of the cave stratigraphy as it appeared in 2000.

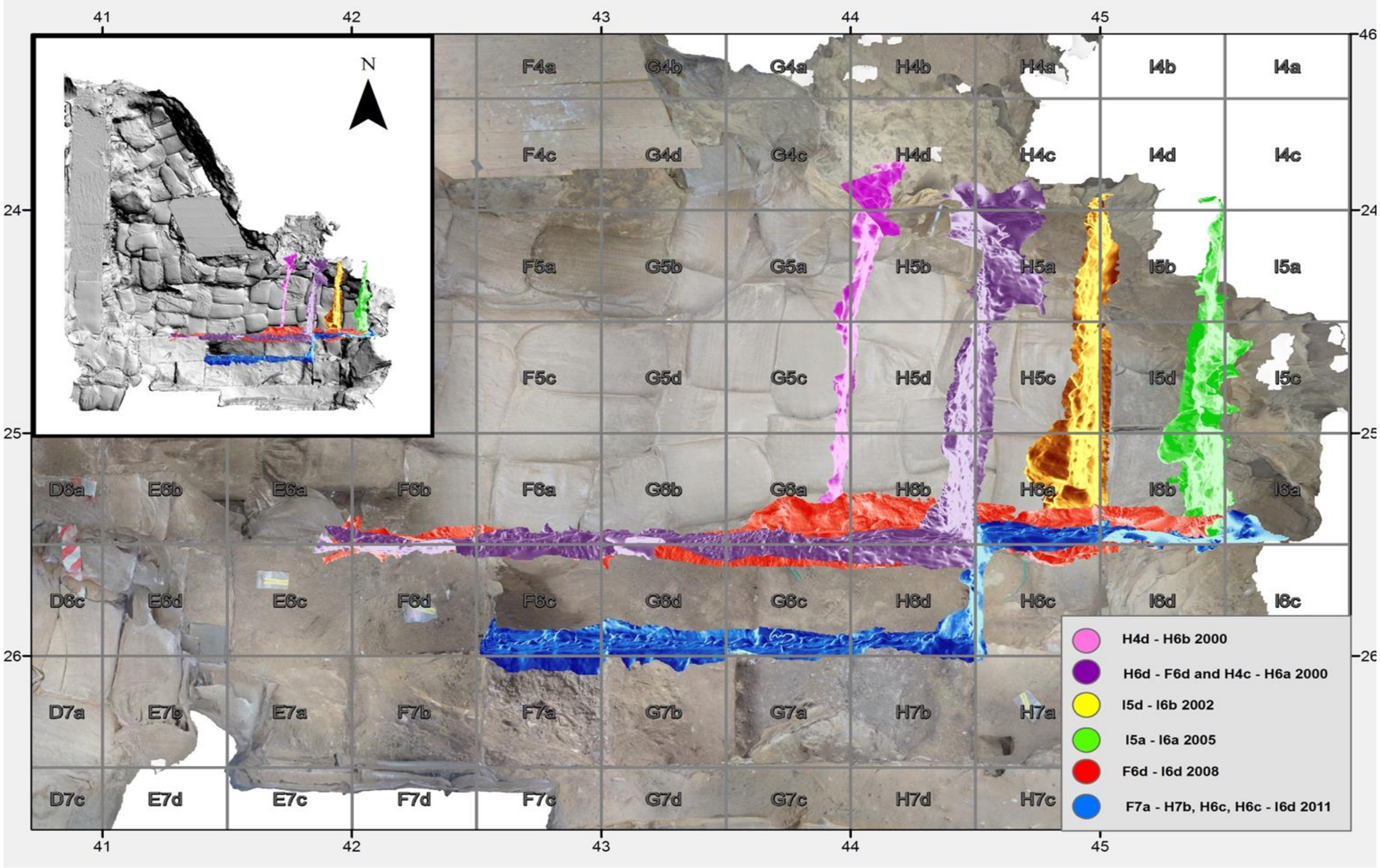


Figure 36. Map of the BBC interior showing the spatial position and relationship between the different archive models and the 2013 model of the excavated areas of BBC .

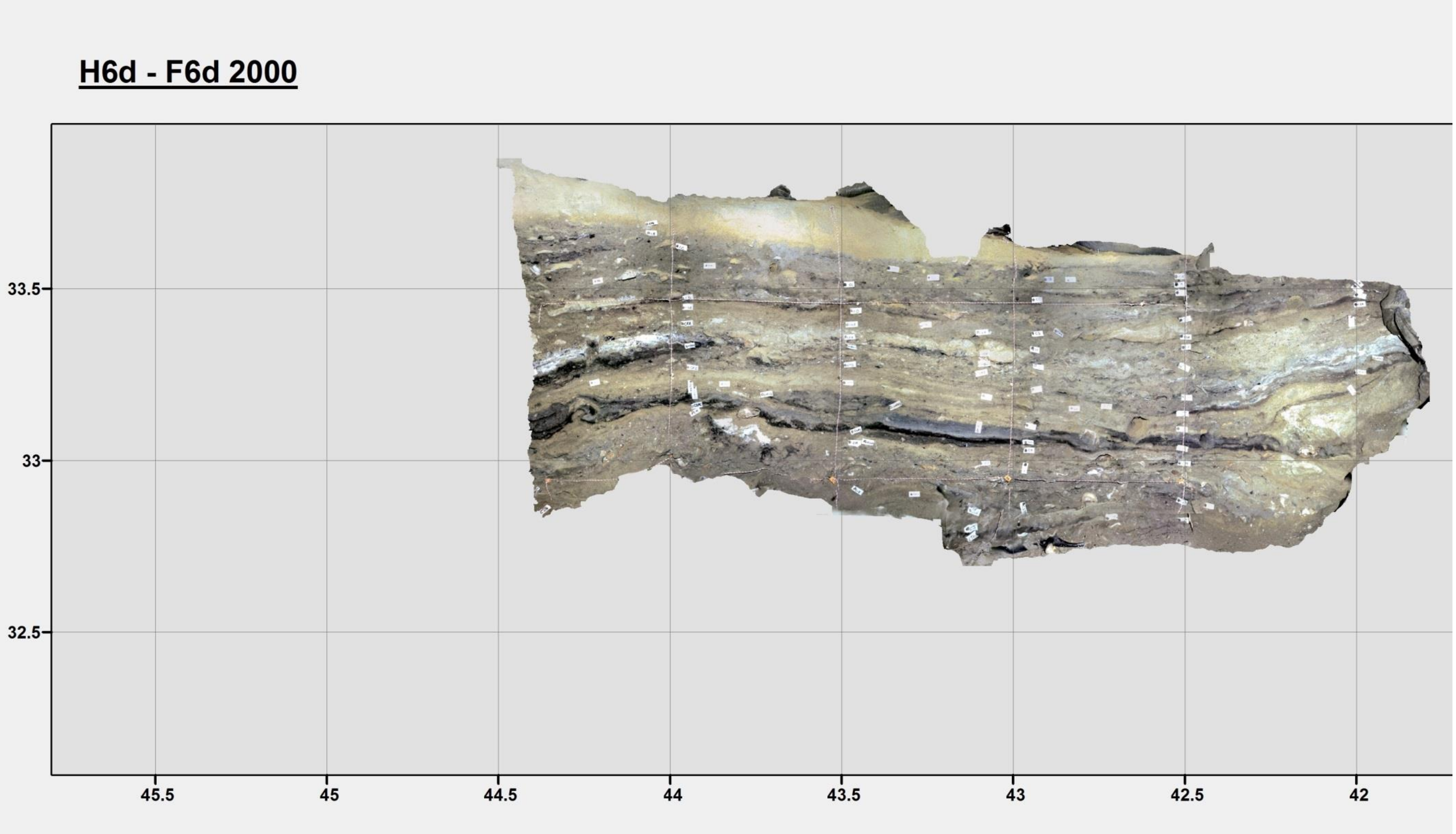


Figure 37: Section profile H6d - F6d. Created using images captured in 2000.

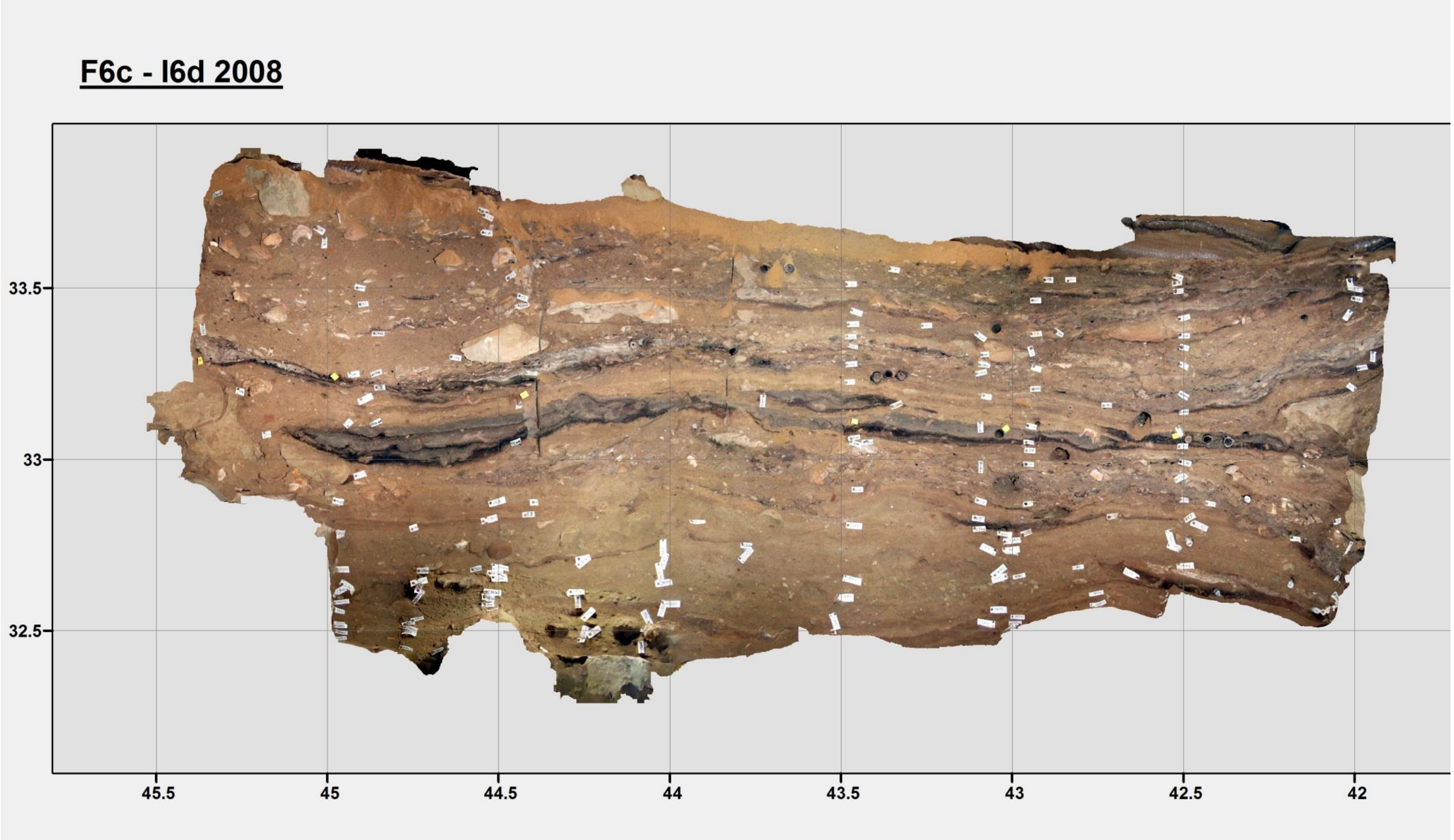


Figure 38: Section profile I6d - F6d. Created using images captured in 2008.

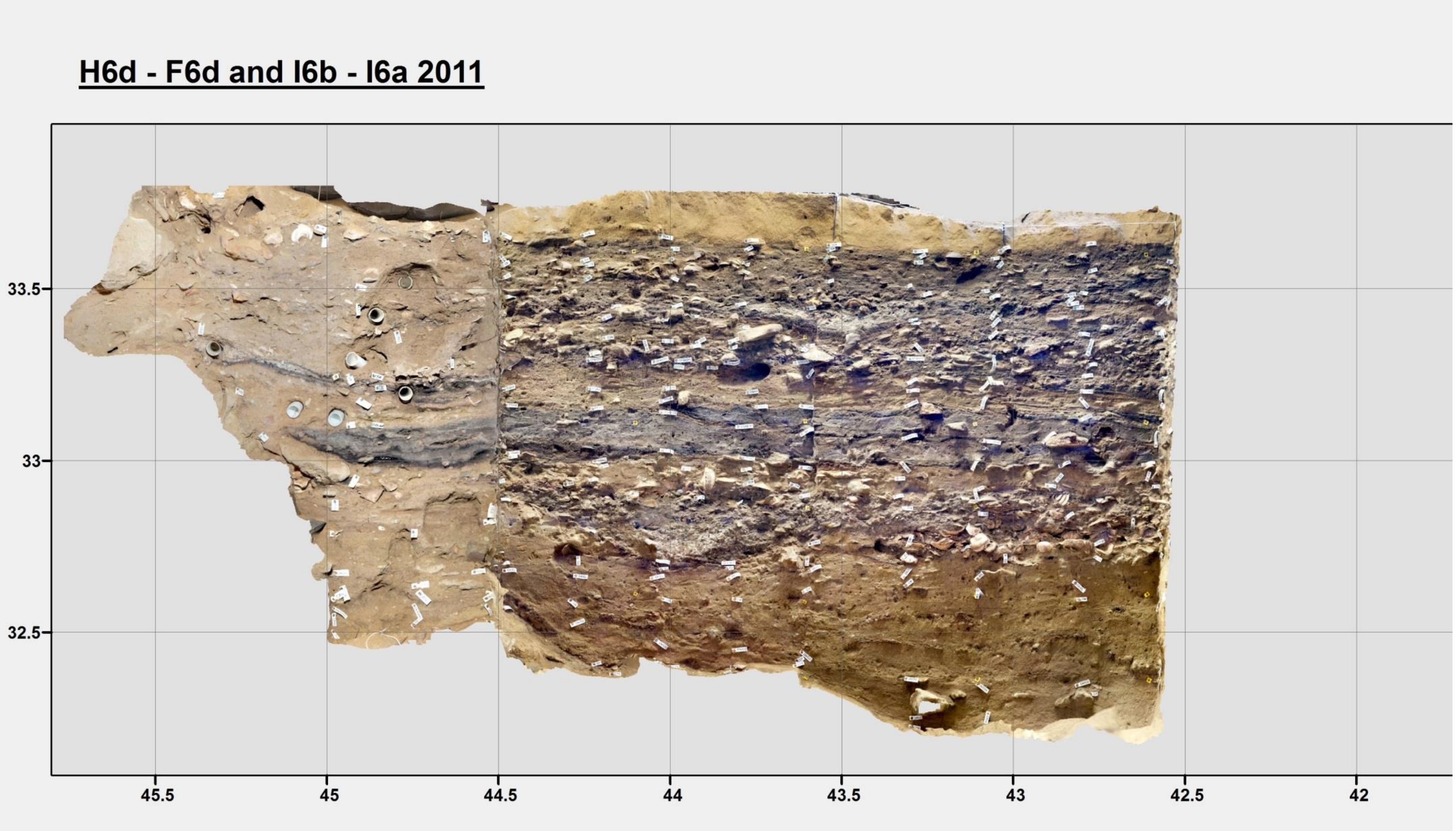


Figure 39: Section profile I6d - H6c, H7b - F7a. Created using images captured in 2010 and 2011.

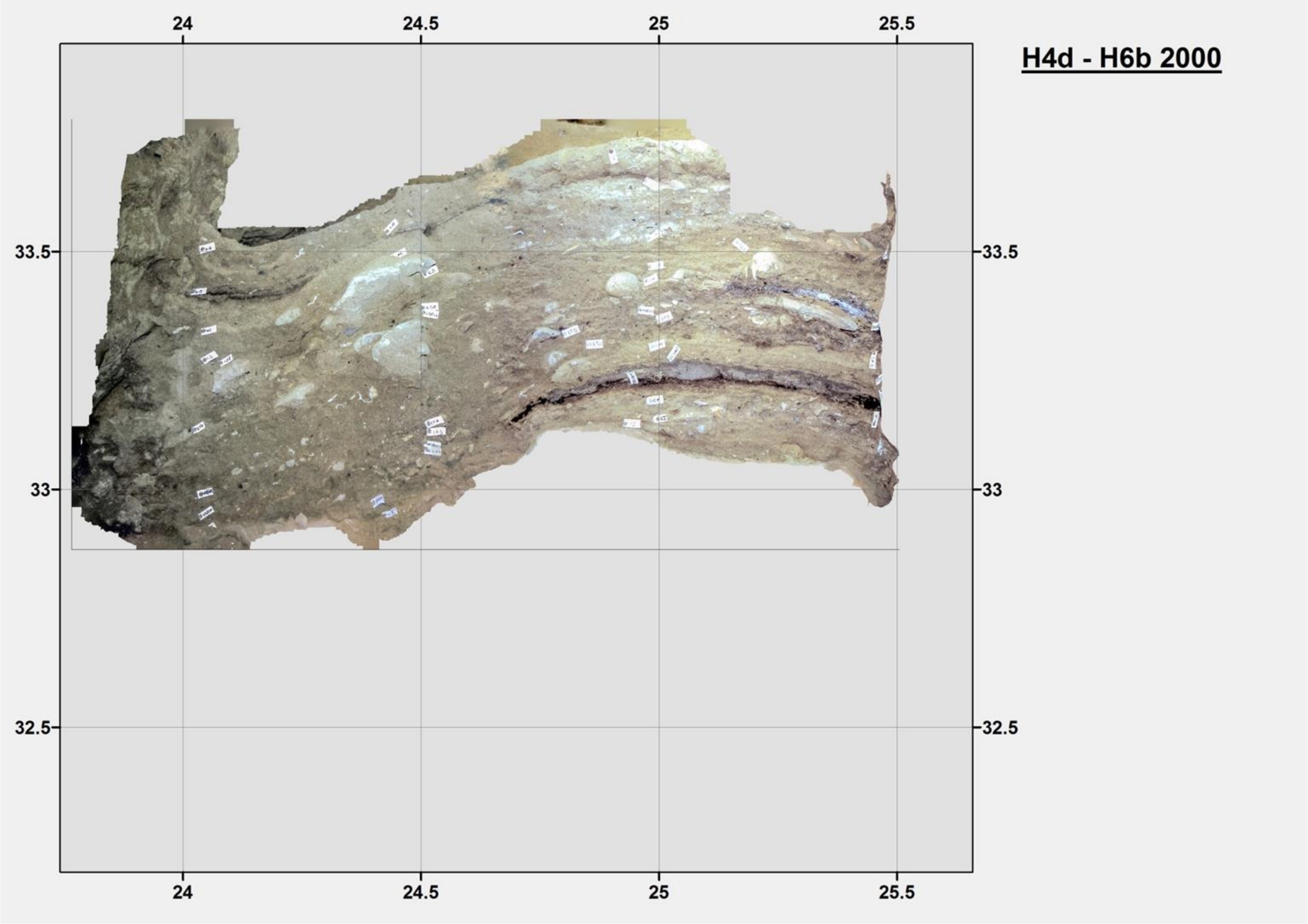


Figure 40: Section profile H4d – H6b. Created using images captured in 2000.

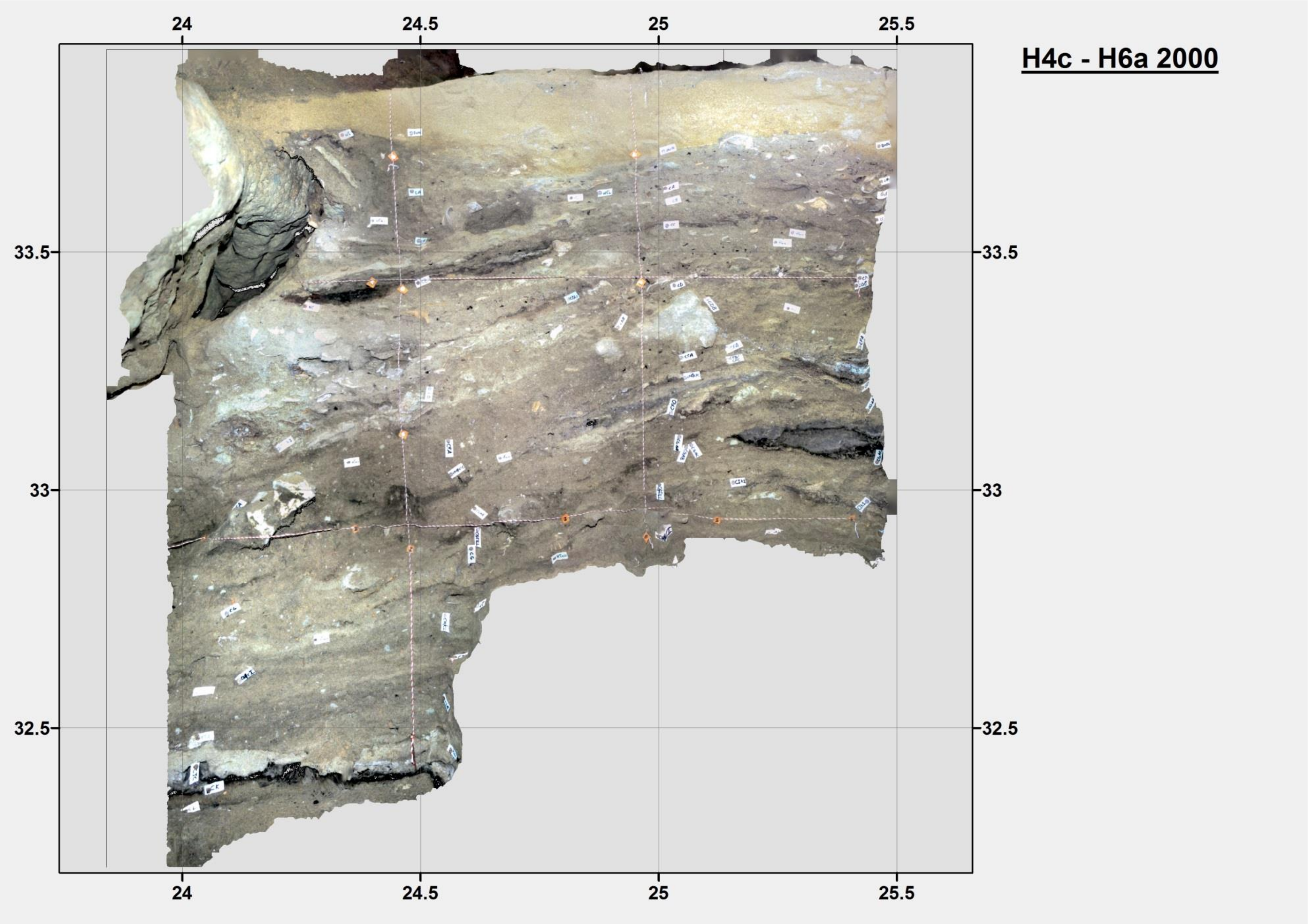


Figure 41: Section profile H4c – H6a. Created using images captured in 2002.

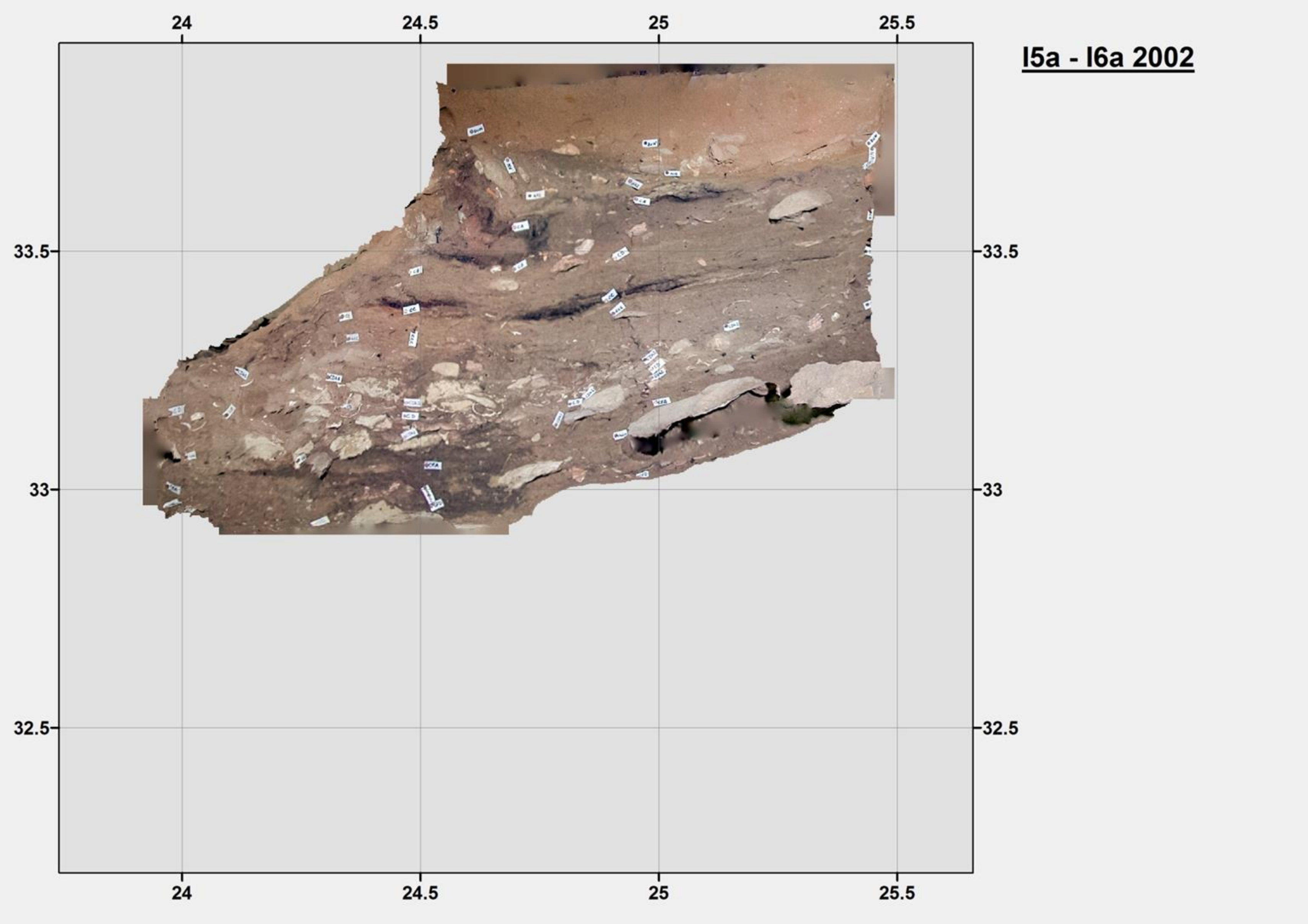


Figure 42: Section profile I5a - I6a. Created using images captured in 2005.

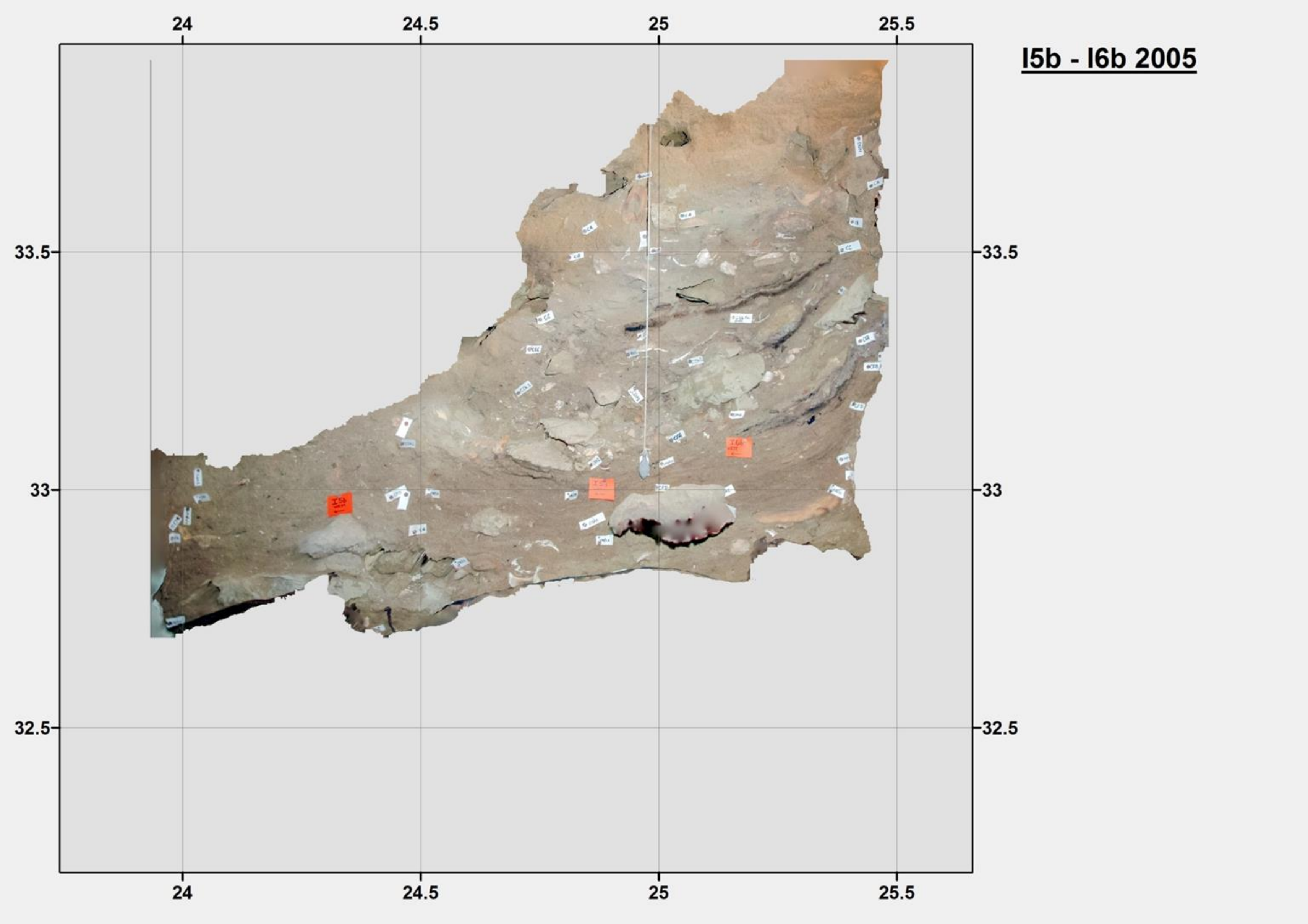


Figure 43: Section profile I5b – I6b. Created using images captured in 2002.

8. DATA EVALUATION

8.1. 2013 Data evaluation

The 2013 photogrammetric recording resulted in three primary datasets: BBC Interior, BBC exterior and BBC washout (chapter 0). These datasets were used to create both an overview and detailed data in the form of orthographic images and surface models with high textural and topographic detail (Figure 19, Figure 20, Figure 21, Figure 22, Figure 23, Figure 24). All data sets are spatially referenced within the local numerical coordinate system at BBC. This means that the data can be combined with other data spatially referenced within the same system without the need for scale and space adjustment.

8.1.1. BBC Interior

Recording the BBC interior was the most challenging of the three case studies. The main problems with the interior recording were the low light conditions, narrow areas and the limited freedom of movement. For the greater part, I was able to successful tackle the issues presented by the cave by following the strategies explained in chapter 0. The key element of this strategy was dividing the cave into manageable areas and using artificial light. The former helped to maintain a good overview of the recorded data making it easier to ensure that each scan was complete. The latter meant that the camera could be handheld, images were taken in quick succession, and I could move around more freely (section 5.2.4).

I have shown that the BBC Interior data has similar spatial accuracy and precision to that achieved using a laser scanner in 2011 (section 6.1), with the added benefit of providing a textured surface. The interior data can thus be combined with other spatial data recorded using the Trimble spatial station without concern that a difference in spatial precision will cause misrepresentation when the data is combined. There are several problems with the BBC Interior scans. The problems primarily concern holes in the surface of the model or low-quality textures which are caused by insufficient photographic coverage. Most of these problems have occurred in the unexcavated west side of the cave (Figure 44). Despite not being able to achieve the same results for the unexcavated west side of the cave as that of the excavated east, this data provides a new spatial and visual overview of the cave as a whole.

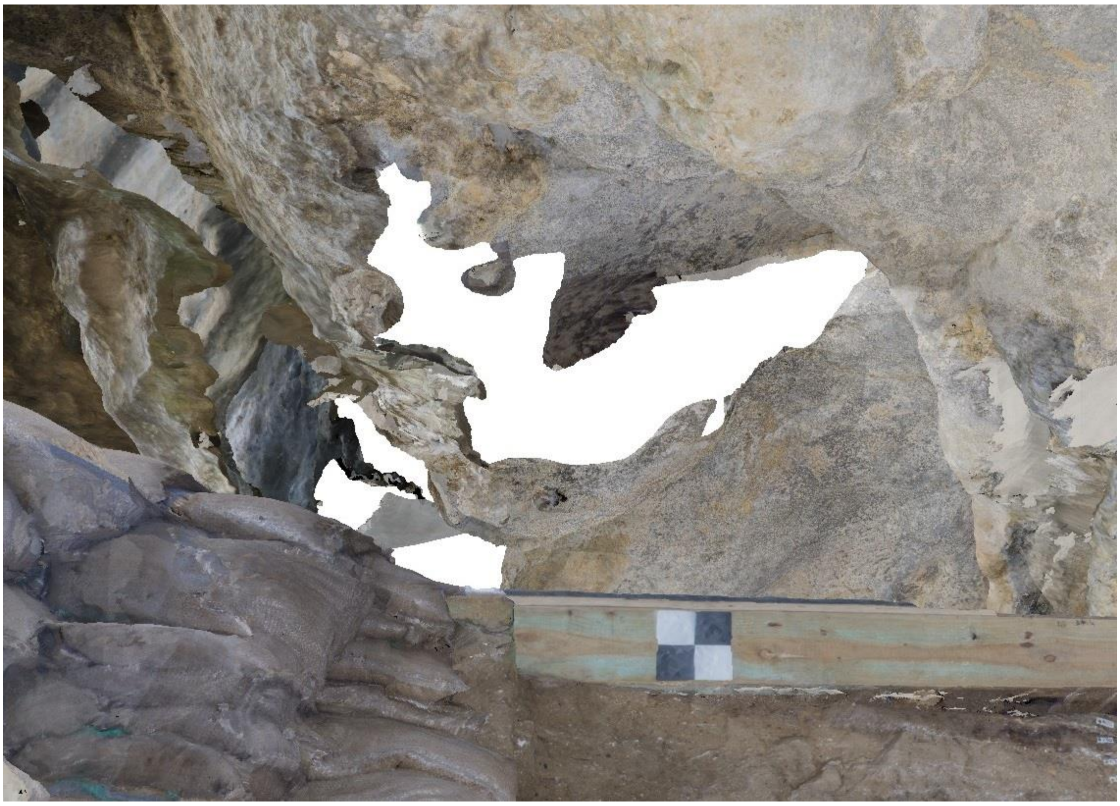


Figure 44.The ceiling above the unexcavated part of the cave (west side) was not properly photographed. This is the only way in and out of the cave. As a result, it was not recorded in the same session as the rest of the ceiling. Unfortunately, the lack of photographic coverage was not realised during the field season. The result was large holes in the ceiling of the cave model.

8.1.2. Washout

The BBC washout covered a significantly smaller area than the interior and was recorded in a similar matter in terms of camera distance, image overlap, and camera angles. The average spatial error for the 15 geographical reference markers is calculated by the photogrammetric solution to be 6mm (chapter 6). TLS data needed to perform a third party evaluation was not available for this area, however, on the basis of the similar size and marker precision between the BBC Interior and BBC Washout it can be safely predicted that the latter data have an equivalent spatial quality as that of the former. The data produced enables us to visually study the spatial relation between the source of eroding material outside the cave and the stratigraphic layers inside (Figure 20).

8.1.3. *BBC Exterior*

The exterior data does not have the spatial accuracy and texture quality as the BBC Interior. Photoscan calculated that the geographical markers had a standard deviation of 21.4cm. When compared to the TLS standard deviation of a compared area was 7.2cm (section 6.1), this suggests that some of the markers had been placed with low precision (section 5.11.3). In addition to the lower spatial precision, the textural reconstruction did not achieve the same level of fidelity. Instead, the texture of both the 3Dmodel and orthographic image were partly skewed (Figure 23).

The less successful reconstruction of the BBC exterior primarily relates to the way in which the data was collected, in turn, caused by the difficult terrain and environmental conditions. Recording a large area from ground level greatly limits the angles from which pictures can be taken. In practice, this means that large parts of the BBC exterior were recreated using images captured from only one side and from an angle that is 90 degrees off from the top down view of the orthographic map (Figure 45).

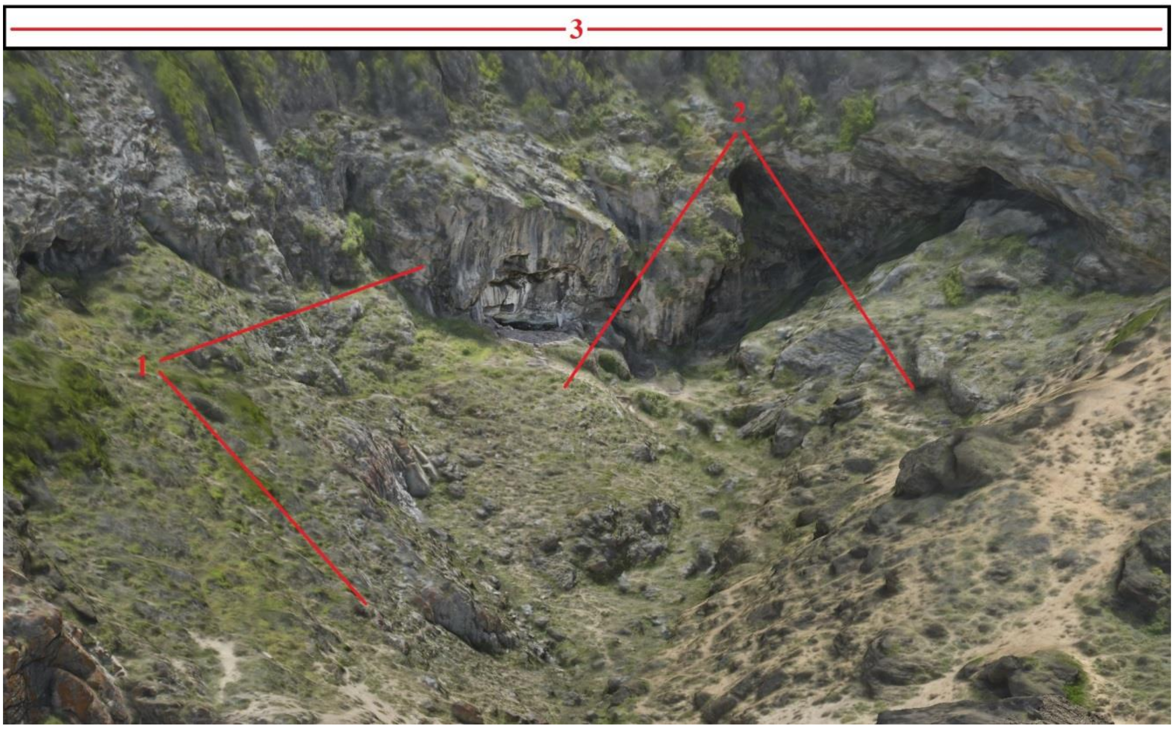


Figure 45: The recording of the exterior landscape was performed at ground level which meant that the images were all captured at an oblique angle (1). Ideally, the exterior landscape would have been photographed from a vertical angle (2) to correspond with the angle which is used in the orthographic map image (3, Figure 23).

The high angle alone should not mean that the point cloud generated using photogrammetry would deviate too much from the TLS point cloud, as both recordings took place from ground level and only a limited number of recording positions were used. There are three other factors which also affected the result of the photogrammetric point cloud, and that could cause deviations:

1) Moving objects such as blowing vegetation and waves meant that the landscape would change to some degree between each image being taken.
2) Much of the exterior had to be photographed from long distances. Hence, a much smaller amount of information was available per square meter than was the case for the interior. The chance of misinterpretation was thus greater.
3) The exterior data was spatially referenced on the basis of 11 geographically recorded reference points. These points proved to be difficult to identify in the photographic material due to the distance from which the images had been captured. Accurately marking these points became difficult as some of the features serving as spatial markers were highly pixelated (Figure 15).

In conclusion, recording the BBC exterior using DSLR camera and the total station was not able to achieve the same precision as the TLS data. On the other hand, the photogrammetric recording covered a larger area (Figure 46). For large scale, topographic data recording the result can be regarded as acceptable.

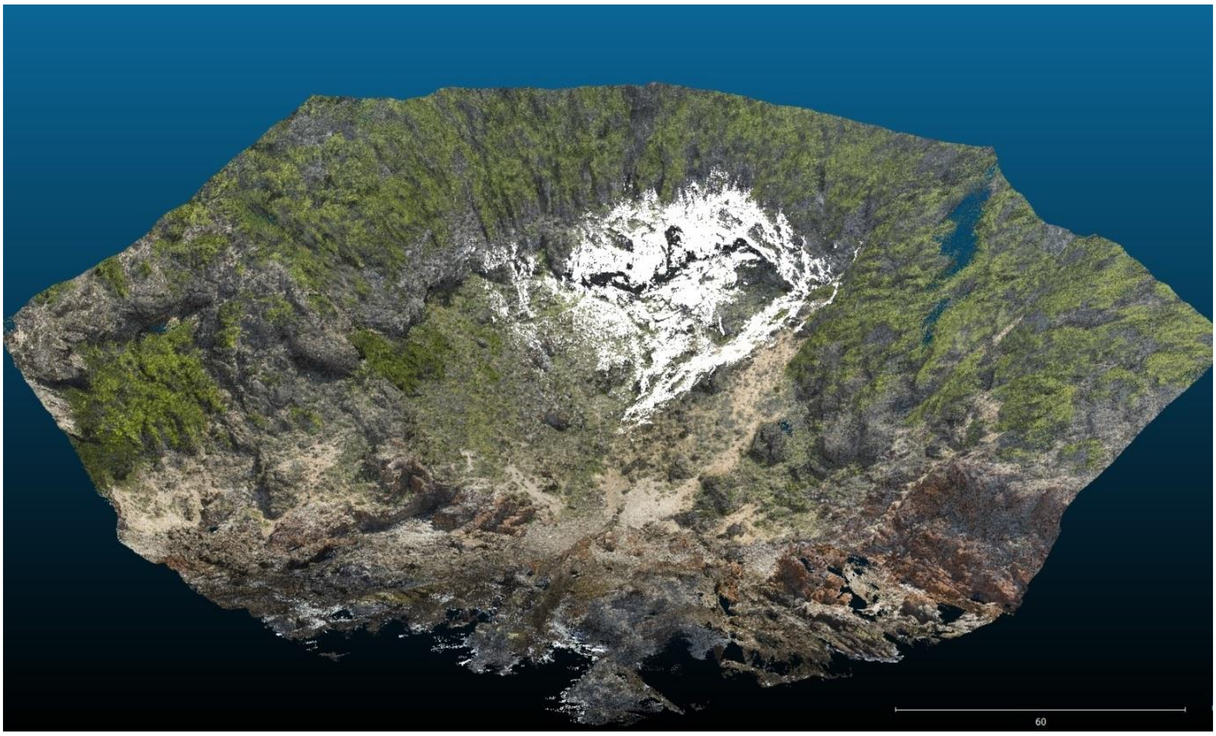


Figure 46. The point cloud created using TLS (white) covers a significantly smaller area than that recorded using photogrammetry (colour). Images created using CloudCompare (units in meter).

8.2. Archive Data evaluation

Using photographic archive images (slides and digital) from 2000, 2002, 2005, 2008, 2010 and 2011, seven sections have been recreated as spatially referenced textured 3D models (Cchapter 6-7), allowing for the gradual 3D reconstruction of the south-east part of BBC and the generation of spatially referenced orthographic images of the respective sections. This reconstruction is four-dimensional as it allows for viewing the excavation history of the site by selectively displaying and hiding sections from the different excavation seasons.

The archive models were not spatially referenced using measurements taken directly from the cave itself but had to rely on spatial information extracted from the 2013 model. This meant that the spatial error became a combination of the transferred from the 2013 data and that caused by the manual identification and placement of reference points.

Alternatives to performing test measurements or otherwise ascertain the spatial precision of these reconstructions are limited. The TSL recording was only performed during the 2011 season and cannot be used. The assessment I was able to perform is based on the spatial error calculated by Photoscan and supported by control measurements performed in Photoscan and ArcMap 10.1. This suggests an accurate orientation and scaling down to a cm level. Overall, the fidelity of the reconstruction is high, and the higher resolution datasets from 2008- 2011 provided the best result.

8.3. Method and data comparison

Here I examine how digital photogrammetry may be integrated with the current documentation process. Is its role complementary or superseding to the current methods of surface recording, digital photography, drawing, total station and laser scanning (3.4, 4.5.4), and how relevant could the role of this method be in future excavations?

8.3.1. How does photogrammetry compare

Comparing the laser scanner to digital photogrammetry, as it was employed at BBC, there are several apparent drawbacks to the former method, first cost, and availability. Digital photogrammetry requires a software license (point 5.2.2 Table 1), yet the laser scanner needs to be rented with a qualified operator and a software solution. The high cost excludes TLS as a method of recording over the full excavation period.

TLS also has limited range and mobility as the minimum range of the scanner used at BBC was 0.5m. It's relatively bulky size, tripod included, prevented recording within the inner chamber. Several smaller areas in the cave were thus excluded from scanning. Photogrammetric recording allowed for larger part of the cave to be recorded, including the inner chamber and surrounding landscape.

A clear advantage with TLS is the way data is generated. The laser scanner has two factors that affect the accuracy and precision of the recording, the scanner quality and its precise set-up (section 3.4.3). Digital photogrammetry, on the other hand, is affected by the camera and total station quality and how they are set up (section 3.4.2 and 0). The accuracy is then further affected by the software solutions ability to align the images correctly and generate a model. How exact the geographical reference markers were recorded at the site and how accurately they are applied in the photogrammetric solution is a key factor affecting the accuracy.

In section 6.1 I show that the standard deviation between the two types of data is only 0.89cm. The CX laser scanner and the VX total station both have an accuracy of 2mm under 30 meters if correctly set up. Considering this and that the photogrammetric solution calculated and average deviation of 1.0cm for the geographical marks, I argue that TSL and photogrammetry at BBC provide datasets with minimal differences in accuracy (L3 Figure 3).

Both the total station and normal photography have clear advantages over photogrammetry. Photogrammetry is not an efficient method to record single point’s positions; neither is it as fast and simple as regular photography. Therefore it does not replace a total station and camera. Photogrammetry is a good method of recording the surface of quadrant layers and sections using a combination of photography and total station (section 4.5.4). The result is quite similar to that which can be created using photogrammetry. Based on the results and experience from my project it is apparent that this type of recording could be performed more efficiently and provide a higher quality result using photogrammetry. Instead of scanning the surface with the total station, a few extra images would be captured with the camera, reducing the recording time. Processing the images into a finished product (photorealistic 3d model, geographically referenced orthophoto etc.) would also be a less labour intensive task due to the high degree of automation offered by the software solution.

Photogrammetry has a clear potential role as part of the BBC recording strategy. It can substitute TLS as a cheaper and more total form of spatial documentation. Conventional photography, drawing and total station point measuring cannot be replaced. Quadrant and section scanning in its current form should be replaced by a photogrammetric recording. Also, photogrammetry provides a way of recording and displaying the relation between occluded areas of the cave that has previously not been possible.

8.4. Comparison between old and new data

The 2013 recording, archive images and the TLS scan in 2011 all resulted in point clouds, and in this way the three datasets are similar. The way in which they were created is different (chapter 0,7 and section 3.4.3), and as a result, the degree of distortion compared to the real word is also different (Figure 3). The TLS scan intentional photogrammetric recording provide a precise spatial record of the cave surface and the local cave exterior. Only the photogrammetric recording contains colour information and consequently stratigraphic information. Both the archive data and the 2013 data provide a photorealistic spatial record of the cave surface and a greater part of the surrounding landscape. However, the archive images were not recorded with photogrammetry in mind and therefore the information it provides is more selective (L2 Figure 3). Because of the higher level of spatial and visual information provided by the photogrammetric recording, it is of higher value for an archaeologist than the TLS data.

8.5. Workflow and strategy evaluation

The recording strategy developed and employed at BBC for the 2013 photogrammetric recording yielded good, but not perfect results. The workflow made it possible to perform a complete recording of the cave interior and the exterior landscape without the need of new equipment, while not interfering with other activities at the site and keeping to the strict timetable. The decision to use a configuration of multiple flashes proved to be a success as it meant that the camera could be handheld and photographs could be taken in rapid succession. In practice, this meant that the entire cave could be recorded in the short time span that was available. The mobility offered by being able to hold the camera, instead of using a tripod, meant that I, as the recorder, had the mobility needed to reach the hard-to-get areas such as the inner chamber. An unpredicted problem with this strategy proved to be the rate at which the batteries of the flash units were depleted. In total, the setup required 13 AA and 2 CR123A batteries and these had to be changed about 3-4 times during the recording.

The strategy of dividing the cave into different sections (Figure 9) also proved relevant as it meant that I could focus on, and complete, individual parts of the cave when excavations were not in progress. Attempting to record the cave ceiling as a single part proved too ambitious. Unable to maintain a good overview the southwest area was not to be properly recorded (section 8.1.1, Figure 44). A field computer allowed for vital testing and evaluation, the image sets as excavations proceeded. Due to restrictions on electrical power, all image sets were not properly tested in the field, however, and would cause some problems

(section 5.3.1). To prevent incomplete scans in the future, a sufficient amount of time should be allocated to testing the recorded image sets.

The Nikon D4 camera and the Nikon Nikkor 24-70mm f/2.8 lens allowed for the successful capture of sharp images in the dark cave interior. Problems with the camera set-up included it being physically large and the ring used to mount the macro flash system limited the lens to 30-70mm. This meant the two narrow west chambers could only be photographed with a limited degree of camera angles. A compact, fixed wide angle lens replacing the large zoom lens is a solution. Alternatively, a compact camera could be used.

The correct identification and manual placement of geographical reference markers provided some difficulties (5.11). In the future, reference points should, therefore, be marked only using the coded marks provided by Photoscan itself, as these can be automatically detected and will increase the accuracy of the placement of geographical reference points within the images (5.3.1). For these markers to work in combination with flash photography, it is important that they have a non-reflective surface to avoid over exposure. Laminating the markers in a matte finish and using a less reflective colour combination will improve the chances of success (Figure 2: Appendix). The strategy used to record the BBC exterior proved successful. If higher quality data becomes necessary in the future, it will require the execution of a more traditional photogrammetric landscape recording. This will, in turn, require new equipment and know-how (section 5.7).

8.6. Recommended BBC Recording Protocols

Based on my experience acquired in digital photography in this project I suggest a protocol that could be applied during future excavations (Figure 47).

Stage of recording	**Considerations and tasks**
1. Task assessment: First, a quick assessment of the specific recording task focusing on three important factors, is performed	**1.1 Goal**: Determine the purposes of the recording to know what the end product must be able to provide.
	1.2 Area size: Set the outer boundary of the area that will be recorded. An additional margin/border should be added around the area that will be recorded. This serves as a safety measure against gaps in the recorded data.
	1.3 Time: The amount of time available to perform the recording will restrict the maximum quality of the recording.

Stage of recording	**Considerations and tasks**
2. Recording plan: A recording strategy is created. Its level of detail and strictness is dependent on the subject. In many cases, the same strategy can be recycled.	**2.1 Required resolution**: On the basis of the task assessment the distance between the subject surface and camera, plus the lens angle is decided to ensure that the model will have the wanted resolution. In some cases, the absolute maximum and minimum distance is predetermined by the cave topography.
	2.2 Need for subdivision: In some cases, a subject may need to be recorded in parts. This may be because the task is large or other activities (excavation, conventional photography, etc.) lay temporary claim to parts of the area which are to be recorded.
	2.3 Geo marker placement: Determine the number of geographical reference markers that will be needed. 4 is a minimum and more is needed for larger areas (> quadrant). Markers are placed before image recording.
	2.4 Movement pattern: Determine a suitable path in which the recorder will move the camera which most efficiently minimizes the risk of disturbing the site, extend the recording time or to capture more images than needed.
	2.5 Equipment: Determine what equipment will be needed (cameras, lens, flash, diffuser) and confirm that the equipment is ready for use (battery power, Memory card space, etc.)
3. Execution: During the recording, there are several aspects the recorder will need to check and evaluate; variable factors that must be considered and adjusted for.	**3.1 Optimal Camera setting**: Preform a quick test to determine the optimal camera settings (aperture, Sutter speed, and ISO) before recording starts. The settings should ensure good with balance, sharp focus and low grain.
	3.2 Ensure consistent data Be aware of the distance to the object, movement distance, and camera angle throughout the entire recording to avoid unintentional deviation from the recording plan.

	3.3 Data check: Depending on the size of the dataset recorded images should be reviewed at regular intervals to ensure that they meet the requirements. When all data has been collected the recorded will perform a fast visual inspection of recorded image before excavation or other alternating activities can start.
4. Processing data in field: To ensure the quality of the recorded data "light" processing must be performed at the excavation basecamp	**4.1 Data sorting:** Data is sorted by date and feature/ area. With each project/feature folder contain a subfolder for compressed and uncompressed image data, and a folder for exported material.
	4.2 Low-resolution data processing: A single project file is created each recording day containing a chunk for each respective dataset. A low-resolution batch process is executed, and the data is visually inspected to determine whether the recording has been successful. Data is good if no tweaking is needed.
5. Post field processing: Data processing is completed shortly after the end of the season, to quickly provide support data for the upcoming post-excavation work.	**5.1 Image Pre-processing**: Uncompressed image data is edited where necessary, converted into .dng and stored under a DNG folder within its respective project folder.
	5.2 High-resolution data processing: The uncompressed image data is processed at the higher accuracy and quality settings required to generate the models each image set was intended for. Sets of similar size and purpose are processed in large automated batches allowing the recorder to prepare or finish other data.
	5.3 Project completion: Predetermined data is exported (orthographic image, DEM, 3D model, processing rapport) into an export folder located under its respective project folder. A data set is completed when each project folder includes a compressed and uncompressed image folder, an export folder and a .psz project file.
6. Storage: Data is stored in a way that ensures longevity and accessibility	**6.1 Accessible storage**: A full copy should be stored on the project servers to allow project members quick access.
	6.2 Long term storage: A full secondary copy will need to be uploaded to the university server and will serve as a long-term backup.

Figure 47. The process of creating a photogrammetric record is made up of 6 stages. To ensure the quality of the recording, different tasks and considerations have to be perform by the recorder. The workflow does not go into each step in detail because the reason for recording and the subject being recorded greatly affects the strategy which has to be applied. The workflow outlined in this table is meant to serve as a guide for future applications photogrammetric recording at BBC and should aid in a successful recording and is intended to prevent curtail mistakes.

The last point of my table, data storage, is something I have not touched on previously in this thesis. It is, however, important to consider when working with digital data, especially when you consider that photogrammetry creates a lot of it. The large challenge here is in two parts. First is the problem of a rapidly evolving system, meaning that my data is stored in a file format that has the potential to become outdated and unreadable in the future. The second problem is the life expectancy of the device on which the data is stored.

These problems are not going to be solved in the field of archaeology; however, some precautions should be taken. Most important is to ensure that all the photographic data is stored in more than a single file format and that the data should be stored in an open file format (Bennett 2015, Barnes 2011). As I have suggested in the workflow table, all images from the Blombos photogrammetric recording will be stored in organised folders as compressed (.jpg) and uncompressed open source (.dng) along with metadata regarding the geographical reference markers. This is meant to ensure that it will be possible to reprocess the data in the future. Successfully ensuring long term storage will probably require some form of maintenance.

8.7. Discussion

Archaeological sites are a finite and non-renewable source of information about the past. Archaeological documentation serves the purpose of preserving information for prosperity and to aid in the interpretation of a site in particular. Only by preserving the information recovered from an archaeological site can researchers begin to interpret the larger picture.

A photogrammetric recording provides information which is different to that of traditional methods such as photography and drawing. For example, a typical archeological drawing depends on the interpretation of the archaeologist and is thus a highly distorted source of information. While less analytical and selective, conventional photography is also affected by the recorder including decisions about distance, angle, exposure and focal length and also what is included in the picture like scale, label, background.

My results in this thesis suggest that photogrammetry has good potential to provide a total and less distorted spatial and visual record of archaeological excavations. Photogrammetric recording allows for freely viewing and measuring any part of the recorded site. Also 3d models, orthographic images, etc. can be easily imported and combined in various solutions leading to new perspectives and comparisons of spatial information. Photogrammetric recording, such as that at BBC, has the potential to serve multiple purposes, many of which were not originally intended. One advantage for the archaeologist is the ability to easily visually “revisit” the site by studying photogrammetric models. This can help to confirm and disprove a memory or recall forgotten aspects of a site. In this regard, digital data’s ability to be shared and made accessible online is a favorable feature as it means that information obtained, regardless of the researchers own geographical location, is available if there is internet access. Thus, the value of photogrammetric data to assist with interdisciplinary archaeological research, for example at BBC, provides a strong argument for its archaeological relevance. Digital photogrammetry benefits from the ability to produce results in a relatively short span of time and has the potential to provide maps and models rapidly, even during the excavation. With the required expertise and equipment, it is possible to have all recorded features and surfaces available shortly after a field season.

8.8. Application Potential/Potential Use

8.8.1. Site preservation planning

The 3-dimensional recording of BBC can be an important tool in the planning, development, and conceptualization of site preservation strategies and actions. One example of this is the decision in 2015 to protect entry into BBC by creating a cage over the entrance. Using the photogrammetric model accurate measurements could be taken by the cage designers without having to travel to the site. This also allows the designers to test different alternatives digitally before starting the construction process and reduces the time, equipment and material needed in the field by allowing the construction to be prefabricated.

8.8.2. Material and stratigraphic study

The photogrammetric data is spatially referenced within BBC numerical coordinates system and provides multi-scale spatial and visual information. Therefore any data created on the basis of it (orthographic images, digital elevation models, 3D models, etc.) can be easily combined with the finds and other forms of spatially referenced data (Figure 48). In turn, this provides a strong visual tool to aid in the interpretation of the archaeological material. An example of this potential use is planar and vertical distribution analysis of the plotted finds (section 4.5.3). The archaeologist will be able to analyse the distribution pattern of different finds groups while observing their precise relation to the stratigraphic layers and cave as a whole.

A second example is using it in combination with a morphological study of the BBC sediments. Here the photogrammetric data helps to provide a link between the microscopic scale of the morphological samples, the larger section and other samples (Figure 48).

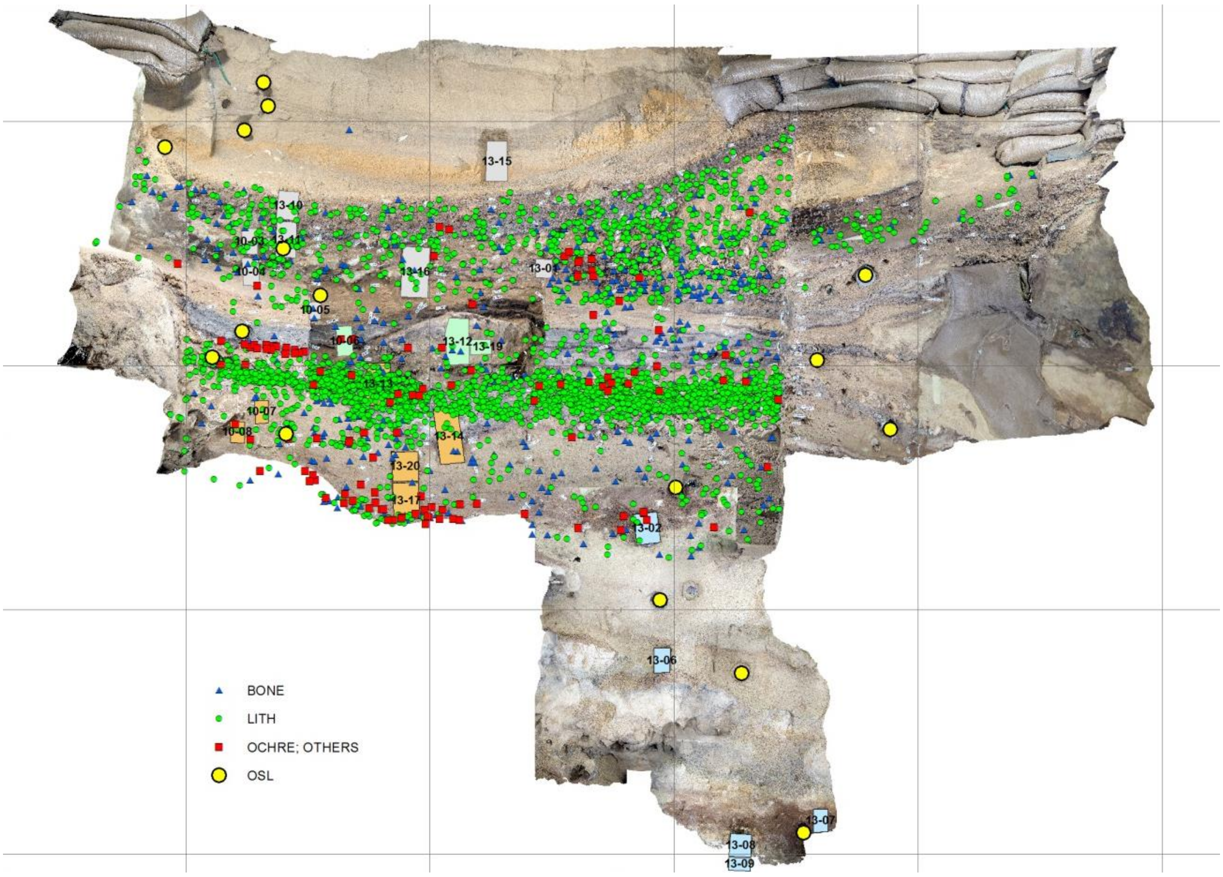


Figure 48. An example of how different types of spatial data can be combined with the photogrammetric data. The vertical distribution pattern of different finds groups is visualised over an orthographic image of the south section and inner chamber. The location from which OSL dating (yellow circle) samples and micromorphological samples (rectangles) have been taken is also shown. (Screen dump from ArcMap 10.1 provided by Magnus Haaland)

8.8.3. *Public outreach*

> *"While it will always be true that archaeologists need to communicate effectively among themselves, it now is abundantly clear that unless they also communicate effectively with the general public… all else will be wasted effort"* (McGimsey et al. 1977a: 89)

An important part of archaeology is to successfully provide the public with a better understanding of the human past and to show how archaeological sites provide the basis for this understanding (section 3.1). BBC is located on private land in a very remote area and contains fragile stratigraphic sections; it is therefore not possible for the public to visit the site in person. A solution can be to use the data I have created to make a virtual visit to BBC that can serve as a part of a public outreach program. 3D visualisation is already a popular tool for public outreach in many archaeological settings. For example, some museums and research projects have online exhibitions containing interactive 3d models of artefacts (https://3d.si.edu/, http://virtualtudors.org/home , http://www.kalmarlansmuseum.se/arkeologi/ida/3d-modeller/) and excavation (http://www.orkneyjar.com/archaeology/nessofbrodgar/) supplemented with written information. Using virtual reality technology, allows us to view the cave model and the exterior landscape as if you were at the site; creating an interactive way of communicating with the public. I have created a preliminary example containing both the cave interior and surrounding landscape (https://sketchfab.com/models/a1288c4c6214428c98b61142bc4ef8c5).

8.8.4. *Archive data potential*

The processing of archive images provides a new set of spatial and visual data (fig) which makes it possible to combine and study stratigraphic units and sections across time. Potentially this technique can be used to create and improve upon the stratigraphic overview at BBC and help to link previously uncovered archaeological material to the more recent excavation record. In other words, material and units excavated before 2011 can be spatially integrated into the numerical coordinate system. As a preliminary example, the ochre processing kit (Henshilwood, d'Errico, et al. 2011) uncovered in 2008 has been reconstructed on the basis of photographs from the photo archive (Figure 49). The toolkit stretched across at least two different quadrants. Using the method and data explained in chapter 6-7 a preliminary 3d reconstruction has been produced. This model places the ochre processing toolkit into the greater site model. These results have the potential to be improved upon, but for this discussion will serve as a further example of what digital photogrammetry may accomplish with a photographic archive. This method has great potential to support further studies of older excavation results both as a tool for re-evaluation and new interpretation.

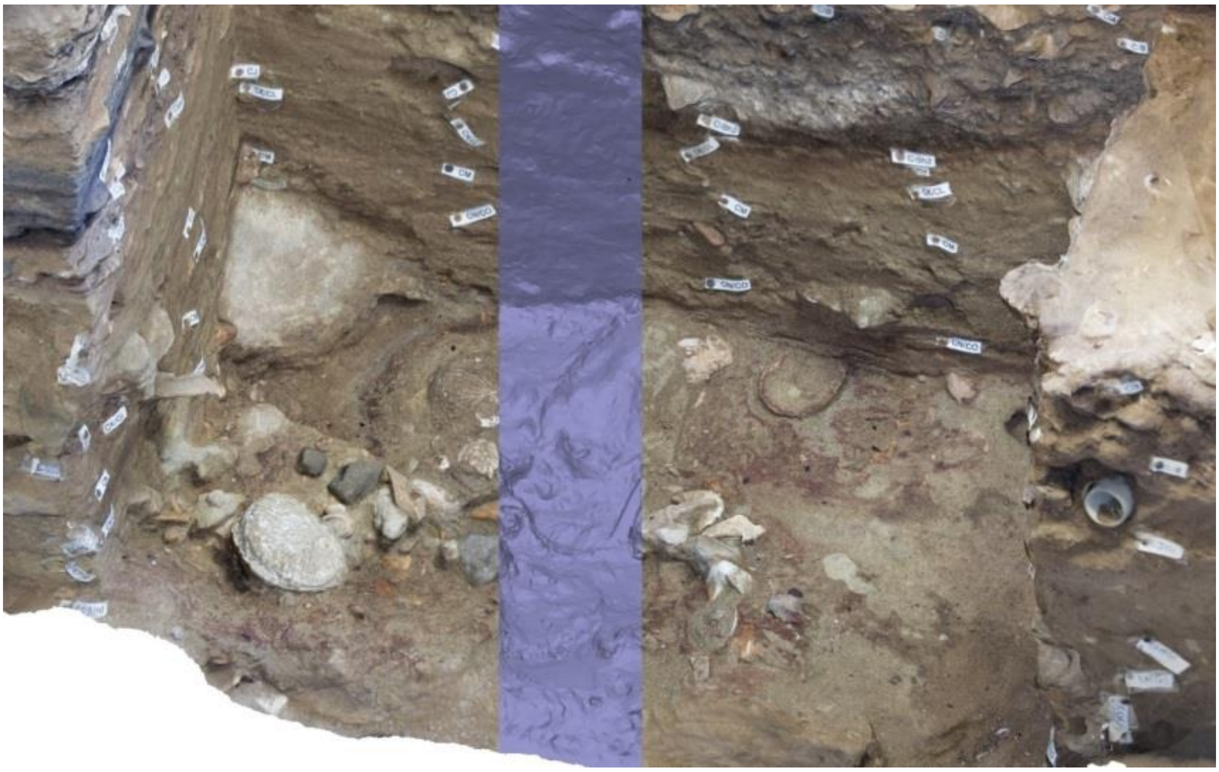


Figure 49. The ochre processing toolkit uncovered in 2008 was recreated as a 3d model using the images form the excavation archive. At this point, the model has not been spatially referenced to the BBC coordinate system. The blue section of the image demonstrates that a high level of topographic detail can be obtained from the images.

9. CONCLUDING REMARKS

There are five goals in this thesis. First, I needed to assess whether and how digital photogrammetry could be successfully used as a standalone method of recording at an archaeological cave site. In doing so, the second goal would be to develop a suitable workflow and provide advice on best practice, which might prove useful for future excavations at BBC or similar cave sites. Having successfully recorded BBC (the cave itself), the third goal was to see if the image archive, created over multiple excavations, contained images that could be used to generate spatially referenced 3D surface models. Once I had acquired sufficient skills and data, then the fourth goal was to assess how digital photogrammetry could be compared to other recording methods employed at BBC. By making this comparison, I would be able to determine whether and how digital photogrammetry could be integrated into the recording routine at BBC. The fifth and last goal was to investigate the relevance of introducing this new recording method, to determine the quality of the information photogrammetric data provides, and to evaluate how it could best be used.

In this thesis, I have demonstrated that digital photogrammetry has the potential to serve as a good method of spatial and visual recording at BBC and similar archaeological sites. However, success in a confined cave site requires a specialized recording strategy and some degree of practice and experience beyond that which is needed in an open air context. If employed correctly it is possible to create a photorealistic surface reconstruction which has a similar spatial accuracy to laser scanning. The potential application of digital photogrammetry is not limited to present and future excavation projects. It can also be used to provide new spatial data on past excavations by utilizing digital and analogue image archives.

The 3d models resulting from this project provide an entirely new perspective of the BBC site. Putting together the datasets allows one to move from landscape to quadrant scale and lets one study the relationships between parts of the site that have previously been excluded from each other and separated by time. The level of information available for an archaeologist studying the site after excavation is vastly improved as they can now view, compare and measure different aspects of the cave surface that was not possible before. Compared to other methods of surface recording employed at BBC, digital photogrammetry offers the least abstracted data sets so far. However, it only provides records of single moments in the excavation process.

Based on the results and discussion in this thesis, I would argue that archaeologists excavating at BBC and similar sites in the future should consider the integration of digital photogrammetry as a standard recording strategy. The relevance of introducing this new recording method is, of course, completely dependent on the data that are used and created. If correctly implemented, it will allow for an expanded understanding of past and present excavations and affiliated recording practices. Making sure that these datasets from the excavated sites are available for future research is a certain way of ensuring that the full benefit of this new method can be appreciated.

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1. APPENDIX FOR CHAPTER 5

Three different sets of geographical reference points were recorded and used to spatially reference the three surface models I recorded during the 2013 season (Table 2, Table 3, Table 4). A series of different forms of markers were used to indicate the position of the reference points. A Trimble VX Spatial station (total station) was used to record the spatial position of all reference markers.

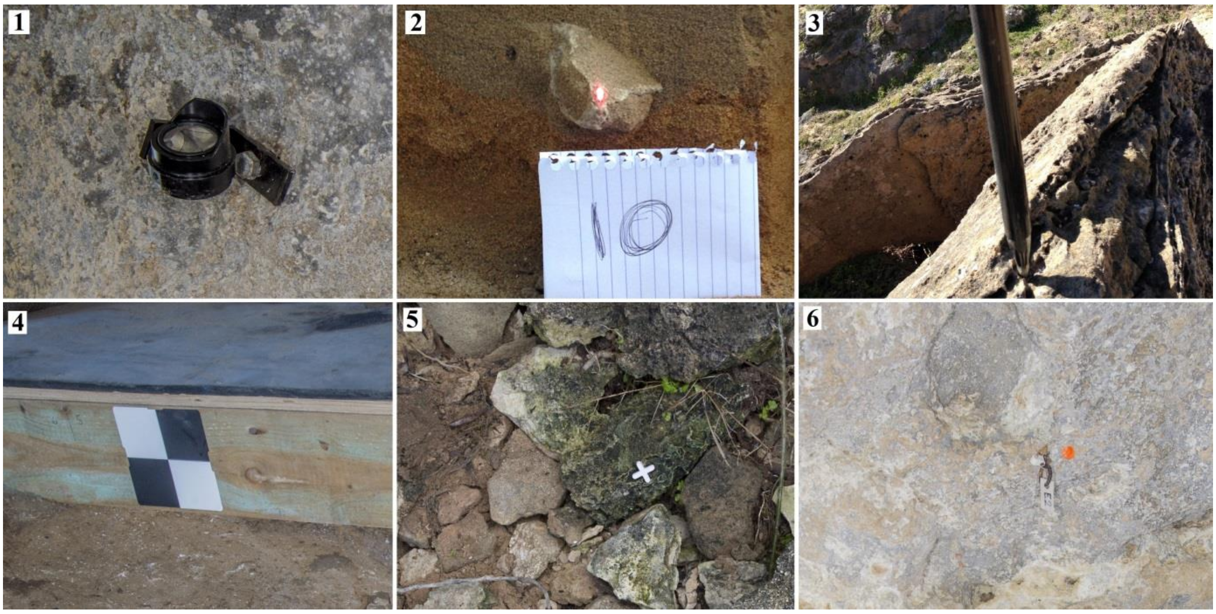

Figure 1. A series of different markers were used to indicate the position of geographical reference points. The nature of the area that was being recorded dictated the type of reference marker that was used. Permanent installations (1, 4), temporary markers (5, 6), the total station's red laser pointer (2) and prism staff (3) were used to indicate the position of reference points.

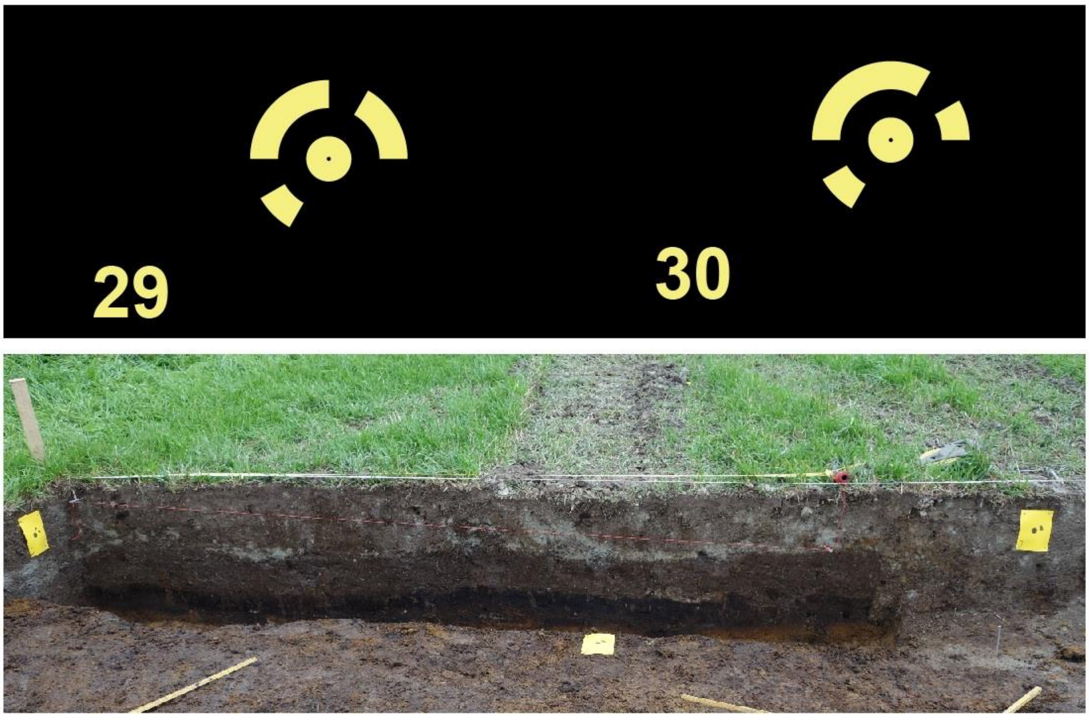

Figure 2. Photoscan provides coded markers which can be exported and printed. In the future, photogrammetric recording at BBC should be performed using coded markers. These can be automatically detected by PhotoScan when they appear in images. Using a colour combination that reduces the chance of overexposure is important when flash photography is performed.

As part of the preseason preparations, I performed an investigation aimed to determine how the different processing parameters affected the processing time. An image set of 40 12megapixle images captured with a Nikon D700 were used to perform this evaluation. The results presented in Table 1 were generated using the Dell Precision T7610 and utilized both its CPU and GPU (Table 2 in thesis).

Quality	**Low**	**Medium**	**High**	**Ultra**
Alignment (generic)	28.9s (25924 p)	70.481s (135611)	273.26 (608943)	
Build Dense Cloud (aggressive)	28.39s (147878p)	152.693s (593254)	585.21s (2396133p)	3676,88s (13506769p)
Build Mesh	4.66s (20000 faces pre-set)	19.672s (60000 med pre-set)	77.24 (479195 high pre-set)	466,976s (2700979 Faces)
Build Texture (average, Generic)	60s (8192x1)	108.2s (8192x2)	161.476s (8192x3)	284,651s (16384X1)
Total time	121,95s	351,05s	1097,19s	

Table 1. To test how the different processing settings in PhotoScan affected processing time, a 40, 12mp. Image data set was used. The times presented in this table were obtained using both the Dell Precision T7610 CPU and GPU.

#Label	X/East	Y/North	Z/Altitude	Error (m)	X error (m)	Y error (m)	Z error (m)	Projections
Chess 1	40.640000	-24.837000	34.385000	0.009663	-0.002935	-0.009088	-0.001467	40
Chess 2	40.680000	-23.161000	34.360000	0.005507	-0.002520	-0.004822	-0.000852	19
Chess 3	40.721000	-21.298000	34.339000	0.004697	0.000013	0.003719	-0.002868	15
E2/RED.1	41.001000	-20.989000	35.196000	0.007092	0.004793	0.003430	0.003944	43
E3/RED.2	41.035000	-22.019000	35.503000	0.010692	0.009164	-0.003857	0.003932	40
E4/RED.4	41.065000	-22.950000	35.489000	0.008913	0.007838	-0.004119	-0.001018	23
E6/RED.4	41.247000	-24.539000	35.192000	0.020480	-0.011064	-0.016875	0.003502	10
P1	45.493000	-24.882000	34.399000	0.012923	-0.009959	0.008226	-0.000394	35
Photogram.14	40.823000	-22.454000	33.583000	0.008104	-0.003341	-0.001757	-0.007171	40
Photogram.15	40.896000	-20.456000	33.718000	0.014501	0.000578	0.012011	-0.008104	28
Point 10	43.883000	-26.734000	33.823000	0.009625	0.004488	0.008316	0.001825	21
Point 11	44.850000	-26.003000	33.102000	0.010423	-0.003208	0.002827	0.009506	27
Red5	45.546000	-24.933000	34.461000	0.005634	-0.001070	0.000162	-0.005529	37
Rocks./RED.7	41.725000	-20.652000	35.137000	0.008803	0.007220	0.001829	0.004693	31
# Total error				0.010565	0.005977	0.007288	0.004773	

Table 2: 14 geographical reference positions were recorded across the interior of BBC. The mean spatial error of the markers indicated position within the photogrammetric model was calculated to 1.05cm.

#Label	X/East	Y/North	Z/Altitude	Error (m)	X error (m)	Y error (m)	Z error (m)	Projections
point 1	46.112000	-30.273000	33.134000	0.002961	0.001509	0.002529	0.000308	43
point 2	46.518000	-30.314000	33.051000	0.004061	-0.001038	0.003887	0.000548	56
point 3	46.886000	-30.326000	32.933000	0.002854	0.000695	0.002762	0.000182	58
point 4	47.260000	-30.220000	32.951000	0.003528	0.001046	0.003067	0.001395	47
point 5	47.915000	-30.226000	32.990000	0.004202	-0.000577	-0.003889	0.001483	44
point 6	47.596000	-30.151000	32.680000	0.004208	0.003428	0.002026	0.001361	45
point 7	48.133000	-30.627000	32.465000	0.004668	-0.000907	-0.004350	0.001432	60
point 8	47.486000	-31.024000	32.251000	0.003127	0.001005	-0.002939	-0.000362	59
point 9	47.769000	-31.150000	32.193000	0.003496	-0.000060	-0.003479	-0.000338	74
point 10	48.635000	-32.025000	32.425000	0.013866	-0.000032	0.013861	0.000362	38
point 11	47.078000	-31.572000	32.019000	0.002638	-0.001336	0.001733	-0.001475	58
point 12	47.992000	-31.955000	31.909000	0.009058	-0.003755	-0.008219	-0.000629	63
point 13	45.597000	-32.793000	32.088000	0.010260	0.007226	-0.006850	-0.002476	14
point 14	46.751000	-32.262000	31.795000	0.004368	-0.002530	0.003364	-0.001167	42
point 15	48.058000	-32.347000	31.825000	0.005873	-0.004672	-0.003503	-0.000625	48
# Total error				0.006138	0.002771	0.005358	0.001135	

Table 3. 15 geographical reference positions were recorded across the BBC exterior washout. The mean spatial error of the markers indicated position within the photogrammetric model was calculated to 0.6cm.

#Label	X/East	Y/North	Z/Altitude	Error (m)	X error (m)	Y error (m)	Z error (m)	Projections
TOPOMAGGIE.1	54.097000	-44.183000	35.960000	0.265296	0.017174	0.264289	-0.015436	19
TOPOMAGGIE.10	-4.142000	-41.871000	20.065000	0.162276	0.159157	0.000058	-0.031663	66
TOPOMAGGIE.11	5.643000	-31.446000	29.928000	0.054004	-0.015633	-0.029848	-0.042204	26
TOPOMAGGIE.12	19.781000	-27.632000	31.704000	0.161857	-0.161805	-0.003599	0.001927	8
TOPOMAGGIE.13	36.389000	-29.955000	34.268000	0.088948	-0.042239	-0.066170	-0.041824	62
TOPOMAGGIE.14	23.625000	-119.890000	11.671000					
TOPOMAGGIE.15	66.732000	-44.195000	52.508000					
TOPOMAGGIE.16	2.979000	-20.196000	39.971000					
TOPOMAGGIE.17	-26.151000	-84.164000	4.925000					
TOPOMAGGIE.2	60.800000	-47.881000	40.075000	0.146048	0.075778	-0.121144	0.030201	28
TOPOMAGGIE.3	59.048000	-69.555000	39.416000	0.251251	0.038268	-0.247916	0.014166	15
TOPOMAGGIE.4	39.405000	-67.296000	29.317000	0.299290	-0.011096	0.294374	-0.052871	13
TOPOMAGGIE.5	26.569000	-71.923000	19.871000	0.304476	-0.047995	-0.296348	0.050791	5
TOPOMAGGIE.6	23.114000	-86.463000	15.148000					
TOPOMAGGIE.7	7.303000	-75.931000	7.339000	0.296983	0.087522	0.276177	0.065305	73
TOPOMAGGIE.8	-13.265000	-117.204000	12.350000					
TOPOMAGGIE.9	-10.186000	-60.855000	9.125000	0.123193	-0.099125	-0.069885	0.021611	19
# Total error				0.214021	0.085787	0.192331	0.038132	

Table 4. 17 geographical reference points were recorded across the landscape surrounding BBC. Not all of these were successfully located within the photogrammetric image set (6, 8, 14, 15, 16). The mean spatial error of the markers indicated position within the photogrammetric model was calculated to 21.

BBC processing parameters

General	
Cameras	1148
Aligned cameras	1142
Markers	14
Coordinate system	Local Coordinates (m)
Point Cloud	
Points	610,206 of 1,016,553
Reprojection error	0.984327 (65.1726 max)
Effective overlap	5.6813
Alignment parameters	
Accuracy	High
Pair preselection	Disabled
Key point limit	40,000
Tie point limit	4,000
Constrain features by mask	Yes
Matching time	21 hours 57 minutes
Alignment time	12 minutes 8 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k3, p1, p2
Optimization time	16 seconds
Dense Point Cloud	
Points	128,764,864
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Dense cloud generation time	2 hours 10 minutes
Model	
Faces	4,955,797
Vertices	2,490,628
Texture	16,000 x 16,000, uint8
Reconstruction parameters	
Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	Medium
Depth filtering	Aggressive
Face count	25,879,143
Processing time	1 hours 30 minutes
Texturing parameters	
Mapping mode	Generic
Blending mode	Average
Texture size	16,000 x 16,000
UV mapping time	1 minutes 16 seconds
Blending time	4 minutes 23 seconds
Orthomosaic	
Size	43,054 x 36,148
Coordinate system	Local Coordinates (m)
Channels	3, uint8
Blending mode	Mosaic
Reconstruction parameters	
Surface	Mesh
Enable colour correction	No
Processing time	13 minutes 29 seconds
Software	
Version	1.2.6 build 2834
Platform	Windows 64 bit

BBC exterior processing parameters

General	
Cameras	762
Aligned cameras	734
Markers	17
Coordinate system	Local Coordinates (m)
Point Cloud	
Points	499,270 of 645,146
Reprojection error	22.0546 (201.366 pix)
Effective overlap	6.14776
Alignment parameters	
Accuracy	Medium
Pair preselection	Generic
Key point limit	40,000
Tie point limit	4,000
Constrain features by mask	Yes
Matching time	46 minutes 59 seconds
Alignment time	14 minutes 24 seconds
Optimization parameters	
Parameters	f, cx, cy, k1-k3, p1, p2
Optimization time	1 minutes 37 seconds
Dense Point Cloud	
Points	30,607,386
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Dense cloud generation time	20 hours 27 minutes
Model	
Faces	6,121,383
Vertices	3,066,368
Texture	16,000 x 16,000, uint8
Reconstruction parameters	
Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	Medium
Depth filtering	Aggressive
Face count	6,121,383
Processing time	20 minutes 49 seconds
Texturing parameters	
Mapping mode	Generic
Blending mode	Average
Texture size	16,000 x 16,000
UV mapping time	1 minutes 35 seconds
Blending time	7 minutes 59 seconds
Orthomosaic	
Size	16,000 x 14,099
Coordinate system	Local Coordinates (m)
Channels	3, uint8
Blending mode	Average
Reconstruction parameters	
Surface	Mesh
Enable colour correction	No
Software	
Version	1.2.6 build 2834
Platform	Windows 64 bit

Washout processing parameters

General	
Cameras	210
Aligned cameras	209
Markers	15
Coordinate system	Local Coordinates (m)
Point Cloud	
Points	185,070 of 207,408
Reprojection error	0.341782 (1.19906 pix)
Effective overlap	5.11099
Alignment parameters	
Accuracy	High
Pair preselection	Generic
Key point limit	40,000
Tie point limit	4,000
Constrain features by mask	Yes
Matching time	10 minutes 50 seconds
Alignment time	1 minutes 10 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k4, p1, p2
Optimization time	Optimization time 4 seconds
Dense Point Cloud	
Points	15,058,913
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Dense cloud generation time	28 minutes 0 seconds
Model	
Faces	2,887,670
Vertices	1,446,514
Texture	8,192 x 8,192, uint8
Reconstruction parameters	
Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	Medium
Depth filtering	Aggressive
Face count	3,011,782
Processing time	9 minutes 43 seconds
Texturing parameters	
Mapping mode	Generic
Blending mode	Average
Texture size	8,192 x 8,192
UV mapping time	1 minutes 8 seconds
Blending time	1 minutes 27 seconds
Orthomosaic	
Size	13,542 x 10,354
Coordinate system	Local Coordinates (m)
Channels	3, uint8
Blending mode	Mosaic
Reconstruction parameters	
Surface	Mesh
Enable colour correction	No
Software	
Version	1.2.6 build 2834
Platform	Windows 64 bit

2. APPENDIX FOR CHAPTER 6

The photogrammetric recording of the BBC exterior covered a greater area than the laser scan recording. A smaller area of the photogrammetric point cloud (Figure 3) corresponding to the most solid area of the TLS data was therefore used to perform the cloud to cloud comparison. The exterior cloud to cloud comparison followed the same workflow as the interior comparison. The initial comparison yielded a standard deviation of 9.5cm and a range of 2.6m. 98.5 present of all values were lower than 40cm and were attributed to gaps in the TLS point cloud (Figure 4). When set to disregard values higher than 40cm, the standard deviation was calculated to 7.1cm (Figure 6).

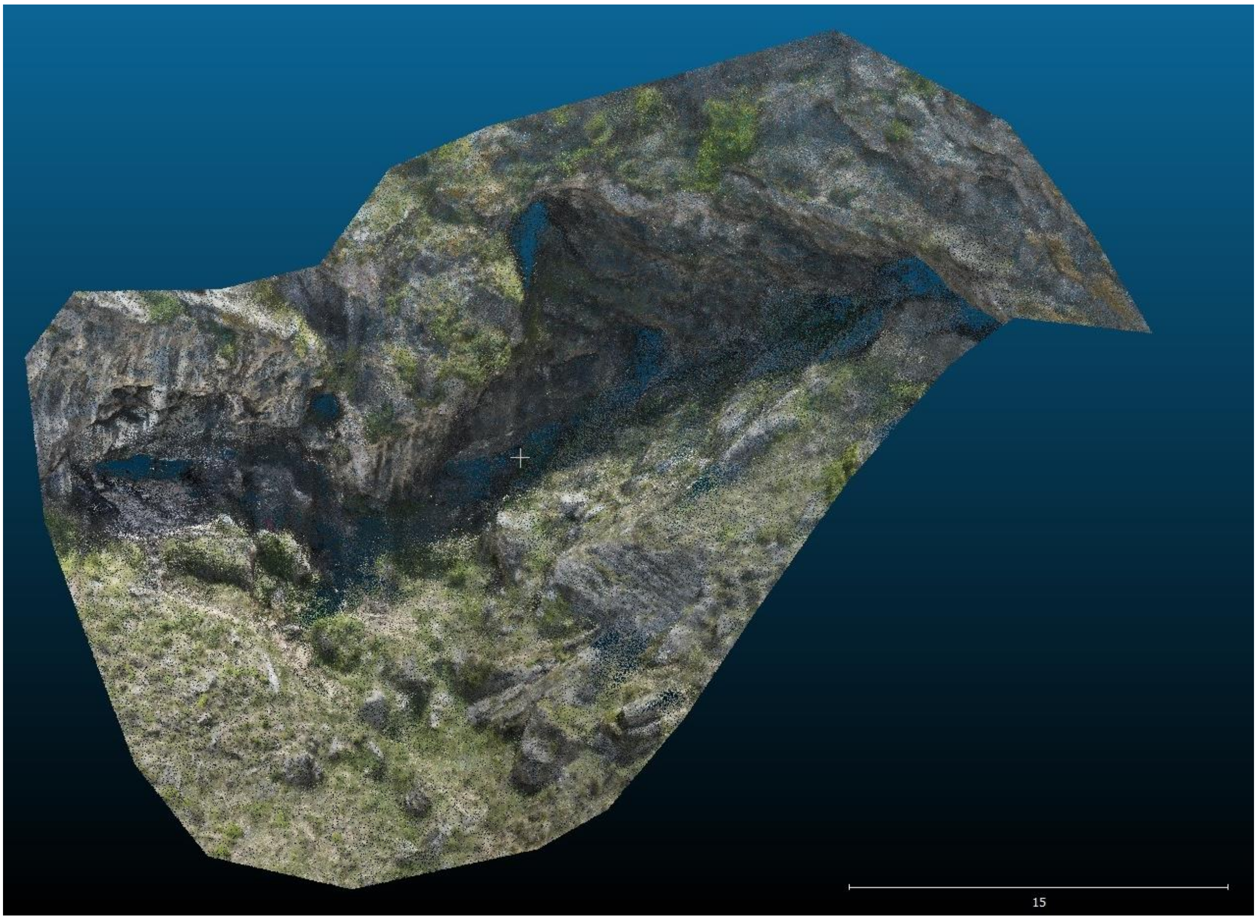

Figure 3. Area of BBC exterior PG point cloud used in the C2C comparison. The opening of BBC is located on the left.

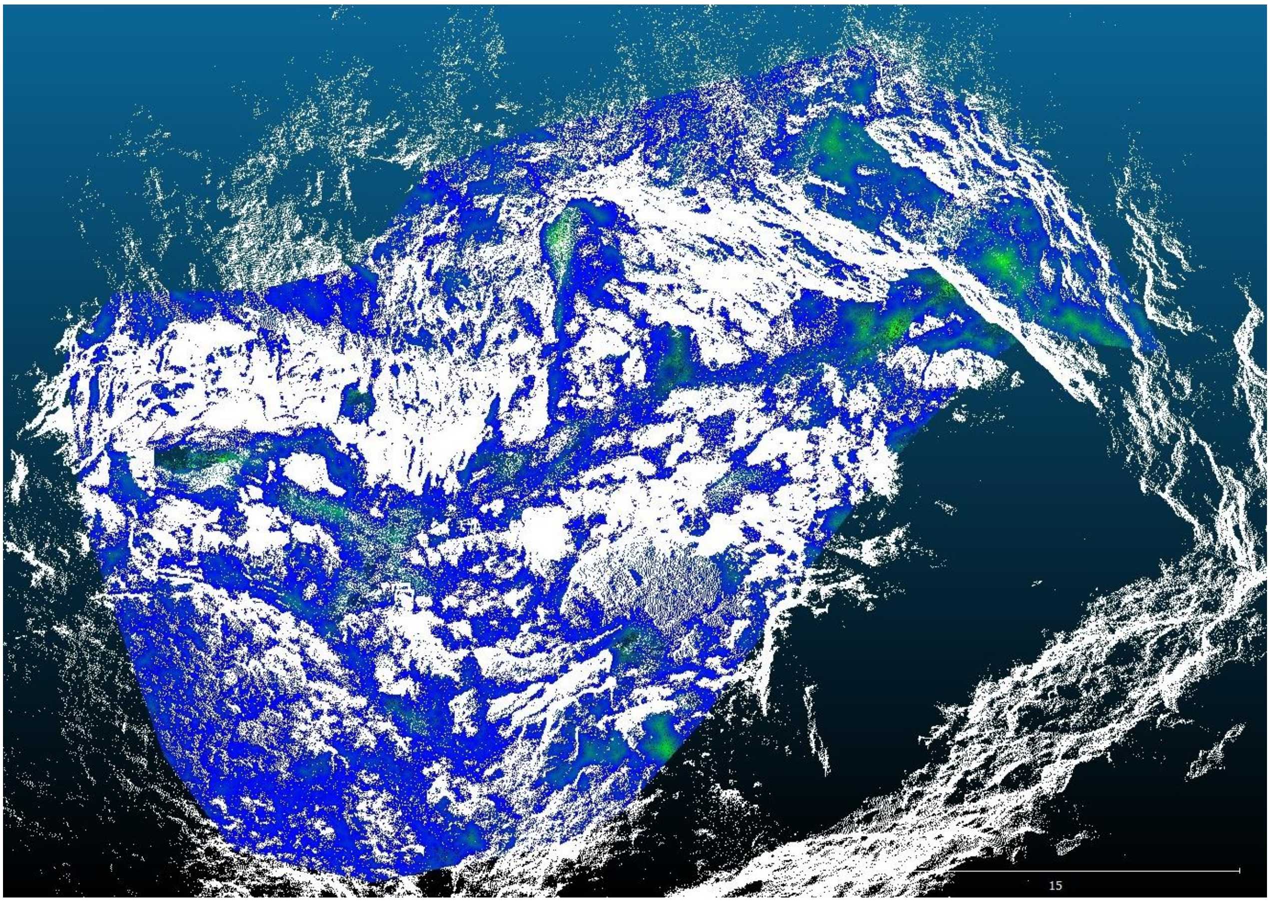

Figure 4. The TLS point cloud (white) contains several gaps. These correspond to the areas where the TLS and Photogrammetric (colour) point clouds deviated the most (green).

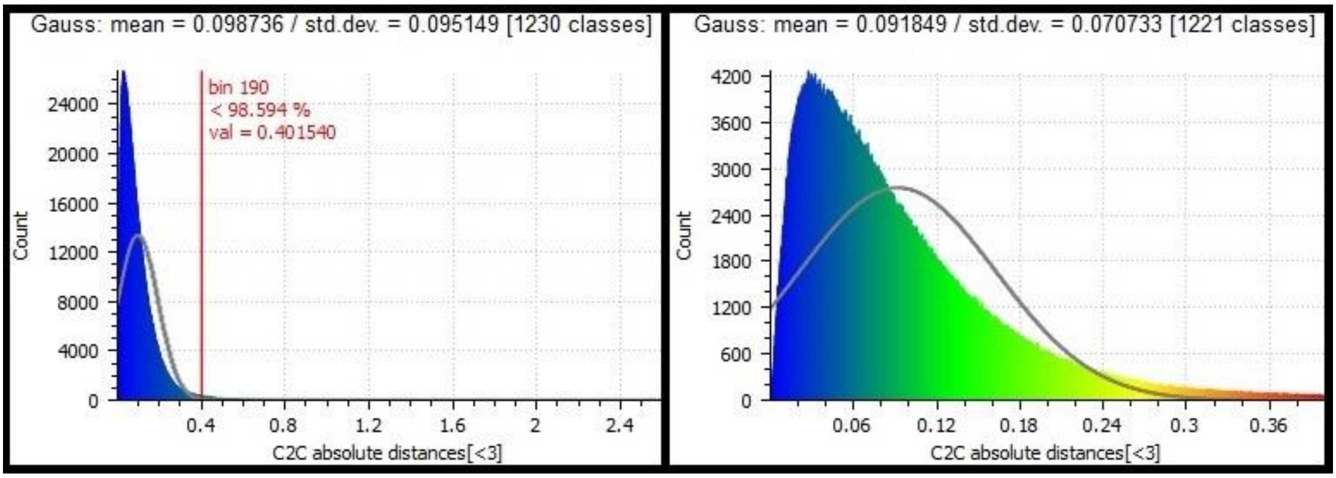

Figure 5. 98.5 present of all values were below 40cm. By excluding these values, standard deviation was brought down 7.1cm respectively

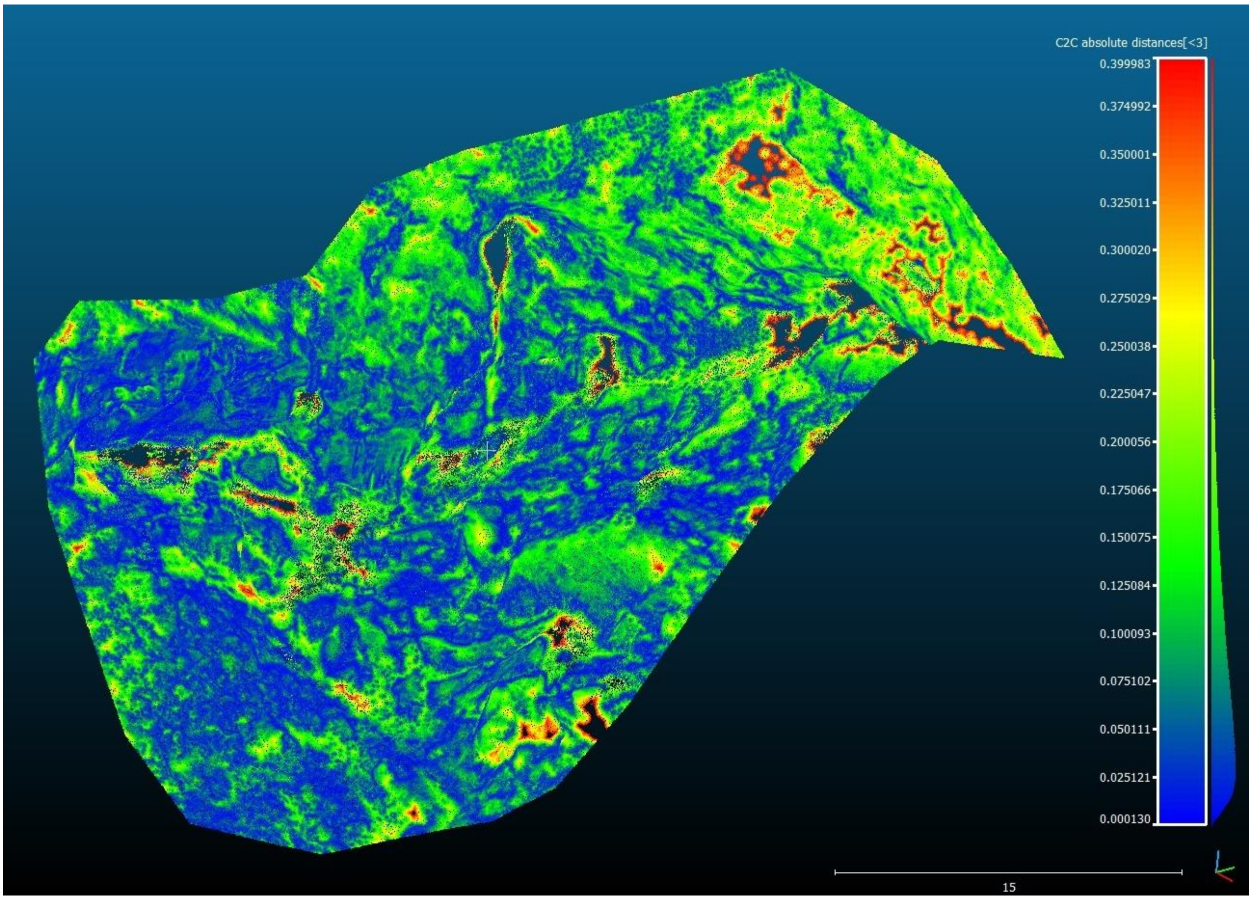

Figure 6. To compensate for the gaps in the TLS point cloud values over 40 cm were excluded (roughly 1.4 present of all values). The absolute cloud to cloud distance was then recalculated.

3D Model 1. Low resolution model of Blombos Cave recorded in 2013 (created using PhotoScan).

3D Model 2. Low resolution model of the BBC exterior landscape (created using PhotoScan).

3D Model 3. Low resolution model of the washout outside BBC (created using PhotoScan).