

Tracing Ice Age Artistic Communities:
3D Modeling Finger Flutings in the Franco-Cantabrian

by

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Supervisory Committee

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Abstract

Finger flutings are lines and markings drawn with the human hand in soft cave sediment in caves and rock shelters throughout southern Australia, New Guinea and southwestern Europe, dating back to the Late Pleistocene. Analysis of these markings can reveal characteristics of the creators, such as age, sex and group sizes. However, despite a comprehensive method of study, data collection is still reliant on in field measurements and is often constrained by physical challenges within the caves. Advances in technology allow us to record archaeological data in three dimensions. Creating 3D models of finger fluting panels would allow for off-site measurements and other forms of detailed analysis. In this thesis, I test three different 3D scanning techniques, photogrammetry, tripod structured light scanning, and handheld structured light scanning, to determine the most appropriate method for the documentation of finger flutings based on factors such as portability, cost, efficiency, accuracy, as well as other challenges present in cave and rock shelter settings. I created replica fluting panels in three different media and created 3D models of them. I then compared measurements taken from the panels in person to measurements taken from the 3D-scanned models to see if there is statistically significant difference between the models and the panel. The results of my experiment show that 3D models of finger fluting panels are accurate representations of the experimental panels and that photogrammetry is the technique that best meets the requirements of finger fluting research.

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Chapter 1: Introduction

Since its discovery, Upper Paleolithic art has captured the minds and imaginations of the public and researchers alike. Upper Paleolithic broadly art refers to paintings, engravings and other marks that were made on cave walls, rock shelters, as well as portable ornaments that were created between 40 000 and 12 000 years before present (BP) (Abadía and González-Morales, 2013). Early studies of Paleolithic art focused on the figurative imagery that was found in caves like Lascaux or Chauvet (Leroi-Gourhan, 1958) and looked to determine the meaning and purpose behind the cave paintings (Abadía and González-Morales, 2013). However, the knowledge that we can gain from studies of Paleolithic art extend beyond questions of meaning. The visual imagery adorning Pleistocene cave walls and rock shelters provide an avenue for researchers to study the visual cultures that Pleistocene people were living in (Nowell, 2017). The visual cultures approach includes not only the art and what can be seen, but also the biological, cognitive and social dimensions of art (Nowell, 2017). This analysis contributes to broader questions of individual identity in the Upper Paleolithic.

Finger flutings are a form of Paleolithic rock art that is created with the human hand on soft surfaces, such as clay or moonmilk using the fingers (Van Gelder, 2015). They are found on cave walls, ceilings and floors throughout southern Australia, New Guinea, and southwestern Europe (Van Gelder, 2015). Finger flutings can form figures and signs, but most commonly occur as non-figurative markings (Sharpe and Van Gelder, 2006a). A forensically informed method developed by Sharpe and Van Gelder (2006a, 2006b) allows researchers to identify characteristics of the individual creators, such as age and sex (Van Gelder and Sharpe, 2009). Since finger flutings are literally the residue of human touch, the study of finger flutings offers a

unique opportunity for the exploration of identity, visual cultures, and how Upper Paleolithic people interacted with the environment around them.

Sharpe and Van Gelder (2006a, 2006b) have developed a comprehensive method to measure and analyze finger flutings. However, the process of data collection is still reliant on in-field measurements of the relevant fluting streams and is constrained by the physical limitations of the cave. With advances in software, equipment, and computer processing power, new methods of digital documentation are emerging. The creation of three dimensional models of finger fluting panels would allow for off-site measurements and give rise to other potential methods of analysis.

3D scanning technologies have been applied to heritage management (Rüther et al., 2009; Remondino, 2011), archaeological documentation (McPherron et al., 2009; Douglass et al., 2015), and rock art studies (Davis et al., 2017; Domingo et al., 2013; Fernández-Lozano et al., 2017; González-Aguilera et al., 2009; Lerma et al., 2010; López et al., 2016). However, only one documented attempt has been made to create a 3D model of a finger fluting site (Zlott and Bosse, 2014), but the laser scanning technology used was not accurate enough to record the finger flutings.

Research Question

The lack of success in 3D scanning finger fluting sites raises a number of questions regarding the application of these 3D scanning techniques; namely, what are the limits and challenges in 3D scanning finger flutings? The purpose of this project is therefore to determine the best method to create high-resolution 3D models of finger fluting panels. My main research question is: What method of 3D documentation creates 3D models that meet the accuracy, portability, and data requirements for the study of finger flutings?

My experimental project compared the measurements taken from experimental finger fluting panels in person to measurements taken from 3D scanned models of the panel. I created experimental panels that replicate some of the main challenges that finger flutings pose and use three different methods of 3D scanning –tripod structured light scanning, handheld structured light scanning, and photogrammetry, to create 3D models of these experimental panels. With the goal of creating an accurate, high-resolution 3D model of finger flutings, choosing the best method of 3D documentation requires an understanding of both the available technologies and the challenges relevant to the object to be scanned. As such, this project explores the current state of 3D digitization technologies as well as the current state of finger fluting research.

My larger research question can be broken down into three main sub-questions:

1. What are the challenges and limits of 3D scanning technologies when applied to studies of finger flutings?
2. In comparison to measurements taken from the panel, are measurements taken from a 3D model accurate?
3. Which 3D scanning techniques best meet the requirements of finger fluting studies?

Thesis Outline

The study of finger flutings has provided evidence in the archaeological record of the active participation of women and children in the creation of Paleolithic rock art (Sharpe and Van Gelder, 2006b). This evidence challenges previous assumptions of exclusive adult male agency in the creation of rock art (Nelson, 2004). As such, studies of finger flutings are informed by the theoretical approaches of both gender archaeology and the archaeology of childhood. These approaches to research stress the importance of understanding the individual in archaeology and understanding the customs and practices surrounding finger flutings allows

researchers to gain insight into how people lived in the Upper Paleolithic. In Chapter 2, I discuss the history of gender archaeology and the archaeology of childhood and how these theoretical approaches fit in to larger questions of individual identity. I explore some examples of how these approaches have been applied in practice and finally, I examine how the study of finger flutings contribute to the understanding of individual identity in the Upper Paleolithic.

Researchers have noted the presence of finger flutings within rock art sites since the earliest discoveries of rock art (Sharpe and Van Gelder, 2006a). However, due to the lack of visual appeal, compared to figurative illustrations, they were largely ignored in discussions of European cave art (Sharpe and Van Gelder, 2006a). In the last two decades, more attention has been given to the study of finger flutings. Sharpe and Van Gelder (2006a, 2006b) were the first to develop a forensically informed and empirically tested method to analyze finger flutings that allows researchers to determine characteristics of the individual, such as age and sex. In Chapter 3, I outline the history of finger fluting studies and summarize the ongoing research into finger flutings. I describe Sharpe and Van Gelder's method of analysis (2006a, 2006b) and use the example of Rouffignac Cave to show how this method is applied. Finally, I discuss some of the challenges that are still present in finger fluting studies. Understanding how finger flutings are studied helps me better understand what is required of the 3D models of finger flutings and what challenges I may face.

Chapter 4 describes the methods of my experimental project. It also includes a discussion of the current state of 3D scanning technologies. I explore the different ways that objects can be documented in 3D and how contemporary researchers have used these techniques in archaeological research. 3D scanners are tools that are becoming increasingly common in archaeological research, particularly in the study of rock art. As such, understanding how other

researchers have employed these tools can teach me how I can best employ 3D scanning technologies to my project.

I present the results of my experimental project in Chapter 5 and use them to address my research sub-questions. The products of each of the three methods of 3D documentation are presented, and the challenges, successes, and failures are discussed. Chapter 6, my discussion and conclusion, explores the implications of my results. I go through the answers to my research sub-questions and bring in outside sources and my own analysis to interpret the results. I also look at the potential applications of 3D models of finger flutings and discuss how this can engender future research questions. In this final chapter, I summarize my research, examine the limits of my project, discuss my conclusions, and explore the possible avenues for future research.

Chapter 2: Gender, Childhood, and Identity

Introduction

This chapter is intended to outline the theoretical background of my project on 3D scanning finger flutings. My research builds on the forensically based research methods developed by Sharpe and Van Gelder (2006a, 2006b, 2009), which will be outlined in the next chapter, that shed light on the characteristics of individual creators of finger flutings, such as age and sex. While my research looks to accurately document in 3-dimensions finger fluting panels as they occur in caves and rock shelters, the ultimate goal of this documentation is to provide an opportunity for an in-depth study of customs and practices surrounding the creation of this form of rock art. In particular, it is hoped that my project can contribute to the ongoing discussions surrounding the importance of studying individuals in archaeology. This work is informed by the theoretical work of gender archaeology and the archaeology of children. In this chapter, I briefly discuss the history of gender archaeology and the archaeology of childhood, how these theoretical approaches contribute to discussions of individual identity, how these theories have been applied in practice, and finally, I will discuss how studies of finger flutings contribute to these larger theoretical questions. It is important to show how previous work has shaped my research in order to better understand the purpose, applications, and avenues for future expansion.

Gender Archaeology

Studies in demography show that, without manipulation, females make up just under 50% of stable populations globally (Labuda et al., 2010). Age structure, on the other hand, is most influenced by childhood mortality rate (Chamberlain, 2000). Since most prehistoric populations likely had childhood mortality rates of at least 50%, this corresponds to an estimation that nearly

half of the living individuals in a stable population were children, or individuals under the age of 18 (Chamberlain, 2000). With women and children making up such large proportions of Paleolithic societies, it should seem obvious that they must have contributed to the archaeological record. However, early perspectives reflected researcher bias and unquestioned Western gender role attributions, leading to the archaeological invisibility of women. This invisibility of gender processes and gender identity in archaeology is rooted in western androcentric epistemologies that extend beyond the study of gender roles. A focus on traditionally “masculine” traits and activities, such as strength and hunting, lead to invisibility of not just women, but also of children and the elderly, who do not embody the “masculine” (Baker, 1997). The invisibility of these categories was first challenged by approaches in gender archaeology (Conkey and Spector, 1984; Conkey and Gero, 1991; Joyce et al., 1993).

Gender archaeology arose in the 1980s as a challenge to the prevalence of processual archaeology (Nelson, 2004). Processual archaeology in the 1960s promoted the idea of “value-free” science and large scale, systems-oriented approaches (Bolger, 2012); critics of processual archaeology pointed out that positivist and materialist perspectives studied abstract behaviours and obscured the importance of individual agency and power structures from which large-scale social phenomena emerge (Nelson, 2004). Challenges to processual archaeology emerged in the 1980s from a number of theoretical perspectives, including Marxism and feminism, which largely emphasized agency, ideology, and power (Bolger, 2012). Conkey and Spector (1984) introduced these criticisms in “Archaeology and the study of gender”, which is considered by many to be a foundational text in the study of gender archaeology as it firmly introduced gender as a distinct and important concept within the archaeological vocabulary (Sørensen, 2013; Nelson, 2004).

Gender archaeology is not simply about making women and other previously invisible categories visible, but rather looks to study individual identity, agency, and power in the past (Conkey and Gero, 1991; Hutson et al., 2012). Ultimately, gender archaeology stresses the importance of the individual and looks at societies from the bottom up, instead of top down (Bolger, 2012). This perspective moves away from essentialising the roles of individuals, but rather looks at gender as dynamic social categories (Bolger, 2012).

Gender is a socially and culturally constructed category that is grounded in biology, but not exclusively informed by it (Gilchrist, 1997). Beyond the conceptual split between sex and gender in the archaeological vocabulary, there have also been critiques of binary modes of gender archaeology (Marshall, 2012; Robb and Harris, 2018; Spencer-Wood, 2006). The importance of multiple genders in prehistory is a relatively underexplored aspect of gender archaeology, due in part to challenges in recognizing alternative genders in the archaeological record (Bolger, 2012). However, since gender is seen as a socially constructed category, it is important to take into consideration fluid conceptualizations of gender that may have existed in the past (Alberti, 2012). Robb and Harris (2018) propose that recognizable binary gender patternings did not arise until the Bronze Age, in the third millennium BC, and prior conceptualizations of gender identity may have been communicated in patterns that are unfamiliar to modern researchers. Without written language, interpretations of gender in prehistory have been largely informed by burials and interpretation of visual imagery. In particular, Robb and Harris (2018) argue that in the Neolithic, depictions of people in art were varied and often lacked identifiable sexual features, which suggested that gender was not a strict binary system that needed to be marked on all imagery. Burial processes in the Neolithic did not have the strict gender dichotomies of Bronze Age burials (Robb and Harris, 2018). Our

understandings of gender in the Upper Paleolithic are also informed by visual imagery and burials (Whitehouse, 2006). Iconographical studies of female figurines from the Gravettian suggest that female bodies were adorned with clothing and decoration that reflected Gravettian understandings of gender identity, power, and values (Soffer et al., 2000). The identification of female hands in rock art show that rock art creation was not an exclusively male activity (Snow, 2013). Bringing together all these strands of research into women in the Upper Paleolithic can provide a more complete description of gender identity and the role of women in Upper Paleolithic communities. Therefore, contemporary approaches to gender archaeology look at gender as a process and embodied experience –not as something that needs to be found in the archaeological record, since evidence of it may not be obvious to contemporary researchers – but rather is embodied and shaped the lifeways and identities of individuals of the past (Joyce, 2008).

Archaeology of Children

The influence of the feminist perspectives on post-processual archaeology also drew increased attention to children in the archaeological record (Lillehammer, 2015). Studies of children in archaeology faced similar barriers to studies of gender in archaeology, since early conceptualizations of the archaeological child were seen as extensions of the mother (Lillehammer, 1989). Even with the rise of gender archaeology, the importance of an archaeology of children and childhood was still devalued, as children were viewed as passive learners in an adult world (Baxter, 2005). However, in subsequent years, new approaches to the study of children in the archaeological record have been developed that highlight the cultural importance of children in the archaeological record and the role of childhood in identity construction (Kamp, 2015).

Childhood plays a key role in the development of skills, belief systems, and personality (Kamp, 2001). Although the experiences of childhood are varied and childhood itself is a culturally constructed category (Baxter, 2005), all adults have gone through the process of development from infancy to adulthood. Childhood has been studied as a period of rapid cognitive development, since periods within early and late childhood mark key milestones of cognitive and social learning (Nowell, 2016).

Many approaches to studying children in the archaeological record center around childhood craft learning (Lillehammer, 2000; Kamp, 2001; Crown, 2007; Finlay, 2015). Since craft production, particularly in prehistory, is likely to have been a necessary part of survival, novices in the archaeological record are often concluded to be children (Shea, 2006). Using ethnographic studies to supplement archaeological analysis, researchers have described processes of learning and skill and how it can be analyzed in some assemblages. For example, Crown (2007) studied learning in potters in the American southwest. She argues that children or novice potters developed motor control and knowledge through repeated practice and thus are, ethnographically, included in craft production at a variety of stages according to their skill levels. Kamp (2001) studied ceramic production in the Sinagua region of northern Arizona and observed the interactions between children and clay beginning at a very young age. She proposed that this early exposure to clay in a play context allowed children to familiarize themselves with the physical properties of clay and practice some of the techniques that would be used in ceramic production in large, more difficult to create, vessels. The development of these frameworks provides a lens through which to look at childhood in the archaeological record and to consider the contributions of children to material culture and their engagement with the world around them.

Beyond learning to become adults, children participate in the world in their own ways. Lillehammer (1989) originally proposed the concept of the 'child's world' in order to capture the idea that children have their own experiences and relationships with the world around them. Since children's psychology and experiential reality is different from that of an adult, their 'world' should be studied differently (Lillehammer, 1989). Lillehammer (2000) later restructured the concept of the 'child's world' into the 'world of children' in order to accommodate for the heterogeneity of the category of 'child' and to unlink the concept of childhood from age determinism in order to center it around aspects of time, space, culture and identity. Children are not passive subjects in an adult world but are active agents that interpret the world around them by appropriating and reinterpreting adult culture to fit their own relational contexts (Sanchez Romero, 2017). In combination of the social dynamics of childhood groups, this process of information reinterpretation can give rise to identity (Sanchez Romero, 2017).

The Individual: Identity, Gender, and Childhood

The importance of the individual actor when looking at archaeological material is often lost in the search for large-scale explanations of change. It was individuals in the past that combined to influence change, thus an understanding of individuals, their agency and the power structures that informed their decisions gives rise to unexplored research questions. But when not specified, agency is usually assumed to be both adult and male (Nelson, 2004), thus a focus on the more invisible categories of women and children challenges previous assumed narratives. Both gender and childhood contribute to identity formation, since both are processes and embodied experiences that influence how individuals engaged with their environments (Joyce, 2008). Materiality and sensual experiences are fundamental to collective understanding and personhood (Joyce, 2005).

Joyce (2007) discusses the life cycle in Mesoamerica and looks at how the experiences of childhood influence the social constructs of gender and identity in adults. Aztec children were seen as “raw materials” that are shaped into their adult forms gradually through habitual action, costume and ornament (Joyce, 2007). Gender and identity are performed through repeated practices that referenced cultural ideas about adult behaviour and appearance (Joyce, 2000). The differentiation of gender identity is continually practiced through life cycle rituals that reinforced participation in both gender and age categories (Joyce, 2000). Material culture can then reflect these practices and performances and can be used to study ideals about gendered bodies in the past (Dujnic Bulger and Joyce, 2012).

People’s engagement with material culture both shape and are shaped by their knowledge of the world (Ingold, 2000). Art and mark-making have long been explored in order to study peoples’ understanding of self and the environment through iconography and other attempts to interpret the imagery (Hays-Gilpin, 2012). Understanding art in prehistoric archaeology should move beyond untestable questions of meaning. Nowell (2017) proposes the visual cultures approach in studying art in the Pleistocene. Visual cultures include not only art and what is seen, but also the biological, cognitive and social dimensions of art (Nowell, 2017). This allows researchers to explore how visual imagery in the Pleistocene were experienced and how these experiences shaped and were shaped by the individuals and their communities (Nowell, 2015).

Nowell (2015) discusses how childhood engagement with visual imagery in the Pleistocene would have played an important role in shaping people’s understanding of the environment. Not only did Pleistocene children have to learn to interpret the two-dimensional images from a young age and apply them to the three-dimensional world, but they were also sometimes active participants in creating imagery (Nowell, 2015). This engagement with art

throughout their lives afforded individuals living within this Pleistocene visual culture new ways of engaging with the world (Nowell, 2015).

Finger Flutings and the Individual

The importance of understanding the individual as put forward by gender archaeology informs the study of finger flutings. Since finger flutings are markings left by human fingers across cave surfaces, they are the residue of touch and are direct evidence of humans interacting with the environment around them. The forensically informed methods developed by Sharpe and Van Gelder (2006a, 2006b), discussed in the next chapter, allow researchers to differentiate between individuals and identify details such as age, sex, and group size of fluters. With this level of resolution into the creation of finger flutings, researchers can interpret the activities that took place within the caves. As a form of visual imagery, researchers can ask questions of how people engaged with the figurative and non-figurative results of finger flutings after they were created. By focusing on the individual and the groups that created the flutings, researchers can begin to interpret some of the cultural practices that took place within the Pleistocene visual cultures.

Since women and children are interpreted to have been active participants in finger fluting, studying flutings gives researcher an opportunity to engage with less explored categories of identity. We can study whether finger fluting practices were influenced by categories of gender or age. Conversely, we can also look at how these practices may have shaped gendered experiences and childhood experiences in the Upper Paleolithic. In interpreting the activity that took place within caves with finger flutings, we are able to come to a more inclusive and complete understanding of Upper Paleolithic lifeways.

Conclusion

This chapter discussed some of the theoretical underpinnings of my research. My interest in the study of finger flutings draws from many theoretical sources but is driven in large part by the goals of gender archaeology as well as the archaeology of childhood. In outlining the history of both gender archaeology and the archaeology of childhood, I illustrated why there is interest in the individual in archaeological research and how archaeologists have approached this in the past. Visual cultures provide an avenue for archaeologists to explore art and other visual imagery from additional perspectives of biology and cognition and thus give a glimpse into how individuals in the past may have understood themselves and the world around them. Research into finger flutings are an avenue for studying people's material interactions with their environment, by touch and by sight and that this research may help us understand the cultural categories of men, women, and children. My next chapter will detail how exactly research into finger flutings is conducted in order to frame the technical requirements of my project.

Chapter 3: The Study of Finger Flutings

Introduction

Finger flutings are a form of Paleolithic rock art that can inform researchers about some of the cultural practices of Pleistocene communities. This chapter contextualizes the study of finger flutings and how 3D scanning technologies can be applied to aid in their study. First, I will explain what finger flutings are, where they are found, and how old they are. Next, I will discuss the history of finger fluting studies, what we can learn from them, and the current methods that are used to study finger flutings. I will discuss Rouffignac Cave in France as a case study of how these methods are applied in the field, what information can be learned, and some of the limits and challenges. The goal of outlining the history, development and current state of finger fluting studies is twofold: first, by understanding the current method of studying finger flutings, I can better assess the technical and physical challenges that would arise during the 3D documentation process. Second, contextualizing the history of finger fluting studies allows me to explore how the application of 3D scanning and 3D models contributes to the larger questions in Pleistocene art and how this can engender new discussion.

Finger Flutings

Finger flutings are lines made with the human hand on soft surfaces, such as clay or moonmilk, a form of limestone precipitate (Van Gelder, 2015). During the Paleolithic, they are found in caves throughout southern Australia, New Guinea, and southwestern Europe (Van Gelder, 2015). In some cases, the flutings are in the form of figures, such as mammoths, owls, and bison. They can also appear as signs such as tectiforms, which are triangular roof-shaped forms. However, in most situations, these flutings appear non-figurative and have been referred to as ‘meanders,’ ‘macaroni,’ ‘serpentine,’ and ‘water signs’ (Sharpe and Van Gelder, 2006a).

In France, finger flutings occur in nearly all cave sites containing Paleolithic art and cover most surfaces (Sharpe and Van Gelder, 2006a).

Finger flutings are commonly found on moonmilk covered surfaces within limestone caves (Bednarik, 1999). Moonmilk is a term that is used to describe the soft cave surfaces and can be divided into two different groups. The first form of moonmilk is the precipitate of calcium carbonate that builds up on the surfaces on the caves as a result of the chemical equilibrium reached between the carbon dioxide within the cave and the limestone walls, also known as speleothem (Bednarik, 1999). The texture of this precipitate can vary, from soft downy crystals to a clay-like consistency (Bednarik, 1999). The other form of moonmilk has been described as clay but is the result of an unexplained process that decays previously dense rock, leaving behind a 'skeleton' that is soft enough to be marked (Bednarik, 1999). Once markings are made onto the surfaces of moonmilk, they can be fossilized through further speleothem growth (Bednarik, 1995). Attempts to date the flutings have been made by studying the patterns of speleothem calcification over the flutings (Bednarik, 1995, 1998, 1999). By taking the dates of the speleothem beneath and over the flutings, estimates for the age of the flutings have been attempted at the Australian rock art sites in Mount Gambier (Bednarik, 1999). However, since the speleothems are radiocarbon dated and the influences of additional carbon sources, such as volcanic activity and native C4 plants, are not completely known, without independent calibration (i.e., testing organic material deposited within the layers), the carbon dates of the speleothem do not provide secure absolute dating (Bednarik, 1998). New developments in speleothem dating have been made using Uranium-Thorium (Aubert et al., 2014; Sauvet et al., 2017), but this process has yet to be applied to finger flutings.

Most finger flutings do not have absolute dates from the speleothem and are dated according to the dates of the caves in which they are found (Van Gelder, 2015). According to these dates, finger flutings in Cantabria span nearly the entirety of the Upper Paleolithic, with some sites dating to 27kya and possibly even older (Van Gelder, 2015). Based on these dates, the creators of finger flutings are assumed to be anatomically modern humans (Sharpe and Van Gelder, 2006a).

History of Finger Flutings Studies

The presence of finger flutings within rock art sites in Europe were noted alongside the earliest discoveries of rock art. However, due to the non-figurative and seemingly random nature of the flutings, they were largely ignored in discussions of European cave art or simply described without a structured methodology of study (Nougier and Robert, 1958). Attempts to decipher the meaning and purpose of the flutings described their appearances as “serpentine,” “water signs,” or assigned other anthropomorphic interpretations (Nougier and Robert, 1958). Lewis-Williams (2002) posited that finger flutings were the results of shamanic rituals, in which the shamans repeatedly touched the cave surfaces. However, as with all debates of meaning in Paleolithic art, it is impossible to truly confirm or deny the hypotheses proposed by contemporary researchers and, as such, research into finger flutings moved away from questions of meaning and towards answerable questions derived from more empirical approaches (Van Gelder, 2012).

Bednarik (1986) conducted early studies of finger fluting streams in Australian caves. He began to look at finger flutings through studying the geochemistry of the medium (1995, 1998, 1999). His early investigation looked at how speleothem can grow over top of finger flutings and how this growth can influence their appearance. Based on his observations of the size of finger flutings, he concluded that juveniles were responsible for over 90% of all flutings (Bednarik,

1999). He also suggested that flutings found deeper in cave systems were created by children while adult flutings were found closer to the entrances because children were more adventurous and explored deeper into the caves (Bednarik, 1999). He began to measure some flutings and proposed a hypothesis that can be falsified but does not describe a clear method of study or offer a comparative analysis of fluting sizes.

Later research into finger flutings applied Marshack's 'internal analysis' method, which was developed primarily to study portable artefacts (1977). This method examines the intersections and cross-sections of lines as well as individual features of the lines, such as depth, width, and shape in order to understand the temporal sequence of their manufacture. Analysis of how the lines are formed can reveal patterns that allow researchers to identify how a tool was used to make the mark and potentially the identity of individual creators. Applying this method of analysis allowed researchers to hypothesize the temporal sequence of finger flutings (D'Errico, 1992; Lorblanchet, 1992).

Recent Studies into Finger Flutings

Sharpe and Van Gelder (2005, 2006a, 2006b, 2006c, 2009) developed a more comprehensive method for the study of finger flutings while working at the French cave sites of Rouffignac and Gargas. This method is based on forensic techniques and experimental results that allowed researchers to classify and analyze finger flutings. A set of nomenclature was created to provide a language to describe and understand finger flutings (Sharpe and Van Gelder, 2006a). First, "finger flutings" or "flutings" refer to lines drawn with human fingers. A "graphical unit," or a "unit," refers to flutings that are drawn with one motion of one hand, or with one finger. A "cluster" refers to a group of units that can be isolated because they show some unity or connection – for example, if the units over-lie each other. The importance of a

cluster is that they can potentially tell what flutings are created by one individual as a continuous act. A “panel” refers to a collection of clusters that can be grouped together separate from other clusters either by distance or orientation. Finally, “engravings” refer to lines that are made with a tool, rather than with the fingers.

Sharpe and Van Gelder (2006b) further break down units of flutings into four different forms based on two factors: first, whether the fluter uses one or more than one finger of one hand to flute and, second, whether the fluter stands in place with his/her hips still, or whether he/she moves the lower body during fluting. *Kirian* flutings describe units where fluters use only one finger and stand still while fluting. *Evelynian* flutings describe units where fluters use only one finger but move their lower bodies. *Rugolean* flutings describe units where fluters use more than one finger and stand still while fluting. *Mirian* flutings describe units where fluters use more than one finger and move their lower bodies. Each of these descriptive categories leads to different sets of questions. If units are created using more than one finger, this can allow for the determination of the ages, genders, and number of fluters. Units that are created while the fluters are moving their lower bodies can give insight into paths that fluters take while fluting and how they moved through space.

Sharpe and Van Gelder studied finger flutings *in situ* and then attempted several experimental recreations in order to study the physical limitations of the fluting motions, how they compare to flutings found in caves, and what further information can be learned (Sharpe and Van Gelder 2006a, 2006b; Van Gelder and Sharpe 2009; Van Gelder 2012, 2015). Sharpe and Van Gelder (2006a) began their experimental studies by investigating the claim that children were the likely creators of the majority of Paleolithic finger flutings (Bednarik, 1999). Their early study compared the finger widths and results of flutings by modern people of various ages

to the flutings that are found *in situ* (Sharpe and Van Gelder, 2006a). They determined that it was most useful to look at flutings made using the index, middle, and fourth (2D-4D) fingers (Sharpe and Van Gelder, 2006a). The central three digits were studied because when flutings are made with one or two fingers, it cannot with certainty be determined which finger or pair of fingers were used to create the flutings. 2D-4D leave the most significant marks, since D1 (the thumb) and D5 (the little finger) leave less significant marks that are frequently not visible. Thus, fluting units created by the three central fingers 2D-4D that did not have significant gaps between the fingers are used in analysis. Measurements are taken across the three-fingered width, near the beginning of the fluting unit, where it is the narrowest. This is important, since the fluting motion can distort the appearance of the finger widths as fluters sometimes splay their fingers apart as they flute and arm motions and pressure can also influence the width (Sharpe and Van Gelder, 2006a).

The experimental portion of Sharpe and Van Gelder's early study (2006a) looked at the finger widths of a group of modern individuals of different sexes, ages, and demographic backgrounds. This group of subjects fluted with their 2D-4D fingers over a smoothed clay surface, and the widths of the narrowest point of the units were measured. The results showed that while some children younger than 2-3 years old were able to create flutings, many seemed to lack the ability to understand the command to flute and were not able to hold and control their hands in the appropriate manner, even with adult assistance (Sharpe and Van Gelder, 2006a). Importantly, experimental replications of finger flutings showed that measurements of the three finger widths (2D-4D) were useful in determining the age of the fluters (Sharpe and Van Gelder, 2006b). Fluting units with 2D-4D widths measuring under 30 mm had to have been created by individuals under the age of 5, as the three-finger width was too small to have been created by

older individuals. Flutings 33 mm and under usually represented a fluter aged 7 or younger, but in some rare cases can also represent young adolescents (Sharpe and Van Gelder, 2006b).

Flutings with widths larger than 34 mm cannot be attributed to individuals of any age category, since children as young as five can have three-fingered widths as wide as 40 mm. In these cases, age cannot be determined from the width measurements alone, though contextual information such as height of the flutings and interaction with other fluters can aid in identification (Sharpe and Van Gelder, 2006b). Since measurements of 33 mm are the upper limit for classifying the age of the individuals in the context of finger flutings, the category of ‘children’ is restricted to discussions of individuals who created flutings that measure 33 mm or less and are therefore aged 7 or younger (Van Gelder, 2015).

Challenges to the measuring and recording process come from a number of sources (Sharpe and Van Gelder, 2006a). The width of the flutings can be influenced by the firmness of the medium and the pressure applied. Measurements of the flutings *in situ* are rounded to the nearest mm, which may introduce error to the data (Sharpe and Van Gelder, 2006a, 2006b). There is not a clear understanding of how the medium shrinks or expands over time and how that may influence the width of the fluting (Bednarik, 1999; Sharpe and Van Gelder, 2006a). The three central fingers (2D-4D) need to be held together, but not overlapping for accurate measurements and the width of the fluting created by these three fingers can be variable over the length of the fluting. There are also physical challenges of the cave setting, since measurements must be taken without touching the fluted medium and the flutings can be located in cramped locations.

Sharpe and Van Gelder took a series of measures to help minimize the challenges (2006a). They compared 10 units of clay flutings from the hands of two individuals (one male

and one female) created using different pressures in order to look for consistency in the width of the resulting flutings (Sharpe and Van Gelder, 2006a). In this experiment, the widths of the flutings ranged 0.5 mm from the mean but finding the correct locations to take measurements can overcome the variability (Sharpe and Van Gelder, 2006a). To overcome this source of potential error, measurements of fluting width are taken at the narrowest part of the unit closest to the beginning, where there is least overlap.

Additional laboratory work experimented with replicating flutings in different media, including plaster, paint, and condensation (Sharpe and Van Gelder, 2006b). In this study, Sharpe and Van Gelder explored what markings were feasible within the anatomical and comfort limits of the human body and what effects the fluting surfaces had on the resulting units. Their results, based on modern human anatomy, found that it is comfortable and practical to flute at a distance of between 30 and 45 cm from the center of the body to the wall directly in front (Sharpe and Van Gelder, 2006b). Fluting at 45 degrees to the vertical is more comfortable than fluting horizontally. It is more comfortable to flute above the head to shoulder level than below the shoulder (Sharpe and Van Gelder, 2006b). Wet surfaces were more comfortable to flute on when the fingers are splayed with more than 2 cm between the fingers than with the fingers closer together, while drier surfaces were more comfortable with less than 1.5 cm between the fingers but required more pressure to make a mark (Sharpe and Van Gelder, 2006b).

Details such as handedness can also be determined, as imprints of the thumb or little fingers can sometimes be found on the sides of three-fingered units (Sharpe and Van Gelder, 2006b). When visible, the flutings created by the little finger begin lower down on the initiation point relative to the other fingers and are usually fainter than the others (Sharpe and Van Gelder, 2006b). Flutings created by the thumb also begin lower down than and at a greater distance from

the other fingers. When the hand is relatively straight, the thumb can drag over the medium nearly at right angles to the orientation of the other fingers (Sharpe and Van Gelder, 2006b). The presence of the thumb on the left or little finger on the right suggests the use of the right hand, while the thumb on the right or little finger on the left suggests the left (Sharpe and Van Gelder, 2006b).

The sex of the fluters can be determined using the relative finger heights of the central three digits (Sharpe and Van Gelder, 2006b; Van Gelder and Sharpe, 2009). Since each of the three central digits have different lengths, flutings show different relative heights at the beginning (2006a). Van Gelder and Sharpe (2009) applied Peters et al.'s (2002) research into the ratio comparing the length of the finger from the tip of F3 to the tip of 2D in comparison to the tip of F3 to the tip of 4D. This ratio compares the lengths of 2D and 4D relative to the central digit, F3. In the 2D:4D ratio, values of <1 means that 2D does not extend as far as 4D, while a value of >1 is the opposite. 2D:4D ratios <1 suggest a male, while 2D:4D ratios ≥ 1 suggest female in modern human populations. According to Manning et al. (1998), this ratio is sexually dimorphic and likely established in utero. However, researchers have criticized the use of the 2D:4D ratio in prehistoric art, since there is a lack of reference data for prehistoric handprints, and the discrimination of sex using direct dimensions do not generalize across populations (Galeta et al., 2014). The critiques of applying the 2D:4D method to prehistoric rock art show that sex determination through direct dimension measurements are not absolute, but in the context of finger flutings, sexing the fluters is simply another method of identifying the individual, which contributes to the broader interpretation of the activities going on within the cave.

Another detail that can be interpreted from flutings is the direction in which a unit was fluted. Buildup of sediment only occurs at the end of the unit, this happens particularly in soft medium, but it does not always occur (Sharpe and Van Gelder, 2006b). Flutings that used multiple fingers usually started at different relative heights, since they are of different lengths (Sharpe and Van Gelder, 2006b). However, relative finger heights do not occur when the fingers are curled at the initiation of the fluting units (Sharpe and Van Gelder, 2006b).

These experimental results can be applied alongside Marshack's internal analysis method of temporal sequencing. In looking at the units that overlay and underlay each other within a cluster, researchers can work out if there was direction (for example left to right, top to bottom, etc.) in the creation of the cluster (Van Gelder and Sharpe, 2009). Applying this analysis alongside the determination of age and sex of the individuals gives researchers insight into how the fluters interacted with one another and with whom they were interacting. Ultimately, this analysis provides a method to study finger flutings that sets aside questions of meaning. Rather, researchers can identify individual fluters and ask questions of who the group of fluters were and study the social structure and relationships among them.

Van Gelder (2012) also tested if it was possible to identify individuals through single finger flutings. However, the results of laboratory experiments showed that the widths of single finger flutings can vary up to 6 mm. This variability is influenced by the thickness of the medium and the ways in which the finger moves to create the fluting. Therefore, it is not possible to use single finger flutings to identify an individual, though flutings drawn with finger widths of 12 mm and greater are very likely not created by children (Van Gelder, 2015).

Sharpe and Van Gelder (2009) tested whether some of the fluted panels could have been a form of written communication. They applied George Zipf's theory that the order of a word in

a frequency list is inversely related to the frequency that it is used in text. Zipf's law is used to differentiate between recognizable communication within a group and noise. When Zipf's law was applied to two panels in Rouffignac, the result of -1 Zipf gradient suggested that they were a form of recognizable communication. However, Van Gelder (2015) stresses that the results of this analysis do not necessarily support the conclusion that finger flutings are a form of writing, but rather that it provides an avenue for future questions about writing and meaning making in the Upper Paleolithic.

Case Study: Rouffignac Cave

Between 2001 to 2013, fourteen caves in Franco-Cantabria were identified as having finger flutings (Rouffignac, Gargas, El Castillo, Las Chimeneas, El Cudón, Hornos de la Peña, La Clotilde, La Estación, El Calero II, Las Brujas, El Juyo, El Salitre, La Flecha and Castro Urdiales) (Van Gelder, 2015). Of these fourteen caves, four caves were found to include flutings by both adults and children (El Castillo, Las Chimeneas, Gargas, and Rouffignac caves) (Van Gelder, 2015). This long-term investigation into these caves showed that finger flutings were not exclusively associated with children but were not an activity that excluded children. Sharpe and Van Gelder's early studies of finger flutings (2006a, 2006b, 2006c) were done in Gargas and Rouffignac Caves. Rouffignac Cave in particular was central to early development of their method of analysis and is studied in particular detail.

Rouffignac cave is located in the French region of Dordogne, 4 kilometers from the village of Rouffignac. It is the most extensive cave system in the Perigord, with over 8 kilometers of underground passages. Rouffignac is well known for the high proportion of mammoth imagery engraved or drawn on its walls; out of the 255 identified representations, 158 are identified as mammoths (Clottes, 2010). In addition to drawings and engravings, Rouffignac

also contains over 500 square meters of finger flutings (Plassard, 1999). Rouffignac has been a known location since the fifteenth century, when it was used as a clay extraction site. It was identified as a rock art site of note in the 1940s and investigated by Romain Robert, Louis-René Nougier, with Charles and Louis Plassard in 1956. In that same year, Henri Breuil authenticated the images as Paleolithic (Clottes 2010). No absolute dating has been done on the cave, but stylistic comparisons of the cave imagery have proposed a Middle Magdalenian date between 13,000 and 14,000 years before present (Plassard, 1999) but could be as old as 27,000 years before present (Sharpe and Van Gelder, 2006b).

Rouffignac is a large and expansive cave system. It takes about 45 minutes to get from the assumed Paleolithic entrance of the cave to the furthest chamber where paintings, engravings and finger flutings occur (Van Gelder, 2015). This suggests that, in order to navigate, the groups entering the cave had the capacity to continually make fire and/or had long-lasting torches. Van Gelder (2015) notes the physical challenges that would have been present within the cave in the Pleistocene, as some areas of the cave would have required crawling, moving sideways with the knees bent, and the navigation of challenging features such as bear pits or rock falls.

Finger flutings are present in eight different chambers (A1, A2, B, D, E, F, G, H, and I) of the cave, and eight different individuals were identified (Van Gelder and Sharpe, 2009). Among the eight individuals three were determined to be children based on the three-finger width measurement, and a fourth individual was proposed to be a youth based on the height of the fluting and the engagement with other child fluters (Van Gelder, 2015). Analysis of the relative finger heights of the flutings in Rouffignac revealed five of the eight fluters were probably female, two individuals that were probably male, and one that is indeterminate (Van Gelder and Sharpe, 2009). There was a child whose finger width measured 28 mm who was

probably female, a child who measured 28 mm who was probably male, a 34 mm individual who was likely a child that was probably female, a 38 mm individual who was probably male, a 41 mm individual who was probably female, a 44 mm individual who was probably female, and a 48 mm individual who was probably female (Van Gelder and Sharpe, 2009). The final individual, was a child whose three-fingered fluting width measured 22 mm that did not leave flutings with relative finger heights that could be analyzed (Van Gelder, 2015). But, based on the motor control displayed by the short flutings, was estimated to have been around the age of 2 or 3.

Specific individuals were identified across the different chambers. For example, the child with the 31 mm measurement appears in all of the chambers except chamber F (Van Gelder, 2015). Her flutings appeared at a variety of heights. Most of her flutings were found at heights that a child of her estimated age (around five years, based on the three-fingered measurement) would be able to reach, but some of her flutings appeared on the ceiling, higher than 2.2 m from the ground. She interacted with both children and adults and was the only individual that would flute with both hands simultaneously (Van Gelder, 2015).

The ability to identify individuals from their flutings and to determine their age and sex gave insight into the activities that took place within Rouffignac Cave. Van Gelder (2015) described the individuals found in each of the chambers of Rouffignac. Children were present in every chamber in Rouffignac and as deep as 0.97 kilometers into the cave but were always accompanied by adults. In chambers where no adult flutings were identified alongside the child's flutings, the child's flutings were found at heights that they would not have been able to reach without assistance (Van Gelder, 2015).

While the majority of the flutings seemed to be non-representational, Barrière (1982) described a fluted illustration of a saiga antelope. This representation is made up of flutings by two separate individuals and if this interpretation is correct, this represents a co-created image. A third fluting stream by the individual with a finger measurement of 31 mm is often included in the interpretation of the antelope image, which would suggest a child's participation in representational fluting (Van Gelder, 2015). Additionally, there were three tectiforms (markings in the shape of a roof or dwelling) found within the cave that were created by children (Van Gelder, 2015). This could be indicative of children participating in the creation of recognized "signs" (Van Gelder, 2015).

Finger flutings were noted in Rouffignac cave since the 1940s, but it was the development of a clear scientific method of study by Sharpe and Van Gelder that allowed researchers to move beyond questions of meaning. This case study provides an example of how this method has been applied and resulting interpretation. Research in the various chambers of Rouffignac cave showed that children and adults, both male and female, were creating finger flutings. The three-fingered measurement allowed researchers to study how people were interacting with the cave walls and each other. By describing the presence of women and children in Paleolithic art, Sharpe and Van Gelder's methods (2006a, 2006b) contribute to larger discussions of archaeology of gender and the archaeology of children. However, despite developments in methodology, research into finger flutings can be limited by researcher's ability to accurately measure and document them.

Challenges still present

Current methods of studying finger flutings have allowed researchers to learn more about the identity of the fluters. However, there are still many challenges that are difficult to overcome

when doing research *in situ*. In particular, the physical challenges posed by the flutings have yet to be overcome. Flutings must be measured without touching the fluted media and can be located on the ceiling and close to the floors (Sharpe and Van Gelder, 2006a). Flutings are located in chambers of caves that are deep into the cave system with limited light sources. These challenges can influence the accuracy of measurements that are taken. While measurements with millimeter accuracy have allowed researchers to identify individuals, even higher measurement accuracy may provide additional insight that were missed.

My research is informed by the previous work into the study of finger flutings and is driven by an interest in overcoming some of these physical challenges. By documenting the flutings in 3D, researchers would then be able to manipulate and measure the subsequent 3D models without needing to adopt contorted positions. Being able to zoom into the models or rotate them for a better perspective may allow researchers to take even more detailed measurements. Further, the model can give researchers the opportunity to apply contextual information to the flutings, such as light, colour, and acoustics.

Conclusion

The purpose of this chapter is to explore the ways in which researchers have looked at finger flutings in the past and how they are currently being studied today. These methods allow researchers to study age, sex, and group sizes of the creators of finger flutings. Ultimately, the ability to identify individuals in finger fluting settings give researchers an opportunity to understand how they interacted with the world around them. Understanding how finger flutings are studied in the past frames my research goals and understanding how finger flutings are studied today frames the technical requirements of my research. I hope to develop a method of 3D documentation that supplements contemporary research and meets the data requirements of

finger fluting studies. In the next chapter, I will further explore how advances in 3D digitization technologies have aided in the study of rock art and detail how it can be applied to the study of finger flutings.

Chapter 4: Methods

Introduction

In this chapter, I review the benefits of 3D scanning, and discuss the practices associated with choosing the correct 3D digitization system. Then, I outline the main methods of 3D digitization available to researchers today and assess the strengths and weaknesses of each method. Choosing the digitization method most suitable to a project begins by understanding the limits and challenges inherent to the technology. Next, I will explore two cases of the application of 3D scanning to archaeological research. These cases were chosen because they also take an experimental approach to applying 3D scanning techniques to archaeological research. They test the accuracy of different 3D digitization systems and their applicability to archaeological research contexts. Following that, I present three cases of how 3D scanning has been applied to rock art in order to understand the challenges of the field environments and the rock art itself and how other researchers mitigated these challenges.

After overviewing the background on 3D scanning technologies, I will then outline my research questions and the methods I will use to answer them. I will discuss how the experimental panels were created. Then, I will discuss the different 3D scanning technologies that were tested, and the technological specifications of each technique. Finally, I will outline how I tested the accuracy and applicability of each technique.

Applying 3D scanning technologies is a relatively new development in cultural heritage and archaeological research. This chapter discusses how 3D technologies are used in archaeology, cultural heritage preservation, and rock art studies, and explores how these technologies can be applied to finger fluting studies. The methods outlined in this chapter are informed by previous applications of 3D scanning and are intended to explore the challenges and limits of these techniques in finger fluting environments.

3D Scanning Technologies in Cultural Heritage Research and Conservation

In the last decade, advances in software, equipment, and computer processing power have made 3-dimensional (3D) scanning accessible to researchers in archaeology, cultural heritage research and conservation. Applications of 3D scanning technologies to cultural heritage have been the subject of many discussions (Allegra et al., 2017; Daneshmand et al., 2018; Davis et al., 2017; Gomes et al., 2014; Howland, 2017; Pieraccini et al., 2001; Remondino and El-Hakim, 2006; Yastikli, 2007; Yilmas et al., 2007). Researchers have applied 3D technologies to rock art research and conservation globally (Chandler et al., 2007; Lerma et al., 2010; Sanz et al., 2010). 3D digitization is only the first step of many in the process of the complete recording of objects and monuments. The goals of 3D digitization vary, and as such, the techniques used in their recording attempt to fulfill specific demands of the class of object or project at hand (Pavildis et al., 2007).

3D digital archives have a number of research and commercial benefits. They can be used as reference in museum archives, in degradation monitoring and in restoration of artifacts (Pieraccini et al., 2001; Santos et al., 2017). Current technologies have allowed for the creation of models of varying resolutions and sizes that serve a number of purposes including documentation in case of loss or damage, virtual tourism in the form of digital access, education resources and more (Remondino and El-Hakim, 2006; Scopigno et al., 2011). 3D digital models allow for the printing of high fidelity physical replicas for both digital and physical repatriation efforts (Isaac, 2015). Digital 3D archives can give researchers opportunities for ‘virtual’ restoration techniques and allow them to experiment with colour, lighting, and other contextual information that may be missing (Pieraccini et al., 2001). Application of 3D digitization to

archaeology and cultural heritage offer archaeologists, researchers, and curators new ways to collaborate, record excavations, and restore sites and artifacts (Scopigno et al., 2011).

3D digitization is considered common practice within the domain of cultural heritage (Koutsoudis et al., 2014). Technological advancements have resulted in a variety of 3D documentation techniques that can produce high quality results, but there is no singular method that is ideal for all projects. Therefore, there are a few considerations in assessing the suitability and applicability of a method. Pavlidis et al. (2007) discuss three components of the object being scanned that need to be considered when choosing the most suitable 3D scanning technique. The first factor is the complexity in size and shape of the object. For example, a scanning technique appropriate for an object at a microscopic scale may not be appropriate for an object at a monumental scale. The second factor is the morphological complexity, which refers to the amount of detail that the object has that would need to be recorded. Higher levels of morphological complexity require scanning techniques with higher resolution, precision, and accuracy. The third factor is the diversity of raw materials. Since 3D scanning techniques usually require machines that project light patterns onto the surface of the object, the material that the object is made of can influence how light reflects off the surface. There are different techniques for recording ceramic objects compared to metallic or glass objects.

Beyond the object itself, there are additional criteria to be considered. Costs of 3D scanning technologies can often pose a significant barrier to access; therefore, budgetary considerations are a key component within decision making (Koustoudis et al., 2014). Since some 3D digitization work within cultural heritage management takes place outside of laboratory conditions, the portability of equipment is another important consideration (Remondino and Rizzi, 2010). It is also important to consider the skill requirements for operating the digitization

system as high skill requirements can also pose as a barrier to usage (Pavildis et al., 2007). There are also considerations of the technique itself, such as the accuracy of the system and the productivity of the technique (Pavildis et al., 2007). Some 3D digitization systems take longer in data collection, while others require more time in post-processing, so setting the most appropriate timeline of the workflow for the project is also important (Remondino, 2011).

As a whole, there are three main steps in 3D digitization as described by Pavlidis et al. (2007). The first step, preparation, involves decisions about the technique and methodology to be used in the project. The second step is the actual digital recording, in which data is collected according to decisions made in the preparation step. The final step is data processing, which involves creation of the model through unification of partial scans, geometric data processing, texture data processing, texture mapping, and other technical touch ups. The completion of these steps results in the creation of a 3D model, but further decisions need to be made about storage of digital data, who can access the model, and how it can be accessed.

Methods of 3D Scanning in Cultural Heritage Conservation

There are a multitude of methods of digital scanning technologies that have been employed in cultural heritage preservation. The following list describes a number of possible 3D scanning techniques that can be employed in the field. This means that techniques that require laboratory settings, such as ideal lighting situations or large and complex set-ups, are not discussed.

Laser scanning techniques: a device emits a laser pattern over the object and an optical sensor, which is calibrated with the emitter, identifies the distribution of the pattern and calculates the depth information through the process of triangulation (Gomes et al., 2014). These devices can range from small scale, handheld scanners, such as Creaform HandySCAN 700, to

large-scale terrestrial scanners, such as LIDAR, which illuminates the objects of interest with pulses of laser light and uses differences in laser return times and wavelengths to make the 3D representation of the object (Crutchley, 2010). Laser scanning techniques are known for the high accuracy in geometry measurements (Pavildis et al., 2007). Laser techniques can be limited by surface properties, such as reflectance and transparency (Gomes et al., 2014), and devices for laser scanning tend to have high costs.

Structured light scanning techniques: a device projects a set of light patterns over the surface of object and records the shape based on disturbances in the light pattern (Gomes et al., 2014). Structured light scanners include handheld scanners that are ideal for detailed recording of relatively small objects, such as the Go!Scan 20 by Creaform. There are also tripod-mounted structured light scanners that can accommodate objects of larger size, such as the DAVID SLS-2 scanner. Since structured light uses the same process of triangulation as laser scanning techniques, it is often confused with laser scanning, as many commercial products cannot be absolutely classified as one or the other (Pavildis et al., 2007). The main difference between the two techniques is the wavelength of light that is projected from the scanner: structured light scanners use light, usually LED light, in a variety of colours, whereas laser scanners use laser light instead (Tong, 2011). However, since the 3D information is captured how the object changes the way light is reflected back to the sensors, surface properties, such reflective or transparent surfaces, can limit structured light scanners (Gomes et al., 2014). In addition, since these scanners use light within the visible light range, ambient illumination can result in less accurate data. (Gomes et al., 2014).

Shaping by shading techniques: the object is photographed under varied lighting conditions, as shading plays an important role in depth perception. The object and camera remain

stationary while the light source is adjusted, and a special algorithm based on the shading conditions on the surface of the object deduces the geometric information (Pavildis et al., 2007). This method can also capture textural information, with some inaccuracy in highly shaded areas (Gomes et al., 2014). Reflectance Transform Imaging (RTI) is a common 3D digitization technique that shapes using shading techniques. MacDonald (2011) tested the accuracy of RTI imaging and found that errors were introduced to the model through the predictive biquadratic functions that are used to process the model with the illumination angles. However, it was noted that the amount of surface resolution lost through the RTI process is comparable to that of laser scanning (MacDonald, 2011).

Shaping by motion techniques: a system generates 3D information based on a sequence of images, usually from a video camera (Pavildis et al., 2007). Common points on the objects are established within the frames of the video, and the 3D model is created from the relative difference between the locations of these common points as the camera moves around (Gomes et al., 2014). This technique is also known as video photogrammetry and is often used in combination with image photogrammetry, discussed below (Lerma et al., 2010). This technique requires only a video camera on site, and the processing software offsite, thus is highly portable. VI3Dim 3D Reconstruction software is an example of the post-video processing software that can generate a 3D model (VI3Dim 2015) and the Pix4D software is an example of a photogrammetry software that uses both video and images to create the 3D model (Pix4D.com). However, the resulting 3D models tend to be relatively low resolution and have low accuracy (Gomes et al., 2014).

Photogrammetry: 3D models can be created from photographs of the object from at least 2 perspectives. The shifts between the perspectives or lines of sight are used to triangulate the

location of the object and its features (Pieraccini et al., 2001). Since the 3D model is derived from a series of images, the textural data is automatically collected (Lerma et al., 2010). This technique is relatively portable and highly accurate (Lerma et al., 2010). Digital photogrammetry, also known as structure from motion (SfM) is a photogrammetric method that is used by archaeologists (Howland et al., 2014). A series of photographs are taken of an object or scene which are then processed through computer programs to create a 3D pointcloud that represents the surfaces of the objects in the photographs. This pointcloud can be processed further to create models, elevation maps, scaled plans and more (Green et al., 2014).

3D Scanning in Archaeology and Cultural Heritage:

As 3D scanning technologies are powerful tools in recording and analyzing cultural heritage, many researchers have explored their applications to archaeology. 3D scanning technologies have been employed for the study of lithic artifacts (Grosman et al., 2008), *in situ* site recordings (McPherron et al., 2009, Douglass et al., 2015), and archaeological documentation and preservation (Rüther et al., 2009, Lerma et al., 2010). Rock art has been a popular subject of 3D digitization, as the contextual information surrounding rock art is often inseparable from the rock art itself (Diaz-Andreu et al., 2006, Ortiz Sanz, 2010, Noya et al., 2015, Plisson and Zotkina, 2015, Williams and Shee Twohig, 2015).

McPherron et al. (2009) attempted to employ structured light scanning techniques in the field in order to create high-resolution documentation of in-situ finds. The team created a 3D representation of excavated surfaces and associated artifacts at two Middle Paleolithic sites in southwest France. Their resulting models had sub-millimeter accuracy and were very good representations of the original colours and spatial data. However, in their process of documentation, they found that there needed to be a significant amount of time put into learning

to use the technologies. Other logistical concerns involved consistent lighting, camera placement, and computing power during post-collection data processing.

Douglass et al. (2015) used photogrammetry to create 3D models in two case studies in the Great Plains. The team compared the 3D models created by photogrammetry to traditional methods of site recording in terms of time investment, mapping detail, and accuracy. Their results found that 3D models could be created through photogrammetry with minimal training and by using standard field cameras and computers. The process of in-field documentation was much faster using photogrammetry in comparison to traditional illustration; however, the post-processing time caused the two methods to have similar time investments, but since much of post-processing can be automated, Douglass et al. argue that photogrammetry can be a more effective tool in site recording than traditional methods. Measurements between marked points were taken in field and on the 3D model and, while the results showed high agreement, they varied between 0.33%-4.46%. However, Douglass et al. point out that the measurements taken on site were done with standard meter tapes and cannot be held as truly accurate values. Overall, photogrammetry created a versatile 3D model with relatively high precision that can be shared and studied with ease.

Sanz et al. (2010) applied photogrammetry techniques using consumer-grade cameras on petroglyphs in northwestern Spain. In their study, three different petroglyphs were digitized using photogrammetry. The process involved placing targets around the intended area and photographing the petroglyph from various angles. The data was then inputted into processing software that cost around \$2700 in 2010, and a 3D model was produced. The accuracy of the model was tested by comparing measurements procured from the petroglyphs manually to the same set of measurements taken from the 3D model. The authors used the Z-axis, or the depth of

the petroglyph carving, as their point of comparison, as it had the weakest agreement between the two sets of measurements. The results showed that the statistical values for error were very low in both tested cases; in the Z-axis, there was a standard deviation of 1.08 mm for the Gargulla petroglyph, and a standard deviation of 0.26 mm for the Formigueiros petroglyph. Relative to the total size of the petroglyphs, the errors were negligible, since the petroglyphs were large and extended over a surface of approximately 1 meter squared. With their results, they found that the process of making 3D digital records of the petroglyphs was efficient and resulted in relatively accurate models that could greatly benefit the study of the rock art.

Plisson and Zotkina (2015) explored the microscopic and macroscopic potential of photogrammetry in the study of rock art by conducting tests at different scales using a variety of photography equipment. In their experiment, they created experimental petroglyphs that were recorded using a number of SLR cameras; the photos were then processed using PhotoScan software, which created the 3D model. They also adapted equipment to enable high magnification data to be stacked on top of the surface relief model. After analysis of the 3D model, the team concluded that photogrammetry was appropriate at the macro-scale in measuring and evaluating some aspects of the rock art not visible to the human eye, such as the reliefs of crystals and other mineral deposits. However, photogrammetry was limited at the microscopic scale, as the short depth of field required for high magnification photography interfered with the creation of a 3D model.

Davis et al. (2017) apply laser scanning, photogrammetry, and 3D photographic reconstruction to a rock art heritage site in Western Australia in order to increase accessibility to these heritage locations for the indigenous Yinhawangka people. In their study, they used terrestrial laser scanning (TLS), a form of large scale laser scanning, to capture the contextual

site information and combined it with photogrammetry and 3D photographic reconstruction, which captured the smaller details of the rock art. They found that since TLS was able to capture 3D data across large areas that had both accuracy and positional certainty and was therefore most suitable to help answer questions of context, such as the distance between two rock art panels. However, this method required a trained operator and sometimes included bulky equipment that limited accessibility. They found that photogrammetry and 3D photographic reconstructions allowed them to visualize key archaeological features in high resolution. The equipment needed for photogrammetry was minimal, with only the camera, scale bar, and tripod, and therefore was highly portable in difficult terrain. The time required to capture the images in the field were short (30-60 minutes). These approaches were ideal for mapping discrete rock art features, and the resulting models can be imported into sight management software, such as CAD. However, Davis et al. (2017) found that since photogrammetry relies on image capture and requires external illumination, it was challenged by changing light conditions outdoors. If a part of the rock art was illuminated by the sun, that portion could be recorded by photogrammetry, while the area in the shadows could not. Overall, Davis et al. (2017) found that combining TLS with photogrammetry allowed them to build a detailed and comprehensive image of the rock art site. This visual output in combination with ethnographic surveys assisted in the interpretation and management of the sites. The virtual recreation of these rock art sites allowed the Yinhawangka people to access these sites virtually and provided opportunity to even better understand the sites and their regional context.

In their 2014 paper, Zlot and Bosse discuss their work with a team of researchers from the South Australian Museum and Flinders University that created a 3D model of Koonalda Cave in south Australia. Koonalda Cave is an archaeological site that contains evidence of flint mining

as well as multiple panels of finger flutings. Zlot and Bosse (2014) produced a 3D laser scanner, small enough to be carried by a researcher, that could record cave data essentially as fast as the researcher could walk through the cave. Their highly efficient laser scanner produced a 3D model of the cave formation. However, the scanner was only able to record data at centimeter accuracy and thus, the resulting model was not able to capture the fine details of the Koonalda finger fluting streams. The authors comment on the potential for other forms of scanning technology, such as photogrammetry, to digitize high-resolution 3D models of the flutings.

However, with the rise of the popularity of 3D scanning in archaeology and cultural heritage, criticisms have been levelled at the role of 3D scanning in research. Howland (2017) takes a critical perspective on how 3D field recording can truly contribute to the broader questions of archaeology. He disputes the so-called 3D Revolution and points to extremely high costs of several forms of 3D digitization as a prohibiting factor. He also warns that researchers must consider how the 3D technologies aid in research goals and tailor the application of 3D approaches to the project or risk simply creating a flashy image that distracts from real research. Greenop and Landorf (2017) also comment that the 3D digitization technologies should work alongside cultural heritage management and research, rather than replace these efforts entirely. Therefore, careful consideration must be given to the purpose of 3D scanning and how it contributes to the research question.

Overall, 3D scanning technologies hold much potential for the future of archaeological research. In particular, the rock art community has devoted much time in the exploration of possible contributions of different methods of digitization. Some researchers have tested the accuracy of the 3D models that are produced by different digitization systems when applied to rock art (Plisson and Zotkina, 2015; Sans et al., 2014), while others have worked to develop

methods that combine different 3D scanning techniques to produce a comprehensive model of rock art sites (Davis et al., 2017; González-Aguilera et al., 2009; Lerma et al., 2010; Zeppelzauer et al., 2015). While cave paintings, petroglyphs and other engravings have been the subject of 3D digital recording, only one attempt at 3D digitization of a finger fluting site has been undertaken and it was unsuccessful due to a lack of accuracy in the laser scanning machinery (Zlot and Bosse, 2014). As such, there is untapped potential for the applications of new technologies to the study of finger flutings.

Research Question and Objectives

Archaeological applications of 3D scanning techniques have resulted in high resolution models that give researchers and other stakeholders new opportunities to engage with the sites. Since studying finger flutings requires close-range engagement with the rock art, and the contextual information is often key to interpretation, the 3D digitization of finger fluting sites could provide additional insight and engagement with the site. 3D digitization is another tool for archaeological research, and therefore must be tested to be appropriate and applicable to the research question at hand. The goal of my project is to take an experimental approach to 3D documenting finger fluting panels in order to develop a method to best document finger fluting panels *in situ*.

Looking into how research into finger flutings is conducted and studying archaeological applications of 3D scanning techniques have formed the key question to my research: What method(s) of 3D documentation creates 3D models that meet the accuracy, portability, budgetary, and data requirements for the study of finger flutings? The development of a method of 3D digitization will allow researchers to take these techniques into the field and produce 3D models of finger fluting sites.

Data Collection: Creating Replica Panels

In order to test the different 3D digitization systems, I created replica finger fluting panels. Under the guidance of Dr. Leslie Van Gelder and Dr. April Nowell, I created 9 sets of replica panels. The panels were created in disposable aluminum pans that were 42.2 centimeters by 30.2 centimeters in size with a depth of 6.7 centimeters. The aluminum pans were filled with clay, plaster, or a combination of the two materials. The clay used was WC-389: Laguna WSO moist clay and the plaster used was DAP Plaster of Paris created from the dry mix. Gloss was poured on some panels to replicate the reflective effect of some calcification processes that occur on top of finger flutings within cave situations.

The three clay panels were set up by pressing about half a centimeter to 2.5 centimeters of clay into the pans. Dr. Van Gelder assisted in creating clay surfaces that more accurately represented the appearance of fluting panels *in situ*. One panel was created to be relatively smooth (Figure 4.1), another with varying depth changes (Figure 4.2), and a third was created with a ledge feature that protruded from the surface of the clay, which cast a significant shadow over the panel when illuminated from a single light source (Figure 4.3). Three individuals created fluting streams at different depths using a combination of single finger flutings and three finger flutings (Figures 4.4 - 4.6).



Figure 4.1: Clay panel 1 with smooth surface.



Figure 4.2: Clay panel 2 with varying depths.

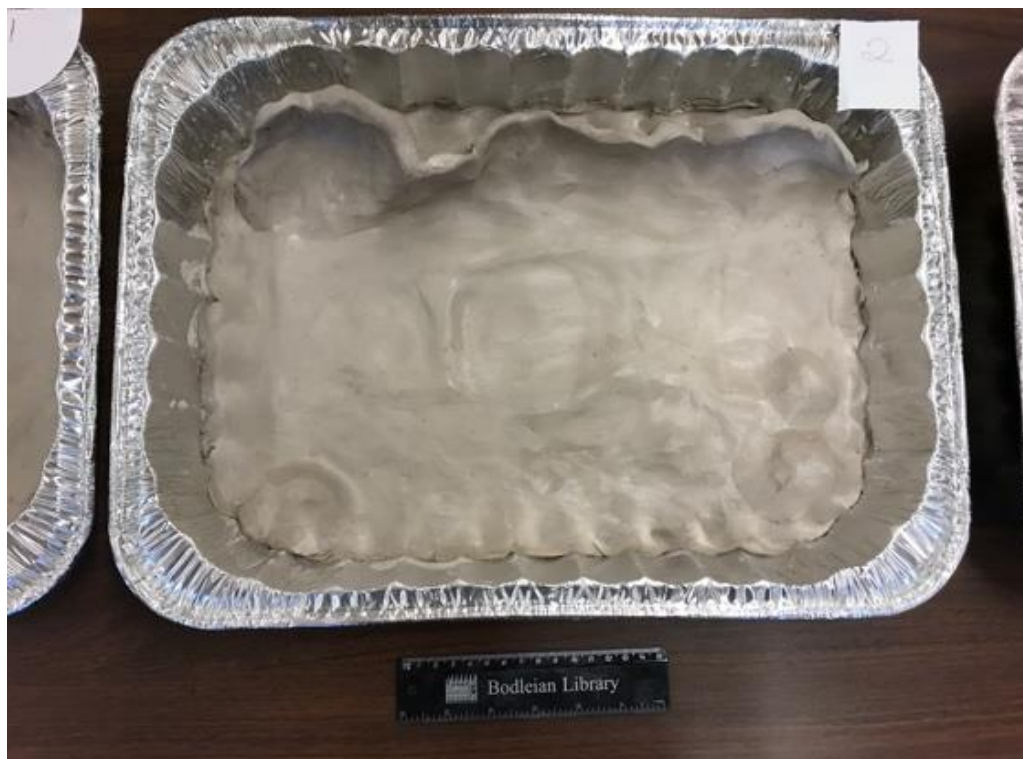


Figure 4.3: Clay panel 3 with a ledge feature.



Figure 4.4: Clay panel 1 with flutings.



Figure 4.5: Clay panel 2 with flutings.



Figure 4.6: Clay panel 3 with flutings.

The three plaster panels were created by mixing the plaster, allowing the plaster to slightly solidify, then fluting on surfaces. Once again, three individuals created fluting streams at

different depths using a combination of single finger flutings and three finger flutings (Figure 4.7).



Figure 4.7: Plaster panel 1.

A third set of three panels were created in plaster with clay overlay. These panels were created in the same way as the plaster panels and allowed to dry overnight. They were then covered with varying amounts of clay to mimic finger fluting panels that sometimes appear two-toned *in situ* as a result of the cave surface geology (Figure 4.8). Glossy varnish was applied to one clay panel, one plaster panel, and one mixed panel to mimic the shine that calcification causes on fluting panels in some caves (Figures 4.8 and 4.9).



Figure 4.8: Plaster panel with clay and gloss.

Over time, it was noted that the created panels shrank as they dried. In particular, the clay panels shrank significantly, causing the panels to crack as a result. However, the plaster panels held up well, though some cracking still occurred. Appendix A contains a complete set of photos of the replica panels. Since measurements were taken after the panels fully dried, the cracking of the panels had no impact on my analysis.



Figure 4.9: Clay panel 3 with gloss.

Figure 0.10: Clay panel 3 with gloss.

Data Collection: Assessing 3D Scanning Technologies

Since there are a variety of portable 3D scanning technologies that can be employed, I assessed the different technologies based on the requirements of this project. I looked at the requirements through the key criteria outlined by Pavlidis et al. (2007): complexity in size and shape, morphological complexity, and diversity of raw materials. Finger fluting panels are highly complex in their size and shape. The panels can vary in size, from a small feature on a cave wall to an expansive panel covering several meters in length and width. While the replica panels that were created are standardized in size, the variety found within *in situ* finger fluting panels means that the 3D scanning technology must be able to accommodate the range of sizes. Finger flutings have a high level of detail. Since the purpose of the 3D models is to allow for accurate measurement, high levels of accuracy are required to capture the morphological complexity of the panels. The surfaces on which flutings are drawn vary as some surfaces are relatively uniform, while others are a mixture of materials. Sometimes speleothem occurs overtop panels (Bednarik, 1995), which can give the surface of finger fluting panels a shiny appearance. The appropriate 3D scanning technology must be able to accommodate these challenges.

Overall, 3D scanning finger flutings face a number of key challenges. First, the digitization system must be highly portable, since finger flutings can occur as far as 0.94 kilometers into a cave system (Van Gelder, 2015). Flutings can be found very low to the ground and very high off the ground, which requires high portability. Researchers often have a limited amount of time to access the cave sites that contain finger flutings; as such, the speed of digital recording should be relatively fast. The most important requirement of the digitization system for finger flutings is high accuracy. Since analysis of finger fluters requires researchers to distinguish individual fluters based on measurements of three-fingered fluting streams that are

accurate to the millimeter (Sharpe and Van Gelder, 2006), the 3D models that are created through the 3D digitization method needs to be able to account for this degree of accuracy.

With these requirements in mind, I was able to narrow down three 3D scanning technologies that would be appropriate for the purposes of studying finger flutings: laser scanning, structured light scanning, and photogrammetry. All three methods are adaptable to a variety of sizes, materials, and morphological complexity and able to create high resolution 3D models that would be required for finger fluting studies. Reflectance Transform Imaging (RTI) was also considered as a potential option. However, since RTI requires a large range of movement by the light source, it was deemed too challenging to use within the physical confines of finger fluting caves.

Agisoft PhotoScan Pro was the photogrammetry system that I used. Agisoft Photoscan was chosen as it has been previously applied to archaeology and rock art successfully by a number of researchers (Douglass et al., 2015; Plisson and Zotkina, 2015; Sans et al., 2010). The Go!Scan 20 by Creaform was tested as a form of handheld laser and structured light scanning. The Go!Scan 20 3D scanner was available at the University of Victoria Digitization Centre. The HDI 120 3D scanner by LMI Technologies, a blue light structured light scanner that operates on a tripod, was tested as a third option.

Data Collection: Photogrammetry

Photogrammetry was conducted using a Canon Rebel T2i camera with a 50 mm lens. The light source was provided by a ProMaster LED 160 camera/camcorder light. The data collection was done in darkness with the single light source. Photographs were taken approximately 75 cm



Figure 4.10: Photogrammetry set up.

250.

from the surface of the panel (Figure 4.10). The model was scaled using three 10 cm scale targets. There was approximately 60-80% overlap between photos, in order to add maximum amount of detail. This amount of overlap follows the suggested amount (Agisoft 2017), since it allows the software to locate landmarks to stitch together the images. Additional photos were taken of significant features, such as glossy areas or surface protrusions. The number photographs taken in the process of photogrammetry ranged from 150 to

The photo set was processed using Agisoft Photoscan Pro software, version 1.3.1, on a custom-built computer. The specifications for the computer are found in Appendix C. Both a dense point cloud and a mesh model were created through PhotoScan.

Data Collection: Handheld Structured Light Scanning



Figure 4.11: Handheld structured light scanner set up.

Two experimental panels were documented using the Go!Scan 20 by Creaform, which is a white light handheld structured light scanner (Figure 4.11). The technical details of the 3D scanner are listed in Appendix C.

Two panels were scanned using the Go!Scan 20, Plaster panel 1, and Plaster and clay panel 1. The panels were scanned on a table surface, in a windowless room. The handheld scanner was plugged into a desktop computer through a USB 2.0 cord. The 3D scanned model was created directly into the VXElements

software.

Data Collection: Tripod Structured Light Scanning

Two panels were documented using the HDI 120 3D scanner, Plaster with Clay Panel 1 and Clay Panel 3. Both the scanner and the panel were set on a table. The panel was propped up approximately a meter in distance from the scanner, which was set on a tripod approximately 50 cm tall (Figure 4.12).

Throughout the documentation process, the scanner was moved around in order to best capture various details on the surfaces of the panels. The HDI 120 scanner used blue structured light and the resulting scans were

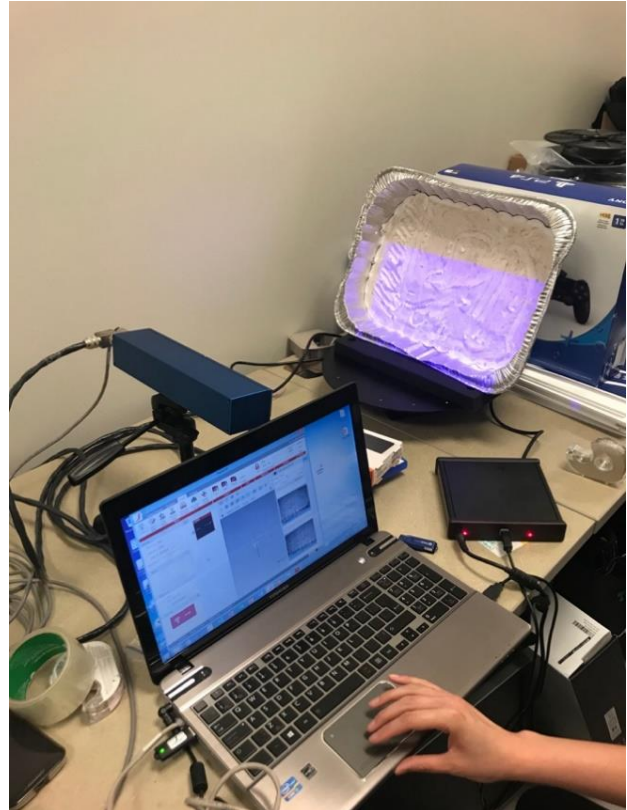


Figure 4.12: Tripod structured light scanner set up.

processed in the FlexScan 3D software. The technical details of the scanner are listed in Appendix A. The model produced by the scanner was then exported into MeshLab, an open source 3D mesh editing software, and scaled according to 3 features of known length on the surface of the experimental panels.

Data Collection: Taking Measurements and Working with the Model

Measurements were taken from the physical panels as well as the 3D models.

Measurements were taken from the panel following the method developed by Sharpe and Van Gelder (2005). Where possible, measurements were taken in locations where 3 finger widths

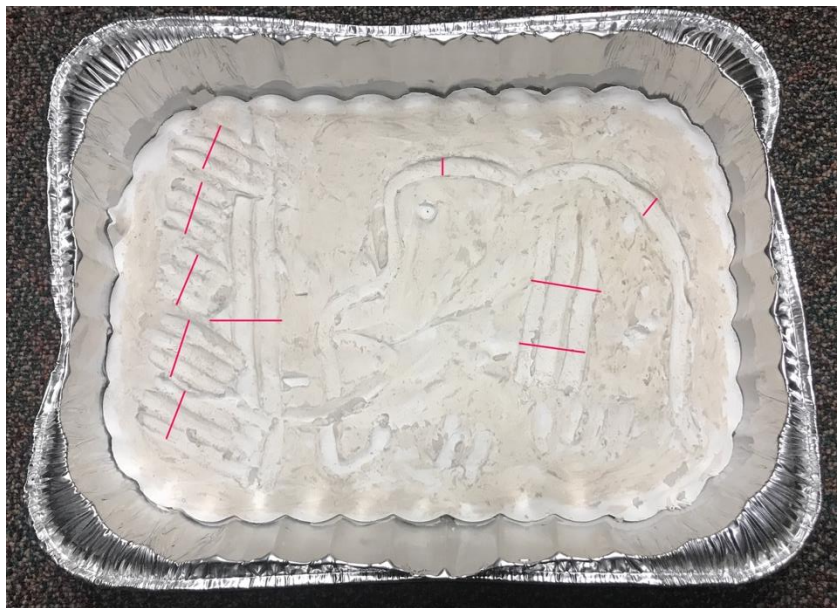


Figure 4.13: Locations on Plaster with Clay panel 1 where measurements were taken.

were clearly indicated, as close to initiation of the stream in the fluting process as possible. This follows Sharpe and Van Gelder's method (2006a), since their experimental results showed that there tended to be less distortion in the width of the flutings closer to the

initiation of the stream and thus it more accurately represented the fluter's fingers. Additional measurements were taken from the panels until 10 different flutings on the panel were measured (Figure 4.13). If there were no 3 finger flutings to be measured, measurements were also taken from single finger flutings. See Appendix for list of measurement locations. In addition to the measurements of finger fluting widths, 3 additional measurements were taken of the depth of the fluting streams. A similar test was conducted by Jalandoni et al. (2018) on digital measurement of rock art in Australia.

These measurements were taken by zooming into the 3D models, turning them around, and otherwise manipulating the images. I noted the limits and challenges of how the models

could be manipulated and what extra information could be gained. Colour accuracy was qualitatively noted from the photogrammetry-created model.

Statistics:

Since the handheld scanner was unable to capture the whole panel, I was unable to test the accuracy of the model. However, I tested the accuracy of the completed 3D models produced by the tripod scanner and photogrammetry. Each of the measurements were taken 3 times from the panel in person and 3 times from the digital model. I then compared the errors between the two sets of measurements as a whole and compared the percentage error between the measurement from the panel and the model for each specific measurement. Finally, a paired t-test was applied to test whether there was statistically significant difference between the two sets of measurements. The results of these tests will be discussed in the next chapter, *Results and Analysis*.

Conclusion:

The methods I have developed to test the viability of 3D digitization technologies to finger flutings are influenced by the ongoing application of 3D digitization to archaeology and cultural heritage management. This chapter discusses how other researchers have applied 3D scanning into their research and how these new developments in technology can be used to answer research questions. Many researchers consider 3D technologies to be an addition to the archaeologist's toolkit and so archaeologists should be aware of the purpose of the tool. While 3D models are certainly an engaging visual component to research, they also aid in research goals. In the case of finger flutings, the creation of a 3D model will help mitigate many physical challenges present in the study of finger flutings and provide avenues for future collaborative efforts. Therefore, it is important to understand the accuracy, the challenges, and the limits of 3D

digitization in application to finger flutings. I use the methods outlined in this chapter to determine which 3D digitization system is most appropriate for this research context.

Chapter 5: Results and Analysis

Introduction

The study of finger flutings provides an avenue for researchers to study how individuals in the Pleistocene interacted with the world around them. The methods of study, outlined in Chapter 3, rely on careful measurement of 3-fingered fluting streams, and analysis of how the streams intersected. Despite the development of a forensically informed and experimentally tested method, the physical constraints of the cave environment still pose challenges to researchers. 3D techniques have the potential to help overcome some of challenges posed by studying finger flutings *in situ*. An accurate 3D model of finger fluting sites would give researchers the opportunity to zoom in on details and take measurements of fluting streams without worrying about many of the physical challenges of working in often tight spaces in low lighting and the possibility of damaging the rock art. As such, my research was informed by one main question: What method of 3D documentation for creating 3D models meets the accuracy, portability, budgetary, and data requirements for the study of finger flutings?

Since 3D technologies are a tool that can be employed by researchers, choosing the most ‘appropriate’ technique relies on an understanding of the broader research purpose. The 3D models of finger fluting sites are created to help researchers overcome some existing challenges of the current methods. The most ‘appropriate’ technique accommodates for these challenges and thus is not defined by a single factor, but rather by a variety of factors, including accuracy, cost, and portability. I tested three different 3D digitization systems that were available in order to answer my research question. Of each of these 3D scanning techniques, I asked the following questions:

1. What are the limits and challenges of 3D scanning techniques when applied to finger flutings?

2. In comparison to measurements taken from the panel, are measurements taken from a 3D model accurate?
3. Which 3D scanning techniques best meet the requirements of finger fluting studies?

These sub-questions allow me to analyze how each 3D scanning technique addresses the challenges that would arise from the study of finger flutings.

Q1: What are the limits and challenges in applying 3D scanning technologies to finger flutings?

Handheld structured light scanning results:

Overall, the handheld structured light scanner was the least successful in scanning the experimental panels overall. The process of scanning the panel took about 20 minutes but was not able to create a complete panel. I attempted to scan 2 panels: Plaster panel 1, and Plaster with Clay panel 1. The handheld scanner uses landmarks on the surface of the object to stitch together the recorded 3D data. However, the rather abstract and homogenous nature of the finger fluting surfaces posed significant challenges to the handheld scanner. Landmarks were found in areas where clear intersections of flutings occurred, but in situations where the flutings were continuous or the areas where the panels were empty, the scanning software could not locate landmarks. In other situations, this lack of landmarks would be corrected by placing markers on the surface of the objects, but since no markers can be placed on the finger fluting surfaces, this posed as a rather insurmountable challenge. In addition, the handheld structured light scanner was tested in a darkened lab setting and not a cave-replicating scenario, so I was not able to test how handheld structured light scanning would function in those settings. This experiment was conducted in the lab in order to understand how structured light scanners would record finger fluting panels and what challenges the material posed the recording process.

The plaster panel was a particular challenge to the handheld structured light scanner (Figure 5.1). The Go!Scan 20 collects 3D information about the geometry of the object by

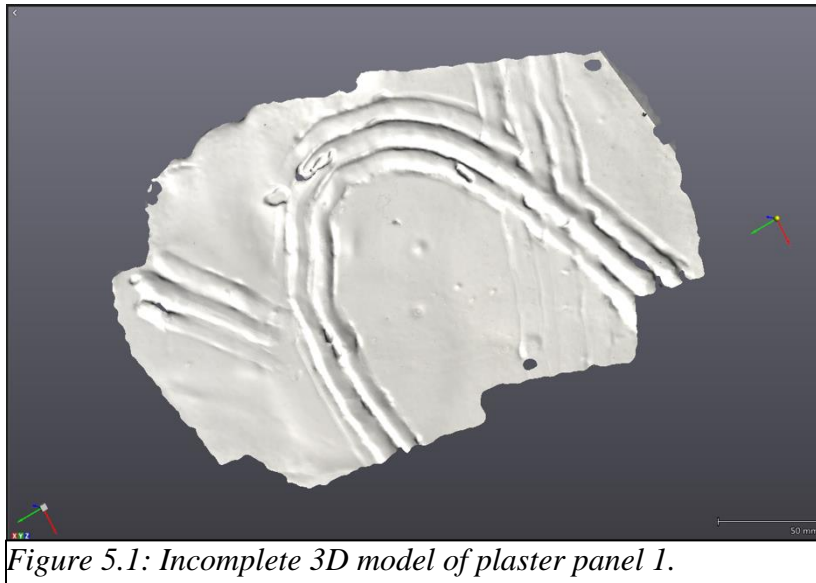


Figure 5.1: Incomplete 3D model of plaster panel 1.

emitting a white light pattern and recording the disturbances to the pattern through the built in sensor. Since the plaster panel was made of only white plaster, the surface was purely white without any changes in colour or texture. This

homogeneous surface caused gaps in the model, since the scanning software could not match any landmarks on some areas of the surface. The white colour of the plaster seemed to influence the way that light was reflected back to the sensor on the handheld scanner, causing the process of 3D digitization to take significantly longer.

The handheld scanner did significantly better in scanning the plaster panel with clay



Figure 5.2: Incomplete 3D model of plaster with clay panel 1.

overtop (Figure 5.2). The clay overlaid on top of the plaster panels changed the colour of the panels enough so that the scanning software was able to more readily find

landmarks on the surface. However, there were still areas on the panel that could not be recorded, despite significant effort.

The challenges that arose while using the handheld scanner are ones that could be further amplified in-field. The process of 3D digitization took place under mostly ideal situations: in a darkened lab room with access to power and light. When the scanner was unable to pick up details in certain areas of the panel, we rotated the panel on the table, which would be impossible to do under real cave situations.

Tripod Scanner Results

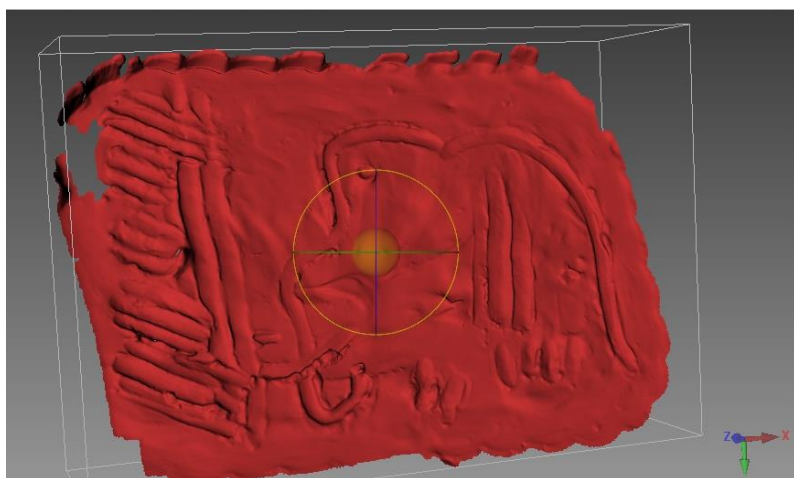


Figure 5.3: Complete 3D model of plaster with clay panel 1.

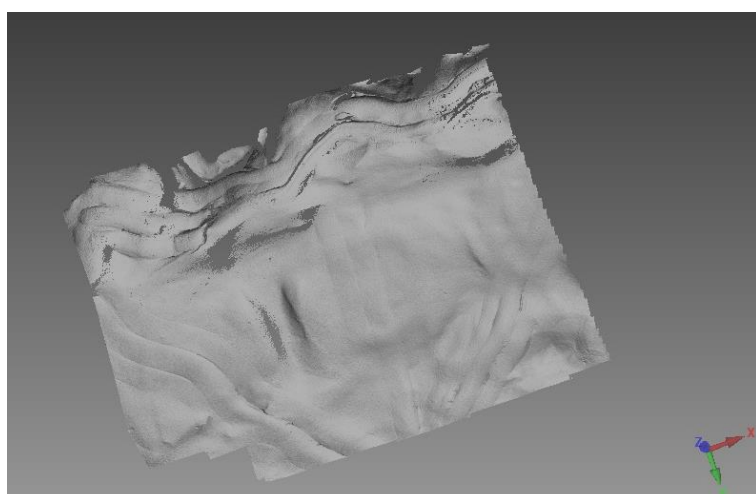


Figure 5.4: Incomplete 3D model of clay panel 3.

The tripod scanner was able to capture the full panel, but still faced a number of challenges. A full scan of Plaster with Clay Panel 1 was completed (Figure 5.3), while an incomplete scan of Clay Panel 3 was done (Figure 5.4). The process of

using the stationary scanner was extremely time consuming, with the complete scan of Plaster with Clay Panel 1 taking a little over 3 hours, and a partial scan of Clay Panel 3 taking around 1 hour. The total scanning surface of the HDI 120 scanner was small, so only small

portions of the panel could be scanned in detail. This meant that the process of digitization was extremely time consuming. Moving the scanner back enlarged the field of view and allowed for faster capture, but this came at the cost of accuracy and detail.

Structured light scanning uses a sensor on the scanner to detect how the surfaces of the objects being scanned disrupt the light patterns that are projected. This method of determining the shape of the object means that what the scanner is able to capture is limited by the line of sight. That is to say, if a feature on the object is not visible from the perspective that the scanner is located, that feature cannot be captured. In this case, Clay panel 3 had a ledge-like feature that mimics the protrusions on some cave walls and there was some difficulty capturing the entire ledge, since the top or bottom of the ledge would not be visible from certain angles (Figure 5.4). To mitigate this, I moved the scanner around and angled it such that it would be able to capture one section at a time. This process was time consuming and challenging.

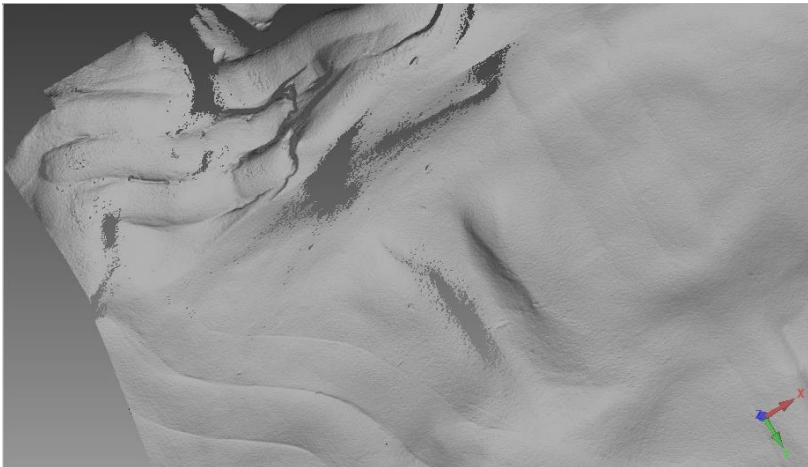


Figure 5.5: Close up image of gaps in the tripod structured light scanner model due to reflective quality of the surface.

Since the tripod scanner was also a structured light scanner, the gloss that covered some portions of the panel was also challenging. The shiny effect caused by the gloss altered how the structured light pattern was disrupted and so

the sensor sometimes faced challenges in capturing those sections. In most cases, we were able to circumvent this issue by taking a few extra scans of the area from different angles, but this did not always work. In some cases, there were still gaps in the model (Figure 5.5).

We were able to overcome most challenges to the process of 3D scanning using the tripod SLS. However, these accommodations were extremely time consuming and took place under ideal lab environments. The panels were scanned on a flat table top, where it was easy to move the tripod closer and further from the panel and change the angle of capture as needed. In a cave setting, the space can limit the range of movement that is required. In addition, this method requires significant time investment in the field and may not be able to capture all of the flutings in the time allotted.

Photogrammetry Results

Photogrammetry was able to capture a 3D model of the panels along with fairly accurate



Figure 5.6: 3D model of plaster panel 1.

colour and texture. The process of photographing the experimental panels took about 30 minutes. The number of photos taken was dependent on the complexity of the panels as well as the details and features on the surfaces of the panels. Models were created of

Clay panel 3, plaster panel 1 (Figure 5.6), and plaster with clay panel 1 (Figure 5.7). Processing the photosets into 3D models took upwards of 14 hours to complete, but most of this is done passively, meaning the program runs without user interaction. There were three main sets of challenges associated with photogrammetry: lighting, taking the photographs, and the post-photograph processing.

The photos for the process of photogrammetry were taken in a cave-replicating situation: the room was darkened and lit with a single light source. The single light source would cast strong shadows on some areas of the panel, which results in a loss of information in those areas. In particular, this loss of information influenced depth information, as these were the areas in which shadows were the strongest. In clay panel 1, the



Figure 5.7: 3D model of plaster with clay panel 1.

ledge feature of the panel produced strong shadows across the areas beneath the ledge and, as a result, the fluting on the underside of the ledge was not entirely captured in the model.

When taking photos for photogrammetry, the photos need to have around 60 – 80% overlap between the perspectives. For the experimental panels, the number of total photos taken varied, as the amount of detail on the panels varied. With the simpler plaster panel 1, I took 113 photos, whereas I took 198 of photos of the more detailed plaster with clay panel. Clay panel 1 was the most complicated to document since I needed to take more photos of the ledge feature in order to capture the details around it, so I took a total of 212 photos. However, fewer photographs can also produce highly accurate results, which would mitigate some of the limits of space and photogrammetry processing. I replicated some of the challenges associated with the cave environment by working low to the ground in a dark, windowless room with one light source, but I was not able to replicate some of the physical challenges, such as the limited space.

These challenges can be overcome with changing the lenses attached to the camera, as well as changing the lighting.

Out of all of the 3D digitization methods tested, photogrammetry was the only one that required significant processing after documentation. Once the photos were taken, the process of making the photoset into a 3D model required significant computer processing power. I processed the models on a custom-built desktop computer that had boosted specifications and the PhotoScan program still required up to 14 hours of processing. The amount of power that the program requires to process scans of large size can pose a challenge to researchers looking to apply photogrammetry into field work. Creating the dense point cloud was the step of processing that took the longest time, in fact, for clay panel 1, the dense point cloud was not created, since the process was set to take over 3 days. The amount of processing power and the time that the model processing requires can be a barrier to the 3D digitization of finger flutings. That said, taking fewer photos would speed up the processing, and make SfM photogrammetry more applicable.

Main Challenges

Each of the 3D digitization methods had their own method-specific challenges. However, there are a few challenges that all of the digitization methods faced. The main challenge is the physical constraints of finger fluting caves. While I attempted to document the models under situations that mimicked the cave environment, there are still other challenges that would occur in caves that I was unable to account for. Since flutings can occur very low to the ground, on the ceiling, in difficult to reach alcoves, and other challenging settings, it is difficult to anticipate the other physical challenges to documentation. All three of the digitization methods require the researcher to maneuver around the panels: the handheld scanner often required several passes across the surface to scan accurately, the tripod scanner needed to be moved closer and further

from the surface to capture details, and photogrammetry required photos to be taken from multiple perspectives. Thus, a more detailed understanding of the physical challenges specific to the cave and the set of fluting panels being documented would be required.

Another significant challenge is that researchers are not able to touch or interact with the surface of fluting panels. This poses a challenge both to the recording process, but also to the scaling process. Since the surfaces of finger fluting panels can be quite homogeneous, the software can have trouble piecing together the model, as was the case for the handheld scanner. As discussed earlier, this is usually rectified by placing markers or landmarks on the surface that are easier for the scanning software to recognize. However, without the ability to place any markers on the surface of the panels, some 3D digitization systems are not useful. Additionally, markers on the surface or surrounding the object are often used to scale the object. Without any markers or scales of known length being placed on the model, the two structured light scanners that were tested could only be scaled through known measurements on the surface of the panel. Since this measurement is done in person, this can introduce error into the scaling process. For photogrammetry, ideal scaling requires three objects of known length. Since researchers are not able to place the scale on top of the flutings, the scales must be set in front of the panels and set up so that they do not cast shadows that may obscure the surface. This challenge can be overcome by placing the scales on the floor, or setting the scale in front of the panel and cutting it out of the 3D model later in post-processing.

Q2: In comparison to measurements taken from the panel, are measurements taken from a 3D panel accurate?

Based on the specifications of the equipment that I tested, all of the technologies claimed to be highly accurate. The tripod scanner (HDI 120 3D scanner) has a 0.06 mm accuracy, the

handheld scanner (Go!Scan 20) has a 0.01 mm accuracy, and the accuracy of photogrammetry is dependent on the quality and the number of photos taken, but can also be very high. However, since the Go!Scan 20 resulted in an incomplete, unscaled scan, I was not able to take measurements from the 3D model that was produced. Therefore, I was only able to test the accuracy of the 3D models created from the tripod SLS scanner and photogrammetry.

In order to test the accuracy of the 3D scans, I calculated the difference between measurements taken off the experimental panels in person (PM) and those taken off the 3D model (MM). To make my measurements of the panels as accurate as possible, I took each measurement three times and used the mean of that measurement as to compare between the model and the panel. Appendix B lists all of the measurements taken from the panel both in person and from the 3D model.

$$(PM1 + PM2 + PM3) / 3 - (MM1 + MM2 + MM3) / 3 = \text{Error}$$

The error between the measurements was recorded as either positive or negative. If positive, it meant that the measurements taken from the 3D model were smaller than the measurements taken from the panel in person. If negative, the opposite is true. Comparing the error at this stage can show the direction of the error, if any.

Then I looked at the average error between the measurements taken in person and the measurements taken from the model. To do this, I added up the absolute values of the error values for each measurement (ER) and divided it by the number of values (n=10).

$$(ER1+ER2+ER3+ER4+ER5+ER6+ER7+ER8+ER9+10) / 10 = \text{Average Error}$$

Table 1 lists the minimum, maximum and average errors from plaster with clay panel 1 compared to the 3D model created by the tripod structured light scanner (SLS) and photogrammetry. Table 2 lists the results from clay panel 3 compared to the 3D model:

Table 1.

Minimum error, maximum error, and average error of measurements taken from plaster panel 1 compared to two 3D scanning techniques.

3D Scanning Technique	Minimum error (mm)	Maximum error (mm)	Average Error (mm)
Tripod SLS	0.060	0.503	0.234
Photogrammetry	0.027	0.370	0.178

Table 2.

Minimum error, maximum error, and average error of measurements taken from the clay panel 1 compared to two 3D scanning techniques.

3D Scanning Technique	Minimum error (mm)	Maximum error (mm)	Average Error (mm)
Tripod SLS	0.050	0.615	0.325
Photogrammetry	0.023	0.53	0.153

The error between the measurements taken from the panel in person and the 3D model is low. Since analysis of the flutings studies three-fingered flutings that are measured in millimeters, the average error would have little to no effect on the accuracy of that reading. For the plaster panel, measurements taken from the model produced by the tripod SLS scanner had a maximum error of ± 0.503 mm and a minimum error of ± 0.060 mm. Overall, the average error between the measurements was ± 0.234 mm. The photogrammetry model was similarly accurate compared to the plaster panel, with a minimum error of ± 0.027 , a maximum error of 0.370, and an overall average error of ± 0.187 . The tripod SLS had a bit more trouble with the clay panel. While the minimum error remained small at ± 0.050 mm, the maximum error was ± 0.615 mm, and the average error was ± 0.325 mm. Photogrammetry produced a model that has a minimum error of ± 0.023 mm, a maximum error of 0.530 mm, and an average error of ± 0.153 mm.

Overall, the average error from the tripod SLS results tended to be higher than the photogrammetry results from both the plaster and clay panels, and the maximum error from clay panel 1 produced by tripod SLS was the highest error recorded. Going back to the model, the measurement locations that produced the maximum errors were areas where the model had small holes and was incomplete. The FlexScan software that was paired with the tripod SLS scanner had a function that filled in those holes through estimation, and likely resulted in the slight errors.

All measurements had some degree of error. This was likely to due to human error that occurred during the process of measuring. Attempts were made to standardize the location of the



Figure 5.8: Plaster panel 1 with labels to mark measurement locations

measurements by placing labels to mark the locations that were measured (Figure 5.8) but finding the exact same location to do the measurement still proved to be a challenge. While the markers were a useful tool in identifying where to

measure the flutings on the experimental panels, it is important to remember that *in situ*, researchers are not able to place such markers on the cave surfaces. However, I was able to set

several markers on the 3D model and label the locations. This function meant that my measurements could be exactly replicated at a later time.

Percentage Error

Douglass et al. (2015) compared the percentage error to see if there was significant difference between their photogrammetry-created 3D model and their archaeological site. Using the same methods, I compared the percentage error between the measurements taken from the panel and the measurements taken from the 3D model. I compare the absolute difference between the measurements from the model to the measurements in person and measure that difference as a percentage of the total measurement. This analysis indicates where the 3D model was more or less accurate relative to the measurements taken from the panel and can show what features or sections are difficult to digitize accurately.

Once again, I took the mean error of the three sets of measurements:

$$(PM1 + PM2 + PM3) / 3 - (MM1 + MM2 + MM3) / 3 = \text{Error}$$

Then I took the mean of the measurements taken from the panel:

$$(PM1 + PM2 + PM3) / 3 = \text{Measurement}$$

Using the mean error and the mean measurement, I found the error as a percentage of the total measurement:

$$\text{Error} / \text{Measurement} * 100\% = \text{Percentage error}$$

The results of this analysis are summarized in table 3.

Table 3.

Percentage error between the measurements taken from the panel in person and the measurements taken from the panel for each measurement location.

Photogrammetry model from Plaster Panel 1		
Measurement Location	Absolute error	Percentage Error (%)

Tripod SLS model from Plaster Panel 1		
Measurement Location	Absolute error	Percentage Error (%)

1	0.113	0.340
2	0.133	0.398
3	0.290	0.653
4	0.273	0.994
5	0.070	0.222
6	0.103	0.313
7	0.370	1.043
8	0.300	0.826
9	0.027	0.073
10	0.100	0.256

1	0.213	0.639
2	0.067	0.199
3	0.223	0.503
4	0.107	0.388
5	0.170	0.540
6	0.130	0.393
7	0.503	1.419
8	0.433	1.193
9	0.060	0.164
10	0.433	1.107



Figure 5.9. Measurement location 7 on Plaster panel 1

As a whole, the percentage error between the models and the panel are low. In most cases, the percentage error is less than 1%. However, measurement location 7 was an area where both the results from the photogrammetry model and the results from the tripod SLS model had a percentage error over 1%. Going back to the panel and looking at the location for measurement 7 (Figure 5.9), the relatively large percentage error may be because of the shallow fluting, which caused the measurement location to be difficult to find consistently.

The tripod SLS had a 1.107% error with measurement location 10 (Figure 5.10) and looking at the measurement location, it is also difficult to find where the edges of the flutings are.

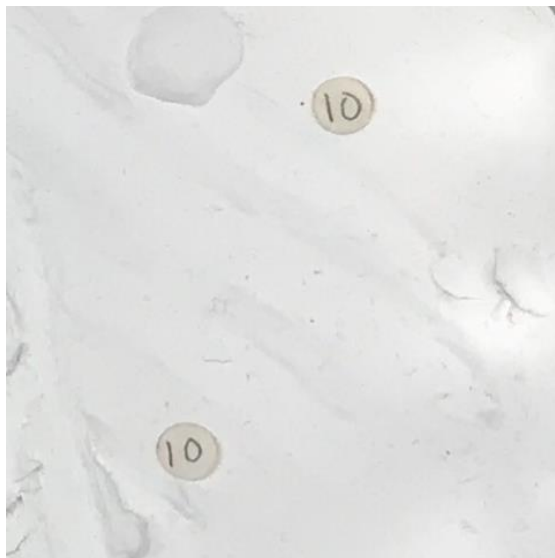


Figure 5.10. Measurement location 10 on Plaster panel 1

There was a smaller percentage error where the locations of the measurements were easily distinguished. Therefore, the relative error between the measurements taken from the model and the measurements taken from the panel are the result of the difficulty in measuring shallow flutings and likely due to human error, rather than technical error.

Overall, the amount of error between the measurements taken from the panel in person and the 3D model is not enough to cause the researcher to confuse flutings by one individual with flutings by another.

Paired T-Test

While the errors between the measurements taken in person and the measurements taken from each of the models seemed to be relatively insignificant to the research goals, it is important to know if the errors were statistically significant. A paired t-test is used to calculate whether two means are statistically different from one another. My paired t-test compared the measurements that were taken from the panel in person to the measurements taken from the model at each location to determine if any of the measurements were statistically significantly different.

Table 4.

Paired t-test results for models created from Plaster panel 1.

Photogrammetry model from Plaster Panel 1		
Measurement Location	T value	P value
1	-1.046	0.405

Tripod SLS model from Plaster Panel 1		
Measurement Location	T value	P value
1	-1.020	0.415

2	0.472	0.683
3	1.375	0.303
4	1.272	0.331
5	-2.646	0.118
6	0.967	0.435
7	-0.942	0.445
8	-0.982	0.430
9	-0.205	0.856
10	0.219	0.847

2	0.303	0.790
3	1.105	0.384
4	0.464	0.688
5	-1.302	0.322
6	-0.471	0.684
7	-0.988	0.427
8	-2.457	0.133
9	-0.276	0.808
10	2.179	0.161

None of the errors between the measurements from the panel and the measurements from the 3D model were statistically significant. Our null hypothesis was that there is no statistically significant difference between the mean of the measurements taken from the panel in person and the measurements taken from the model. To reject the null hypothesis, the p values must be smaller than 0.05. Nearly all of the p values were extremely high, meaning that we cannot reject the null hypothesis and thus there is no statistically significant difference between the two means. The t value identifies the difference between the sample data and our null hypothesis. Some of the measurements, measurement 5 on the photogrammetry panel, for example, showed a large t value. However, since the p value is still above the critical p value, it is not statistically significant. The larger t values in this analysis is likely due to the small sample sizes.

Looking at the error values show that the difference between the panels in person and the 3D model would be negligible to the analysis of finger flutings, and the result of the t -test show that there is no statistically significant difference between the two sets of measurements. Therefore, measurements taken from the 3D model are accurate, when compared to measurements taken in person.

Q3: Which 3D scanning technique best meets the requirements of finger fluting studies?

Pavlidis et al. (2007) listed nine criteria for choosing an appropriate 3D digitization system: cost, material of digitization subject, size of digitization equipment, portability of equipment, accuracy of the system, texture acquisition, productivity of the technique, skill requirements, compliance of produced data with standards. Of these criteria, the most important for finger fluting digitization are cost, portability of equipment, accuracy of the system, productivity of the technique, skill requirements, and compliance with data requirements. Since the accuracy of the system was assessed as my second sub-question, I will discuss the other criteria. The results of these criteria are summarized briefly in table 4 and show that based on these criteria, photogrammetry is the most successful and cost-efficient method to document finger flutings in most settings.

Table 5.

Summary of the results of key criteria when choosing a 3D digitization system

	Handheld Scanner	Tripod Scanner	Photogrammetry
Cost (USD)	~\$20,000	~\$15,000	\$179 Standard \$3499 Professional edition
List of in-field equipment	Handheld scanner, USB connecting cord, calibration board, laptop	Scanner, tripod, Ethernet connecting cord, calibration board, laptop	DSLR Camera, light, scale
Estimated weight of equipment	Scanner: 930 g Laptop: 2.4 kg Cords and calibration board: 500 g Total: 3.83 kg	Scanner: 1.35 kg Laptop: 2.4 kg Tripod: 1 kg Cord and calibration board: 500 g Total: 5.25 kg	Camera: 740 g Light: 500 g Scale: 150 g Total: 1.39 kg
Recording time	20 minutes incomplete	3 hours	30 minutes
Post-Processing	N/A	N/A	5-10 hours

Since one of the main barriers to 3D digitization is the cost of the equipment (Koustoudis et al., 2014), it is important to consider the differences between the cost of the equipment. Of the digitization systems tested in this experiment, the handheld scanner, the Go!Scan 20, was the most expensive. The scanner, cord, and software had a total cost of around \$20,000, which does not include the computer/laptop that would be required to run the software. The tripod scanner, the HDI 120, had a total cost of around \$15,000, which includes the scanner, connecting cord, one small tripod, and the software. Once again, these costs do not include the laptop that would be required to run the software. Photogrammetry was the cheapest of the three digitization systems, since the software, Agisoft Photoscan costs \$179 for the standard license, and \$3499 for the professional edition license. Educational licenses can be purchased by accredited institutions at \$59 for the standard license and \$549 for the professional edition license. However, this price is for the software license and does not include the camera, light, tripod or any external equipment. Photogrammetry can be done with consumer grade cameras (Sans et al., 2010) and most research teams have a camera that can be used. Lighting is required for photogrammetry, and a large battery-operated LED light can be purchased for around \$100 USD. Overall, photogrammetry is the most affordable of the three digitization methods tested.

All three of the digitization methods were relatively portable. The equipment was small enough that it could be carried in one bag. Both the handheld scanner and the tripod scanner require a connection with a laptop, the weight of an average laptop is around 5 pounds, or 2.4 kilograms (Piltch, 2018). The total weight of the equipment required for the handheld scanner was around 3.83kg. The total weight of the equipment required for the tripod scanner was 5.25 kg, since the scanner itself was a bit heavier and the tripod was required for the scanner. In this case, I used a small tripod, since the panels were scanned on a table top, but if this scanner was

to be used in the field, a larger (and therefore heavier) tripod would be required. The total in-field equipment required for photogrammetry was significantly less, requiring only the camera, a light source, and the scales. The total weight of my equipment was around 1.39 kg, but this weight can vary, according to the light and camera that are being used. While all of the equipment was small enough to be transported, the tripod scanner, the HDI 120, needed to be plugged into a power source to operate. This means that it may not be useful in all cave environments. Therefore, the handheld scanner and photogrammetry are the two digitization systems that would be applicable to finger fluting sites.

The productivity of the digitization systems varied. The results from the handheld scanner were incomplete, since there were areas on the surfaces of the panels that did not have landmarks that the software could recognize. In areas where the software could recognize landmarks, the process of digitization was fast, since the Go!Scan 20 captures up to 550,000 points per second. However, there were areas that required repeated scanning in order to capture the full details of the surface. The tripod scanner also had a fast capture rate: up to 328,300 points per second. But the field of view for high resolution capture of 3D geometry was small, so the scanner needed to be moved around in order to capture the panel in full detail. As such, documenting the 42.2 cm by 30.2 cm experimental panels took over 3 hours. Both of these structured light scanners required some processing after the models were created in order to fill in holes and scale the model. However, this time was negligible compared to the scanning process. Photogrammetry took a significantly shorter amount of time in the documentation process: between 150 to 250 photographs were taken of the experimental panels in around half an hour. The largest time sink for photogrammetry was the processing of the model. Even with a powerful computer, the creation of the dense point cloud took anywhere from 5 hours to 10

hours. However, this process is passive, as the program can be started and left for the processing time without being monitored. Overall, since one of the limits to the study of finger flutings is the amount of time researchers have access to the caves, photogrammetry is likely the best option as it requires the least amount of time in-field.

The skill requirements for the three methods of digitization that were tested were low. The main challenge to both the handheld and the tripod scanners were learning to calibrate the scanner. Once the scanner was calibrated, the scanning process was straightforward and intuitive. After the panels were scanned, the post-processing was fairly simple as well. Adding the scale and filling in holes in the model were easily accomplished within the software provided by the scanners. Photogrammetry, on the other hand, was slightly more challenging to use. Since the 3D geometry is determined using different angles in the photographs that are input into the software, there is some skill requirement to take in-focus and clear photographs that can be used. Additionally, processing the model in the software also requires understanding of the functions that a beginner would not have. The skill requirements of photogrammetry are not insurmountable to researchers but will take some practice to work through efficiently. Of the three methods of documentation, both of the structured light scanners are intuitive and have lower skill requirements to use, but researchers can learn to use photogrammetry relatively quickly.

The data requirements of finger fluting research require a complete model that has at least millimeter accuracy and is able to be exported to neutral 3D file formats so that they can be shared among researchers. There are several 3D file formats, several of which are proprietary and are unable to be opened by software developed by other companies. Therefore, it is necessary that the files that are created by the digitization methods can be exported into neutral

file types so that they can be accessed by other researchers. In terms of producing the model, only the handheld scanner did not produce results that complied with the data requirements. The Go!Scan handheld scanner created a model that had several holes and was unable to create the complete model of either of the panels that I attempted to scan. The software that is used by the Go!Scan scanner, VX Elements, can export 3D models into several different file types (.dae, .fbx, .ma, .obj, .ply, .stl, .txt, .wrl, .x3d, .x3dz, .zpr). While the areas that the handheld scanner were able to capture were accurate and the data could be exported, they were incomplete and did not fulfill the data requirements of this project. The tripod scanner produced scans that were accurate and complete. Once scaled, I was able to take measurements off the models and export the files into a few file types (.3d3, .asc, .obj, .ply, .stl, .fbx, .raw, .png) from the FlexScan software. There were a few areas that had some holes, but these could be filled with extra scans of the areas in question. Photogrammetry produced models that were also accurate and complete. With accurate scales, I was also able to take measurements from the dense point cloud model. In addition, even without colour calibration, the model still had good colour capture. The models created through Agisoft PhotoScan could be exported as both dense point cloud models and mesh models in a few different file types (.obj, .3ds, .dae, .ply, .stl, .dxf, .fbx, .u3d, .wrl, .kmz, .pdf).

Based on cost, portability of equipment, accuracy of the system, productivity of the technique, skill requirements, and compliance with data requirements, photogrammetry is the most appropriate method to document finger flutings for most researchers. The main barrier to much of 3D documentation is the cost of digitization systems and Agisoft PhotoScan is the least expensive of the three methods tested. Photogrammetry requires the least amount of time in the field and the least amount of equipment. The models that are produced are high quality and can

be exported to all major 3D file types. Photogrammetry would therefore be the best choice for 3D digitization of finger flutings in most settings. However, in smaller confined spaces in which multiple photo perspectives cannot be taken, photogrammetry may not be as accurate and therefore alternatives need to be explored.

Finger flutings that occur in spaces that have limited maneuvering room pose a significant challenge to all three of the digitization methods that I tested: the handheld scanner needs the researcher to run the scanner over the surface of the object a number of times for accurate capture, the tripod scanner needs a flat surface to be set down and moved around on, and photogrammetry requires multiple photos. In these situations, scanners that can be mounted to an arm and extended into these smaller spaces may be able to record the flutings.

Conclusion

In order to determine the most appropriate method of 3D documenting finger flutings *in situ*, I conducted an experimental project that attempted to replicate finger flutings and the environment. Since choosing the right 3D scanning technique is influenced by a number of factors, I broke down the larger research question into three main sub-questions.

First, I asked what the limits and challenges were when applying each of the 3D scanning techniques to the finger flutings. In order to answer this question, I documented the process of creating each of the 3D models and noted the challenges that arose. The handheld scanner had significant trouble with finding landmarks on the surface of the panels, but the tripod structured light scanner and photogrammetry were both able to create complete models. The main challenges that were common across all three scanning techniques were the physical limits of the cave environment. Each of the techniques also had their own limits. The handheld structured light scanner and the tripod structured light scanner tended to have trouble with the glossy areas

of the panels. The tripod structured light scanner was limited by the line of sight, which meant that scanning the ledge feature on Clay Panel 3 was a significant challenge. The challenges that faced photogrammetry were largely the physical constraints of the cave. However, the post-processing of the photos and the creation of the 3D model required a powerful computer to run the software for several hours. All of the 3D scanning techniques that were tested had limits but understanding how these limits would influence their use in the field suggests the challenges posed by photogrammetry was the most easily solved.

My second sub-question was whether the measurements taken from the 3D models were accurate. To answer this, I looked at the difference between the measurements taken from the panel in person and the measurements taken from the 3D models created by the tripod structured light scanner and photogrammetry. Since the study of finger flutings relies on three-fingered measurements that are rounded to the closest millimeter, the average error for the structured light scanner, ± 0.234 mm for the plaster panel, and ± 0.325 for the clay, and the average error for photogrammetry, ± 0.178 for the plaster panel, and ± 0.153 for the clay, were negligible. Although the difference between the panels and the 3D models met the research requirements, I tested whether the measurements taken from the panel in person and the measurements taken from the 3D models were statistically different. To do this, I conducted a paired t-test. The results of this test showed that none of the locations measured showed a statistically significant difference, confirming the accuracy of the 3D models.

My last research sub-question which of the 3D scanning techniques tested best met the research requirements of finger fluting studies. I assessed each of the scanning techniques based on cost, portability of equipment, accuracy of the system, productivity of the technique, skill

requirements, and compliance with data requirements. Each of the techniques had their own strengths and merits, but photogrammetry met each of the criteria the best.

The results of my sub-questions lead me to conclude that: Photogrammetry creates high-resolution, high-accuracy models of finger fluting panels. It is a portable, cost-efficient 3D digitization system that can be exported into accessible file types. Of the three methods tested, it is the method of 3D documentation that best meets the requirements of accuracy, portability, and data.

In the next chapter, *Discussion and Conclusion*, I will bring in outside sources in combination with my own observations in order to expand on these results. Additionally, I will outline potential applications of my research and the overall significance.

Chapter 6: Discussion and Conclusion

Introduction

3D digitizing rock art is relatively common practice for researchers today (Davis et al., 2017; Domingo et al., 2013; Fernández-Lozano et al., 2017; González-Aguilera et al., 2009; Lerma et al., 2010; López et al., 2016). The application of 3D digitization to a finger fluting cave was attempted in the past by Zlot and Bosse (2014) but the resulting model did not produce the accuracy required for proper analysis of the fluting streams in the model.

The results of my experimental project are a starting point in understanding how 3D scanning techniques can be applied to finger flutings. In testing three different methods of 3D digitization, I am able to better understand the strengths and weaknesses of tripod structured light scanners, handheld structured light scanners, and photogrammetry. Understanding the challenges and the limits to 3D scanning experimentally produced finger fluting panels is an important step to choosing the most appropriate method to document finger flutings *in situ*. The 3D models of the fluting panels have accuracy requirements that need to be tested, since analysis of finger flutings relies on measurements of three-fingered flutings that are accurate to the millimeter. In this chapter, I discuss my results in detail and how some of the challenges that arose during my experiment can be overcome in future research.

3D scanning finger fluting panels is only the first step in applying 3D technologies to finger fluting research. In the discussion portion of this chapter, I look at how other researchers have used 3D models in their analysis of rock art and how this can be applied to the study of finger flutings. 3D scanning techniques are a useful tool for archaeologists to gain insight into rock art and other archaeological research. It is important to understand how 3D models can contribute to our larger research questions and the forms of analysis that we are interested in.

R1: There are many method specific challenges to 3D scanning, but some challenges are common across all three techniques that were tested.

Each of the three 3D scanning techniques that were tested had their own method specific challenges. It is important for researchers to be able to deal with the challenges that arise in order to apply these techniques *in situ*. While there are steps that can be taken during the documentation process that can help deal with some of the challenges that arise, the best way to document finger fluting sites is through combining the different 3D scanning techniques.

The main challenges across all three scanners was the challenge of space. I took some steps in my experiment to mimic the cave environments and the potential physical challenges, but it is difficult to completely account for this challenge without examining the specific caves that are being documented. Each of the finger fluting caves that have been studied has its own challenges that need to be accounted for. In addition to that, each of the 3D scanning techniques that were tested had its own physical limitations as well. Photogrammetry requires photos of the object from a variety of angles, which can be inhibited by the cave. In cases where photogrammetry cannot be used, there is potential to apply structured light scanning techniques. Handheld structured light scanners only require the researcher to run the scanner over the surface until data collection is complete. While handheld SLS techniques struggle with larger objects and surfaces without clear landmarks, they can deal with some of the physical challenges that limit other techniques. Although current handheld SLS have problems scanning surfaces without clear landmarks, future software and hardware development may increase the program's ability to identify unique markings on scanned surfaces.

Tripod structured light scanners need to be set down on the ground in order to operate, but it is possible to reach tight/challenging spaces by attaching articulated arms. In their scan of

the footprints in Pech-Merle, Pastoors et al. (2017) used a structured light scanner attached to a tripod and a long extension arm to avoid contact with sensitive surfaces and reach the areas of interest. Other researchers have combined Unmanned Aerial Vehicles (UAV) with photogrammetry to produce 3D models of archaeological sites. López et al. (2016) used UAVs and photogrammetry to create photorealistic 3D models of architecture at the megalithic necropolis of Panoría. The process of 3D documentation with the UAVs took around 3 hours of data collection compared to the 34.5 hours that it took to complete detailed ground plans of the tombs using traditional hand-drawn methods. In addition, they found that the 3D model was 10 times more accurate than hand-made drawings (López et al., 2016). Depending on the challenges present at a finger fluting site, advances in 3D digitization technologies such as extension arms and UAVs can potentially mitigate the physical constraints of the cave.

When documenting my experimental panels, I came across the issue of computer processing power. In particular, the creation of 3D point clouds from photographs during the process of photogrammetry required computers with high processing power. The amount of time and processing power required to create a 3D model using photogrammetry is dependent on the number of photographs that are taken. In the case of the experimental panels, I took between 150 and 200 photos of each panel in order to create an extremely high-resolution model. However, since finger fluting streams are measured to millimeter accuracy, it would be possible to create a model that meets the accuracy requirements without such a large set of photos. Taking slightly fewer photos of the panel would speed up the processing of the model and require less computer processing power to complete.

Manipulating and analyzing the 3D models, regardless of the method of digitization, also required high computer processing power, especially if the model was of extremely high

resolution. In the case of my experimental panels, they were small enough that the computer processing power that was required to manipulate the model remains within the realm of accessibility for most researchers. However, larger models of high resolution require significant computer processing power. Since finger fluting sites are large cave environments, and the fluting panels themselves can cover meters in size, scans of the flutings may need to be combined in order to create the complete model, which also requires computer processing power. Lerma et al. (2010) created a high resolution, photorealistic model of Parpalló cave, but warned that most computers today are not equipped to manipulate the whole model at that level of high resolution. In order to overcome this problem of computer processing power, they suggest that the model be broken up into smaller pieces that contain areas of interest (Lerma et al., 2010). For finger fluting sites, breaking up the model of the complete cave into areas of interest could accommodate the high computer processing requirements, and models of lower resolution can be used to study the caves as a whole.

High performance computing is another potential solution for the high computing power requirements for 3D scanning. Since there is such a large quantity of data that is collected from 3D scanning technologies, employing high performance computing can speed along the processing of the 3D models. High performance computing is also known as “supercomputing”, which uses a series of connected computers that work in parallel to complete tasks much faster than would be possible with a traditional computer (White, 2017). Supercomputing can be accessed by researchers by applying for grants from programs such as the National Science Foundation’s Extreme Science and Engineering Discovery, which grants researchers access by the hour to one of the NSF’s largest computers, or through paying for access to commercial supercomputers, such as Amazon Elastic Compute Cloud, Microsoft Azure, and Google

Compute Engine (White, 2017). Such supercomputers could complete the required processing of the 3D model in a fraction of the time it would take on a traditional desktop computer and could be a viable solution to some of the challenges of computing power present in 3D documenting finger flutings.

R2: 3D models are an accurate representation of the finger fluting panel.

While none of the measurements taken from the model were statistically significantly different from the measurements taken in person based on the T-test results, all the measurements had some degree of error. The reason for this error was likely not due to inaccuracies of the model, but rather due to human error in the measurement process. The panels are abstract and usually non-representative, and fluting widths vary even within a single stream. Even with a marker placed on the surface of the panel, finding the exact same location to measure proved to be a challenge. This can be observed in the variability of the measurements taken from the model in person. Since *in situ* measurements of finger flutings cannot involve putting markers on the surface, 3D models can provide consistency in measurement locations, since virtual markers can be placed on the models and labelled to show where each measurement was taken.

R3: Photogrammetry was the method of 3D digitization that was the most appropriate in documenting finger fluting panels.

Of the three methods of 3D scanning that were tested, photogrammetry was the most successful in documenting the experimental finger fluting panels. Photogrammetry is a technique that is relatively inexpensive, highly portable, created accurate and high-resolution models that can be exported into a variety of file types that are accessible to other researchers. However, although photogrammetry produced the best results of the 3D scanning techniques that I tested,

this experiment does not preclude that other methods of 3D scanning can also be applicable to the study of finger flutings. Additional testing of different 3D scanners will provide further insight into how contemporary 3D scanning technologies can tackle the challenges posed by finger flutings.

While photogrammetry was the best option to document my relatively small experimental panels in detail, *in situ* the 3D documentation of finger flutings would likely require a combination of techniques. Photogrammetry is usually used in close range to document objects in high resolution in combination with a large-scale method of 3D scanning (Domingo et al., 2013; Fernández-Lozano et al., 2017; Lerma et al., 2010). Combining the two methods would expedite the process of 3D documentation. Terrestrial laser scanners are able to capture larger areas quickly in relatively low resolution. Using TLS to capture the cave environment, and photogrammetry to fill in details of the fluting panels would allow researchers to combine the two techniques for optimal efficiency and resolution.

Ultimately, the results of this experimental project show that photogrammetry is a highly accurate and efficient method to capture the details of finger flutings panels in 3D. It is able to overcome many of the challenges that researchers encounter within the cave environments and meet the budgetary and data requirements. However, the optimal method to document finger fluting sites in its entirety is to combine close range photogrammetry with a large-scale scanner, such as a terrestrial light scanner, or a larger structured light scanner.

Combining 3D Scanning Techniques:

Combining two or more methods of 3D documentation allows researchers to overcome the limits of specific 3D scanning techniques. Since each digitization system uses different techniques to collect the 3D data, combining two or more of the methods can help account for

some of the limits of one single method and fill in the gaps in data collection that may arise as a result. For example, laser scanners or structured light scanners would work better in low-lighting situations but may not be able to capture the detail of reflective surfaces. In such cases, photogrammetry can be used to model the details of those surfaces and the resulting mesh or point cloud model can be combined later in editing software.

Researchers have successfully combined different 3D scanning techniques in order to produce complete 3D models. Different 3D scanning techniques are combined to account for the weaknesses of each technique. Lerma et al. (2010) combine Terrestrial Light Scanning (TLS) with close range photogrammetry in order to create a 3D model of the Upper Paleolithic cave of Parpalló. The researchers used a TLS system to capture the large-scale structure of the cave and close-range photogrammetry in order to record the details of the rock art and engravings. Since 3D models created by 3D scanners are either point clouds or meshes created from polygons, they further added textural details to the models by using photographs that were taken on site. This created a high-resolution model that is photorealistic. Domingo et al. (2013) also combined TLS and close-range photogrammetry in order to document rock art at Cingle de la Mola Remigia. Fernández-Lozano et al. (2017) created a photorealistic model of two rock shelters in the southwestern area of León that contains three panels of Castrocontrigo Neolithic rock art. They used a combination of handheld, white light, structured light scanning (SLS) and photogrammetry to produce their model. Since the area of study contained complex topography, which included steep hills and overhanging rock shelters that would make TLS and other traditional topographic survey methods challenging, the researchers chose to use a calibrated white light SLS. They used the 3D point cloud produced from the white light SLS as a reference to constrain the accuracy of the photogrammetric approach (Fernández-Lozano et al., 2017). The

combination of the two techniques produced a high-resolution 3D model that allowed them to analyze previously unexplored details. The successes of these 3D documentation projects show that the combination of close range photogrammetry another digitization system can overcome the challenges present in the field. These examples show that the combination of two or more 3D documentation methods help overcome the limits of a single method of 3D documentation.

Applications and Future Steps:

The creation of an accurate 3D model of finger flutings is the first step in the application of 3D technologies to finger fluting research. It is important to consider how the creation of a 3D model furthers research goals. Once we have a model, what do we do with it? The creation of a 3D model of a finger fluting panel would allow researchers to take more accurate measurements and set down markers for replicability of measurements. But there are several other potential research applications of 3D finger fluting models.

Researchers can interact with 3D models in ways that may not be possible in the field. In the case of rock art research, the models can be scaled, rotated, and illuminated to examine details and potentially reveal previously unknown information (Lerma et al., 2010). The results of these rotated 3D images can then be captured in 2D and imported into different software, such as GIS, for example, for further analysis. The model itself can be imported into software such as AutoCAD and arcGIS, which allows researchers change the lighting surrounding the models, add colours to the models, and with the help of 3D viewfinders, see what is visible from a given location (Domingo et al., 2013). Researchers can apply other methods of analysis, such as computer vision to the models.

Since one of the main limits to the study of finger flutings is access to the finger fluting caves, producing an accurate, photorealistic 3D model of the site can give researchers virtual

access to the site. Researchers can virtually go back to an area of interest in the 3D model, increase the scale for more detailed analysis, and take a 2D image from the model. Increasing the accessibility of finger fluting sites can provide more opportunity for research.

Carrero-Pazos et al. (2018) created scaled 3D models of prehistoric rock art panels in Galicia, Northwest Iberia through photogrammetry. Researchers then applied oblique lights over the 3D models, in order to study the motifs present. They also exported the model into MeshLab, an Opensource software that allows researchers to manipulate 3D models, and used a technique called Radiance Scaling, which adjusts reflected light intensities depending on the surface curvature and the characteristics of the material (Carrero-Pazos et al., 2018). This manipulation of the 3D model revealed motifs on the surfaces of the rock art panels that were not previously visible. They then applied exaggerated shading techniques that were inspired by methods for cartographic terrain relief and through this analysis, they discovered even more motifs that were previously unknown. Once these motifs were found, they were traced digitally by the researchers and added to previously known motifs to create a more complete image.

Manipulating the lighting and applying exaggerated shading techniques to 3D models of fluting panels may reveal flutings that are not as visible within the cave environment. Since some sites, such as El Castillo, have fluting streams that have been damaged by contemporary interactions (Van Gelder, 2015), applying exaggerated shading techniques to 3D models of these panels may show insight that was previously unknown.

Domingo et al. (2013) 3D scanned Levantine rock art at Cingle de la Mola Remigia and discussed the various methods that the 3D model aids in their analysis. They were able to take digital tracings of each rock art motif and isolate it from the rock surfaces. Such 2D tracings are useful to identify faded motifs and distinguish images that are superimposed on top of each

other. They also used the 3D model to study the spatial relationship between the motifs at the site and the relationship between the motif and the surfaces of the rock. This analysis allows researchers to study technical limitations of the rock surface and how that may have influenced decision making in the execution of panels, compositions, and scenes (Domingo et al., 2013). They also used the 3D model to gain multiple viewpoints of the same motifs and replicate the composition and motifs that an observer standing at certain locations in the rock art site would theoretically see.

Much of the analysis that Domingo et al. (2013) did on their 3D model of the rock art at Cingle de la Mola Remigia can be replicated on 3D models of finger fluting sites. Finger flutings are particularly interesting because researchers can identify the individuals who created the streams, as such, being able to digitally trace the streams and isolate each individual and study the spatial relationships between their flutings can give insight into how that individual moved through the cave. This form of analysis has been done by Sharpe and Van Gelder (Van Gelder, 2015) using the traditional methods of analysis but being able to view the cave in its entirety through the 3D model may provide additional insights. Digitally tracing the fluting streams and isolating them from the cave surfaces allows flutings streams to be compared to each other. This can give insight into a fluter's fluting idiosyncrasies –for example, studying the average length of a fluting stream by produced by one individual or other patterns that may arise through this analysis.

Domingo et al. (2013) use their 3D model to study the relationships between the rock art and the rock surfaces that they are located on. Finger flutings studies may also benefit from a similar approach: how fluters interact with certain characteristics of cave surfaces, such as protrusions and changes in the thickness of the moonmilk, to see how these characteristics

influence the process of fluting. Understanding how the surfaces limited flutings can provide additional insight into how fluters were interacting with their surroundings.

Perhaps one of the most intriguing applications of 3D modelling finger fluting caves is the potential to analyze the flutings from multiple viewpoints. Since the amount of time researchers can spend in finger flutings caves is limited, and the areas that can physically be accessed is also often limited, the 3D model provides an opportunity for researchers to study what theoretically would be visible to an observer standing at a certain location in the cave. The lighting of the model can be adjusted to study how that affects the visibility of the flutings. Since the flutings are usually abstract in nature, studying what an observer may have been able to see may provide insight into the purpose of and practices surrounding finger flutings.

Once the 3D models of finger flutings panels are produced, software can be written to aid in more efficient analysis of the flutings. For example, computer vision approaches may be able to aid in identifying individuals as software can be written to identify three-fingered fluting streams of specific widths. Geometric morphometric approaches were used by Nelson et al. (2017) to predict the sex of individuals who created hand stencils with over 90% accuracy. They used landmarks on the fingers and palms of the stencils to accurately determine the sex of the individual. Similar analysis of finger flutings may yield additional information about the identity of individual fluters based on landmarks that may be identified by analyzing the fluting streams in 3D.

Data Storage

One aspect of generating 3D models that requires careful consideration is the curation of digital data. Once a 3D model is generated, it needs to be carefully stored in order to aid future research. Lerma et al. (2010) comment that data should be stored in digital form at maximum

resolution. The data should be saved on different media, not only of the final product, but also the original raw data without compression. Such careful storage of data allows future manipulation and editing of data without the need to return to the site. They suggest that the data is exported into different formats, suggesting that public formats, such as LASer (LAS) file format, are better to guarantee performance and integrity (Lerma et al., 2010). Since the goal of my project is to aid in open access science, I decided to upload the 3D models created during the experiment to a public repository, SketchFab (<https://sketchfab.com/>) that allows people to interact with the models online.

Creating the 3D model of a finger fluting site is only the first step in applying technological advances to the study of finger flutings. The models can be manipulated and analyzed in ways that would not be possible *in situ*. However, beyond the 3D documentation of the finger flutings, considerations towards data storage are also important due to the large quantity of data that is gathered when creating 3D models. Creating 3D finger fluting sites is not simply about creating the model and therefore, it is important to consider the steps that are taken to analyze and store the information.

Summary of Research:

One documented attempt has been made in the past to create a model of a finger fluting cave site. This attempt by Zlot and Bosse (2014) used a portable laser scanner that created a 3D model of Koonalda cave with centimeter accuracy. While this scanner was able to capture the cave formation, there was not enough accuracy to do in depth analysis of the flutings, since they are measured in millimeters. In their paper, they suggest that photogrammetry would be able to produce high resolution 3D models that would be able to document the finger flutings. The results of my experiment show that, of the three methods of 3D digitization tested,

photogrammetry was the most effective in creating a 3D model of my small, experimental panels. Since my main research goal was to determine the most appropriate method of 3D scanning finger fluting panels *in situ*, I broke down my research questions to address the main challenges and limits of 3D scanning finger flutings, the accuracy of 3D digitization as a whole, and ultimately what the most appropriate 3D scanning technique is for the project at hand.

Through the experiment, I found that each method of 3D digitization came with its own set of challenges, but the main challenges to 3D scanning finger flutings were the physical limitations of the cave environment and this was common across tripod SLS, handheld SLS, and photogrammetry. Overall, photogrammetry was most successful in overcoming the physical challenges of the cave, since the digital camera has high portability. On the other hand, the other two methods of digitization that I tested were not as successful, but this was due in part to the equipment that I was testing. There are forms of tripod structured light scanning that can be maneuvered into challenging spaces with extension arms or unmanned aerial vehicles.

Through the documentation of the experimental panels, I found that the resulting 3D models were all highly accurate. The results of the T-test showed that there was no significant difference between the sets of measurements taken from the panel in person and the measurements taken from the model. Since the models are scaled from objects of known length within the 3D scan, having an accurate scale plays an integral role in the accuracy of the overall model.

From the results of my experimental project alone, photogrammetry is the most appropriate method to 3D digitize finger fluting panels. It is a cost-effective method of 3D digitization that does not require significant amounts of time in the field to use. It is also highly portable, accurate, and can be exported into files that are accessible to other researchers.

However, my experimental panels are of a much smaller scale than whole finger fluting caves. In the cave setting, it is important to capture the entire cave formation in order to contextualize the occurrences of the finger flutings. With such a large-scale object to be documented, combining photogrammetry with a method of 3D digitization that can rapidly capture large scale models would produce the best results. Terrestrial laser scanning, for example, would be able to quickly capture the cave formation in lower resolution. TLS in combination with photogrammetry would be a time efficient method to produce a complete 3D model of a finger fluting cave site.

Conclusion

3D scanning technologies are a popular topic amongst rock art researchers. Not only are 3D models visually compelling, they provide opportunities for researchers to learn even more about the objects that they are documenting. A 3D model of finger fluting sites are opportunities for researchers to interact with the fluting panels and fluting streams in new and exciting ways that are unavailable in traditional documentation and research methods. Since finger flutings are usually non-representative, our analysis of them is based on measurements and observations. With the creation of a high-resolution 3D model, more detailed observations and measurements can be taken from finger fluting panels that would previously been impossible.

The process of finger fluting was a Pleistocene mark making activity that involved males, females, adults and children. Although we are only able to clearly determine the sex of the individuals that created the fluting streams, researchers also infer that this is also representative of gender. The act of finger fluting was an interaction between an individual, his/her environment, and male and female fluters of various ages. The act of finger fluting is both part of the embodied experience of living in the Pleistocene and a part of the Pleistocene visual culture

and can therefore tell us twofold about what it was like to live in the Upper Paleolithic. Learning more about the fluters, their identities, and the cultural practices surrounding finger flutings helps us uncover more about how Upper Paleolithic individuals lived in and looked at the world around them.

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Appendix A

Figure 13. Plaster panel 1.



Figure 14. Plaster panel 2 with gloss.



Figure 15. Plaster panel 3.



Figure 16. Clay panel 1.



Figure 17. Clay panel 2.



Figure 18. Clay panel 3 with gloss.

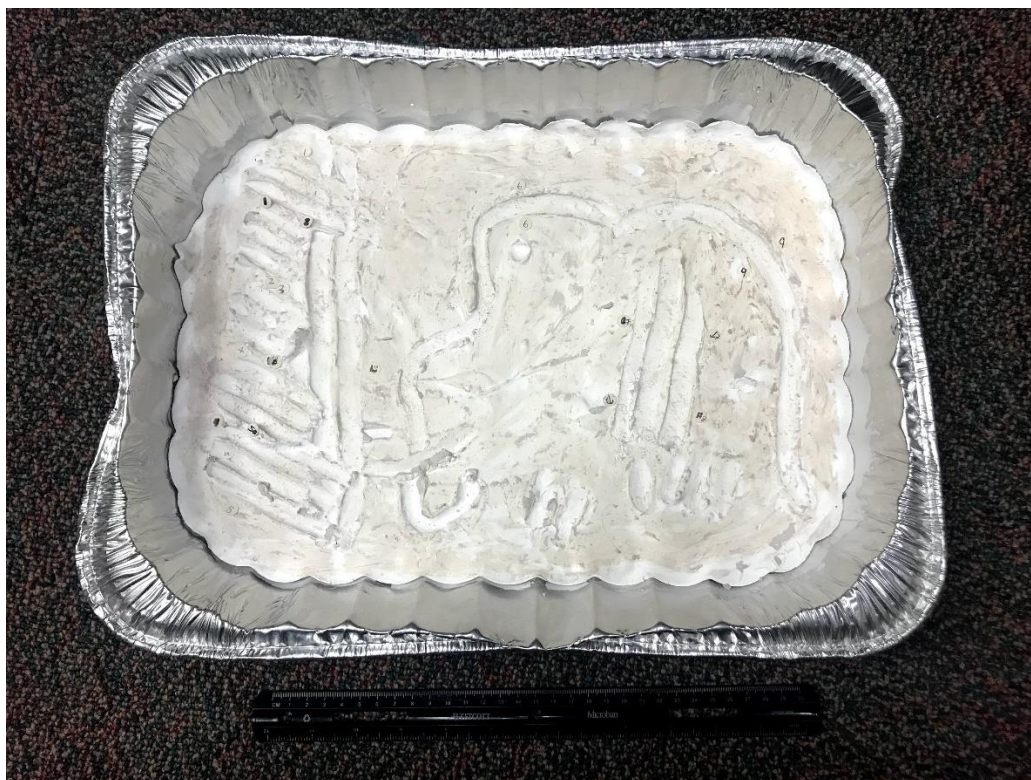


Figure 19. Plaster with clay panel 1.



Figure 20. Plaster with clay panel 2.

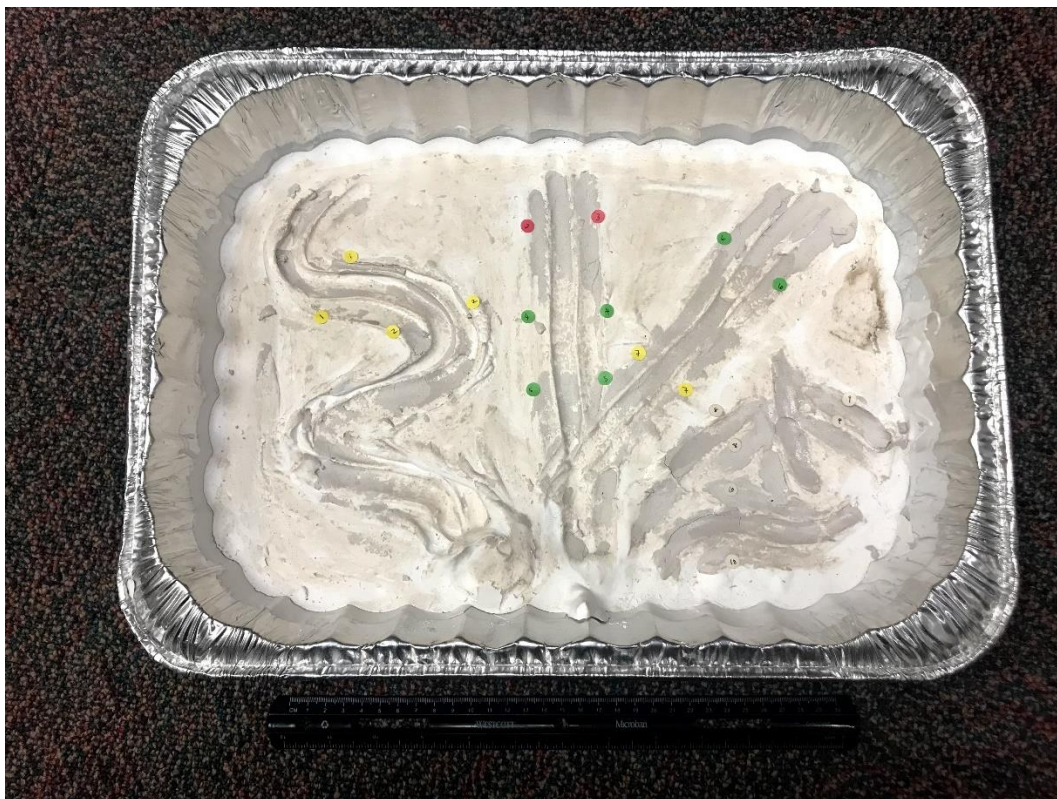


Figure 21. Plaster with clay and glass panel 3.



Figure 22. Plaster panel 1 with marked measurement locations.



Figure 23. Plaster panel 2 with marked measurement locations.

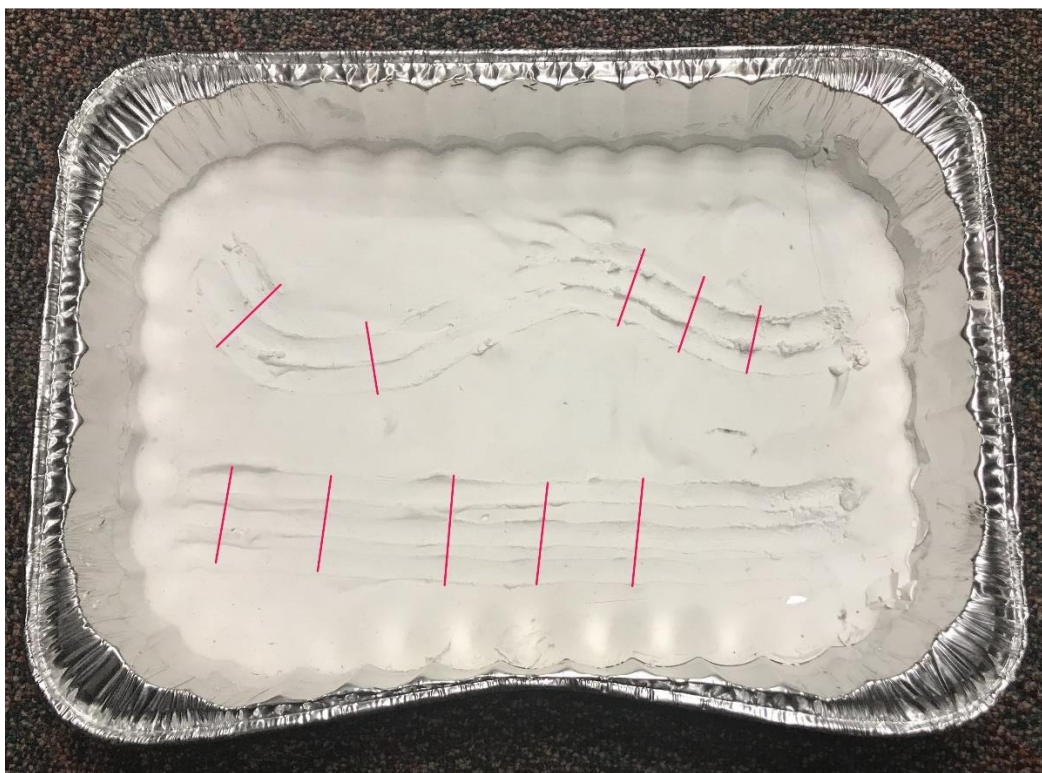


Figure 24. Plaster panel 3 with marked measurement locations.

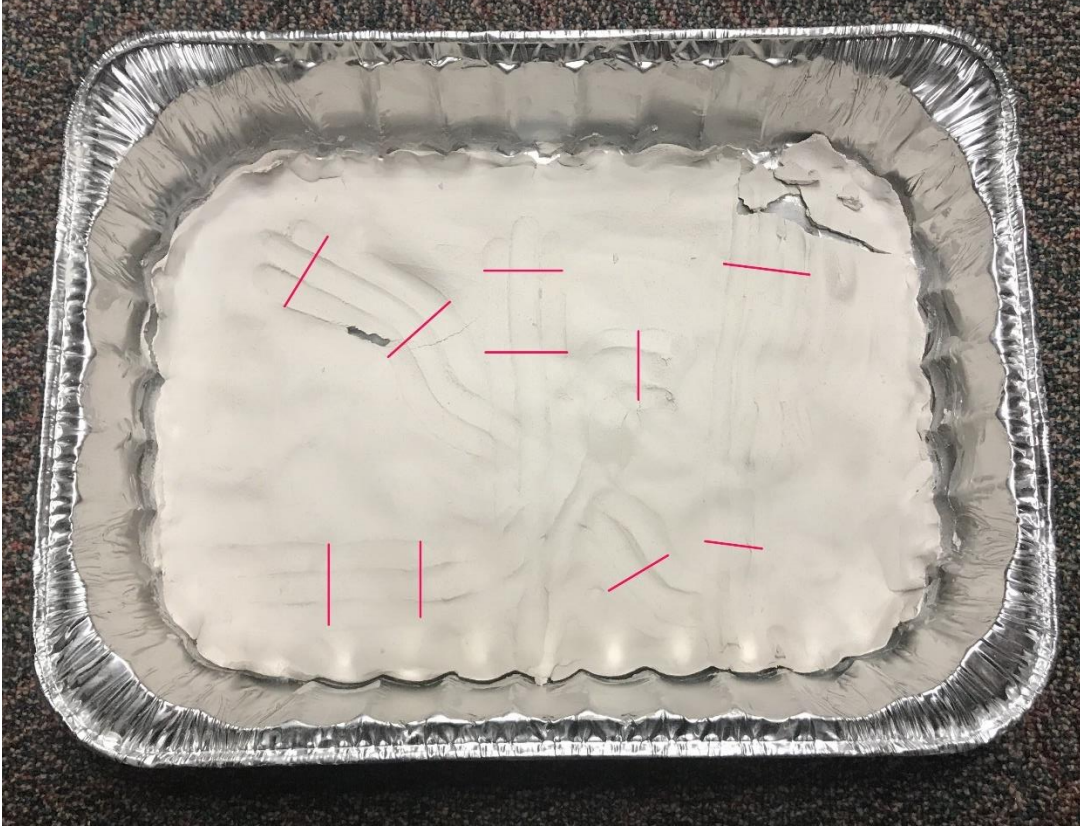


Figure 25. Clay panel 1 with marked measurement locations.

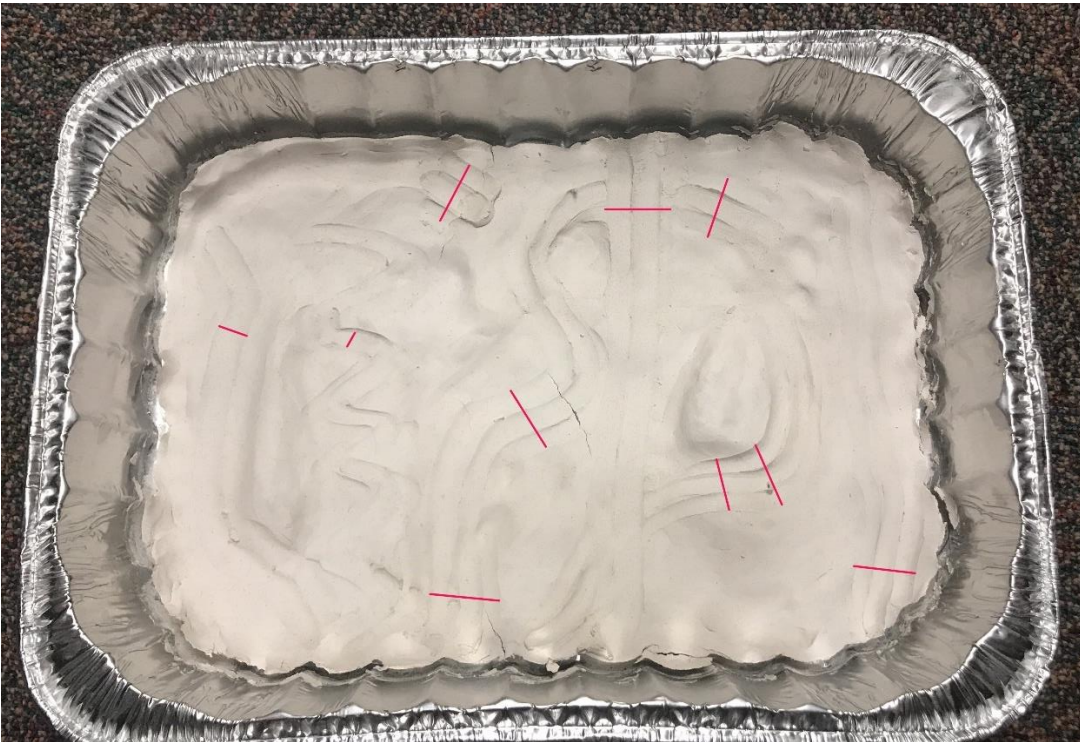


Figure 26. Clay panel 2 with marked measurement locations.

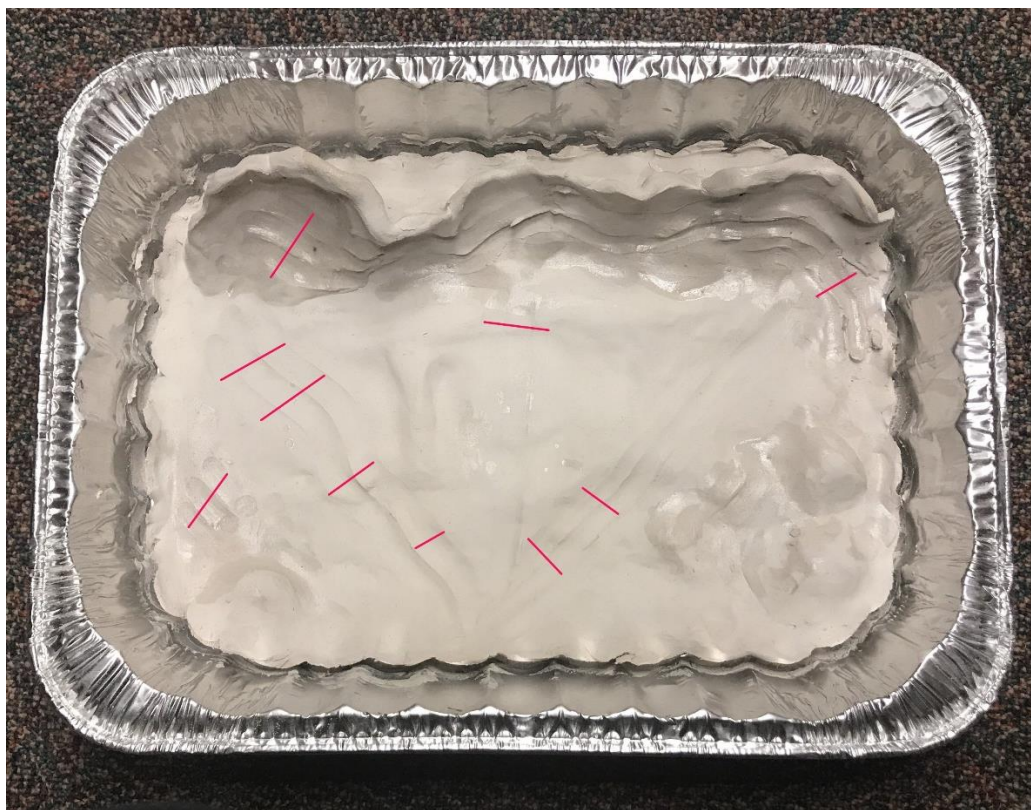


Figure 27. Clay panel 3 with marked measurement locations.

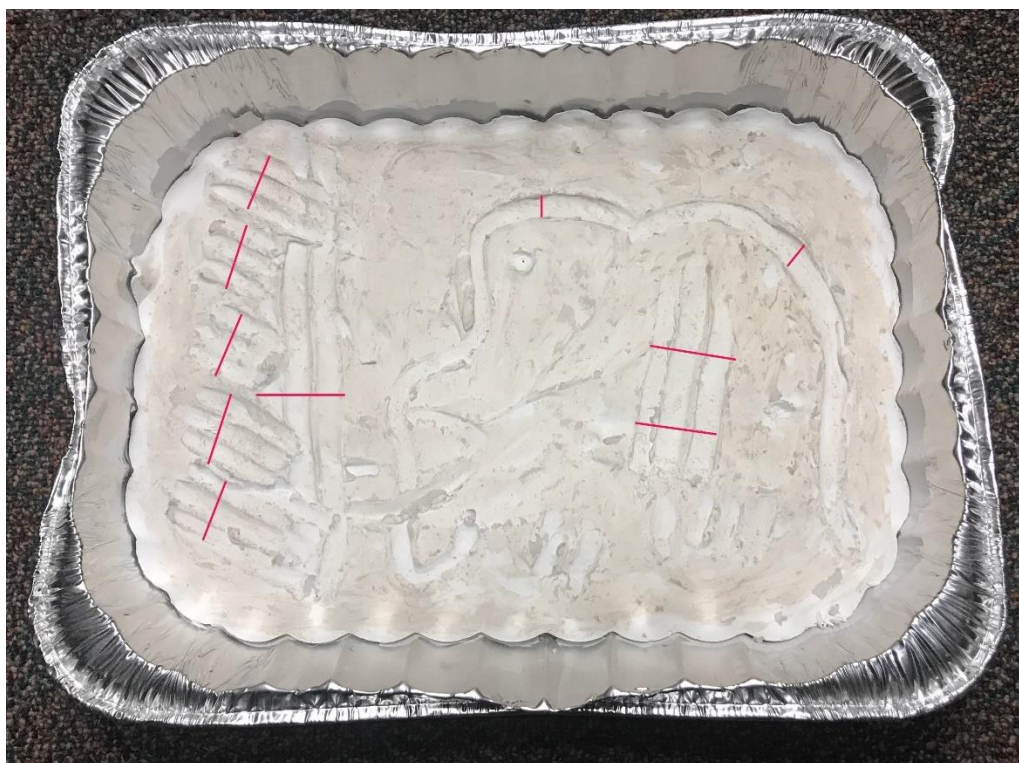


Figure 28. Plaster with clay panel 1 with marked measurement locations.

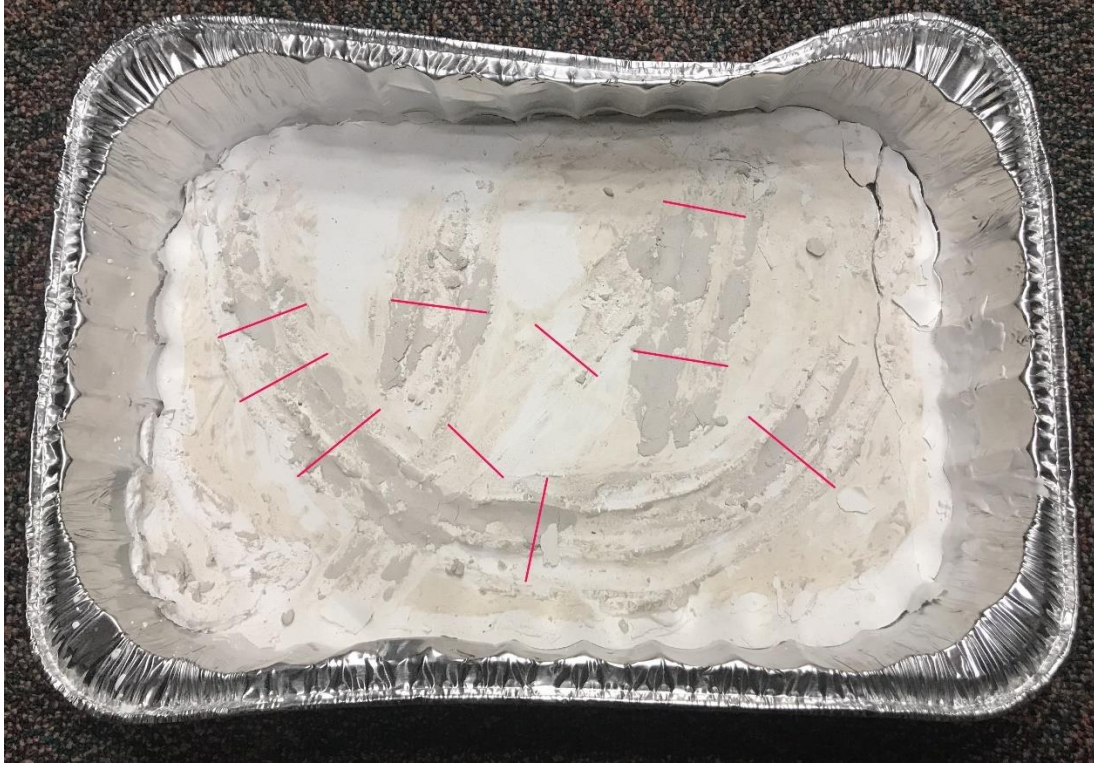


Figure 29. Plaster with clay panel 2 with marked measurement locations.



Figure 30. Plaster with clay panel 3 with marked measurement locations.

Appendix B

Table 6.

Measurements taken from 10 locations on plaster panel 1 in person.

LOCATION	1	2	3	MEAN
1	33.37	32.99	33.5	33.2866667
2	33.74	33.3	33.76	33.6
3	44.71	44.88	44.38	44.6566667
4	27.35	27.98	27.99	27.7733333
5	31.82	31.18	31.29	31.43
6	33.19	33.3	32.92	33.1366667
7	35.51	35.33	34.45	35.0966667
8	35.9	36.4	35.8	36.0333333
9	36.7	36.25	36.47	36.4733333
10	39.83	38.96	38.91	39.2333333

Table 2.

Measurements taken from 10 locations on the structured light scanner produced 3D model.

LOCATION	1	2	3	MEAN
1	33.5	33.6	33.4	33.5
2	33.7	33.6	33.3	33.5333333
3	44.5	44.3	44.5	44.4333333
4	27.7	27.6	27.7	27.6666667
5	31.8	31.6	31.4	31.6
6	33	33.2	33.6	33.2666667
7	35.1	35.9	35.8	35.6
8	36.6	36.5	36.3	36.4666667
9	36.4	36.7	36.5	36.5333333
10	39	38.7	38.7	38.8

Table 3.

Measurements taken from 10 locations on the SfM photogrammetry produced 3D model.

LOCATION	1	2	3	MEAN
1	33.7	33	33.5	33.4
2	33.5	33.7	33.2	33.4666667
3	44.3	44.3	44.5	44.3666667

4	27.4	27.3	27.8	27.5
5	31.9	31.2	31.4	31.5
6	32.9	33.2	33	33.03333333
7	35.2	35.7	35.5	35.46666667
8	36.6	36.1	36.3	36.33333333
9	36.5	36.5	36.5	36.5
10	39	39.7	38.7	39.13333333

Appendix C

Table 1

Technical specifications of the computer used to process the photogrammetry models.

Feature	Computer Specifications
Central processing unit (CPU)	Intel - i7-774X (Overclocked to 4.6 GHz)
Memory	Vengeance 16GB DDR4-3000
Storage	Samsung – 960 EVO 500GB M.2-2280 SSD
Graphics processing unit (GPU)	GeForce GTX 1050 Ti 4GB
Motherboard	Asus – PRIME x299-A ATX LGA2066

Table 2

Technical details of the Creaform Go!Scan 20.

Feature	Go!Scan 20
Accuracy	Up to 0.100 mm
Resolution	0.100 mm
Measurement rate	550,000 points /s
Scanning area	143 x 108 mm
Stand-off distance	380 mm
Depth of field	100 mm
Working Range	0.05 – 0.5 m
Weight	930 g
Dimensions	154 x 178 x 235 mm
Operating temperature range	15- 40 ° C
Operating humidity range	10-90%

Note. Data gathered from <https://www.creaform3d.com/en/metrology-solutions/handheld-portable-3d-scanner-goscan-3d>

Table 3

Technical details of the LMI HDI 120 3D Scanner. MAKE SURE TO KNOW THAT THIS NEEDS TO BE PLUGGED IN AND WHY THIS WAS TESTED (when we don't have access to plug-in)

Feature	HDI 120 3d Scanner
Accuracy	60 – 118 microns
Resolution	0.11 mm
Acquisition speed	328,3000 points /s
Scanning area	124 x 120mm to 192 x 175mm
Stand-off distance	300 mm
Depth of field	180 mm
Working Range	0.3 m
Weight	1.35 kg
Dimensions	49 × 74 × 276 mm
Operating temperature range	0 – 50 ° C
Operating humidity range	25 – 85%

Note. Data gathered from <https://www.aniwaa.com/product/3d-scanners/lmi-technologies-hdi-120/>

GLOBAL ROCK ART DATABASE –REPOSITORY FOR 3D MODELS

MEASUREMENT RESULTS (present more data)