NO ROSE WITHOUT THORNS:
ASSESSING 3D SCANNING METHODS IN ARCHAEOLOGY THROUGH CASE STUDIES FROM ḪATTUŠA

A Master's Thesis

by
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Ankara
August 2023

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To my grandfather

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The Graduate School of Economics and Social Sciences
of
İhsan Doğramacı Bilkent University

by

YİĞİT PEKZEREN

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By Yiğit Pekzeren

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Arts in Archaeology.

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ABSTRACT

NO ROSE WITHOUT THORNS: ASSESSING 3D SCANNING METHODS IN ARCHAEOLOGY THROUGH CASE STUDIES FROM ḪATTUŠA

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Over the last two decades, 3D scanning has become an increasingly important tool in archaeology, and it has seen steady growth in practical applications. However, despite this new wave of experimentation and integration of 3D methods in archaeological routines on a global scale, they are still rarely part of research in Turkey. The first main aim of this thesis is therefore to showcase the advantages of these techniques to help develop a community of 3D scanning users in this country through the employment of the exceptional work at Ḫattuša as a case study. The second aim is to assess what the best 3D tools according to research questions, availability of expertise, and budget actually are.

The case study revolves around the "Ḫattuša Project," which features 3D scanning of significant archaeological and landscape features, including Nişantaş and the nearby Chamber 2, Yazılıkaya, the gorge between Büyükkaya and Ambarlıkaya, and the Great Temple. The methods used in the project provide useful arenas for investigating the strengths and weaknesses of the 3D approaches across different questions related to epigraphy, art history, architecture, and landscape archaeology. After presenting and assessing the application of 3D techniques at Ḫattuša, I evaluate the most commonly used 3D scanning techniques in archaeology, such as laser scanning, structured light scanning, and photogrammetry, according to several parameters, including data accuracy, price, learning curve, and ease of use. This allows me to identify the best practice to include 3D tools in archaeological fieldwork and research routines. It also provides an opportunity to discuss the potential shortcomings of current 3D methods and to identify areas where new technologies may significantly improve current products.

Keywords: 3D scanning, digital archaeology, photogrammetry, Hattusa, LiDAR

ÖZET

GÜLÜ SEVEN DİKENİNE KATLANIR: 3B TARAMA YÖNTEMLERİNİN ḪATTUŠA VAKA ANALİZLERİ ÜZERİNDEN DEĞERLENDİRİLMESİ

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Arkeolojinin son yirmi yılında, 3B tarama giderek daha önemli bir araç haline geldi ve pratik uygulamaların sayısında istikrarlı bir artış görüldü. Buna karşın, 3B yöntemler dünya çapında sıklıkla denense ve arkeolojik rutine entegre edilse de Türkiye'deki araştırmalarda hala nadiren yer almaktadır. Bu nedenle bu tezin ilk ve temel amacı, Ḫattuša'daki istisnai projeyi bir vaka çalışması olarak kullanarak, Türkiye’de 3B tarama çalışmalarının sayısını artırmaya yardımcı olmak için bu tekniklerin avantajlarını sergilemektir. İkinci amaç ise farklı araştırma soruları göz önünde bulundurularak, uzmanlık ve bütçe durumuna göre en iyi 3B araçların hangileri olduğunu değerlendirmektir.

Vaka çalışmaları, Nişantaş ve yakınındaki 2 No’lu Oda, Yazılıkaya, Büyükkaya ile Ambarlıkaya arasındaki vadi geçidi ve Büyük Tapınak gibi önemli alanlardaki arkeolojik ve peyzaj özelliklerinin 3B taramasını içeren "Ḫattuša Projesi" etrafında şekillenmektedir. Projede kullanılan yöntemler, epigrafi, sanat tarihi, mimari ve peyzaj arkeolojisi ile ilgili farklı sorularda 3B yaklaşımların güçlü ve zayıf yönlerini araştırmak için yararlı örnekler olarak öne çıkar. Bu tezde, Ḫattuša'daki 3B uygulamalar tanıtıldıktan ve değerlendirildikten sonra, lazer tarama, yapılandırılmış ışık taraması ve fotogrametri gibi arkeolojide en yaygın kullanılan 3B tarama teknikleri veri doğruluğu, fiyat, öğrenme ve kullanım kolaylığı gibi çeşitli parametrelere göre analiz edilmiştir. Bu sayede 3B araçları arkeolojik saha çalışmalarına ve araştırma rutinlerine dahil etmek için en uygun uygulamalar belirlenebilmiştir. Ayrıca tez, mevcut 3B yöntemlerin potansiyel eksikliklerini tartışma ve yeni teknolojilerin mevcut araçları önemli ölçüde geliştirebileceği alanları belirleme fırsatı da sunuyor.

Anahtar Kelimeler: 3B, dijital arkeoloji, fotogrametri, Hattuşa, LiDAR

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CHAPTER 1

INTRODUCTION

1.1. Scope and Aims

The rapid development of data processing and optical technologies over the last few decades has paved the way for 3D scanning and modeling tools that have the potential to be very useful for many different commercial and academic fields (Campana, 2014: 7; Oguchi, Hayakawa & Wasklewicz, 2011: 197). Archaeology inherently requires documentation at different scales, surfaces, and objects. From massive architectural and geographical themes to small pottery sherds that occupy only a few cubic centimeters of space, archaeological documentation involves many targets of research (see Siart, Forbringer, & Bubenzer, 2018). Although most archaeological foci can be recorded by manual measurement, drawing, and description methods, different 3D scanning instruments using different technologies can take fruitful and functional records of these elements. Firstly, the 3D scanning tools digitally preserve research objects to ensure their existence for future generations, even if the original artifacts are lost. Secondly, these tools enable researchers worldwide to study and collaborate remotely, overcoming geographical barriers. Additionally, the high resolution of 3D models allows detailed analysis beyond the naked eye's ability, enhancing specific features. Lastly, they facilitate the creation of 3D reconstructions for immersive virtual reality experiences, enhancing historical visualization and understanding. These benefits emphasize the significance of 3D tools in advancing archaeological research and discovery.

As a result of the increasing use of 3D methods in archaeological research worldwide, the number of 3D studies of landscapes, excavations, monuments, and materials have increased dramatically in the archaeological literature. In addition to the benefits of these tools, the widespread use of these methods has created some methodological challenges. Issues such as integrating datasets from different 3D tools or making scanning tools suitable for addressing specific research questions have found their way into some of the studies examining 3D applications (see Beraldin, 2004).

While 3D scans have been carried out by some researchers to provide purely 3D imaging (see Guidi, Remondino, Russo, Menna, Rizzi & Ercoli, 2009; Forte, Dell'Unto, Issavi, Onsurez & Lercari, 2012), for others, they have been used as a tool to access 2D (also referred to as 2.5D) topographic datasets (see Davis, Brady, Megarry &Barton, 2013). These different scanning approaches, with their different contributions to archaeological interpretation, often result in diverging implementation methods and instruments.

In line with archaeology's demand for 3D tools, major and comprehensive studies contributing to developing 3D studies as a methodological discipline have begun to appear in the literature. With the emerging trends in contemporary archaeology, such as remote-sensing applications, digital geo-archaeology, and geophysics, the theory and methodology of both laser-based and image-based 3D scanning methods have been extensively published, especially in the last decade (Heritage & Large 2009; Opitz & Cowley, 2013a; Ioannides, Magnenat-Thalmann, Fink, Žarnić, Yen & Quak, 2014; Remondino & Campana, 2014; Siart, Forbriger & Bubenzer, 2018).

3D methods can be found in some of the archaeological research projects conducted in Turkey. However, very few archaeological excavations and research projects using these methods are directed or published by Turkish archaeologists (e.g., Büyüksalih, Kan, Özkan, Meriç, Isın & Kersten, 2020). Apart from these limited number of examples, other places where 3D scans have been actively and intensively used and academically published include Çatalhöyük (Forte, 2009; Forte et al., 2012; Forte, 2014a), Sagalassos (Mueller, Vereenooghe, Vergauwen, Gool, Van & Waelkens, 2004), Ephesus (Düffort, Breuckmann, Kalasek & Quatember 2012), Kaymakçı (Roosevelt, Cobb, Moss, Olson & Ünlüsoy, 2015), Hierapolis of Phrygia (Chiabrandoa, D'Andria, Sammartanoa & Spanòa, 2018), and Pinara (Hinzen, Schreiber & Rosellen, 2013). In most of these examples, non-Turkish research teams conducted the 3D survey. In many instances, the researchers involved in 3D scanning are not regular practitioners of excavations in Turkey, but foreign teams temporarily invited to undertake the scanning work. Since these visiting 3D specialists are not necessarily specialized in Southwest Asian or Anatolian archaeology per se, two significant challenges may arise. First, it is more difficult to interpret their 3D results because they are not experts in material culture, and the scanning procedures may not be fully tailored to answer the archaeological research questions. Second, they are less likely to invest in creating a new generation of Anatolian archaeologists (Turkish and foreign) familiar with 3D scanning methods. Based on these observations, it can be said that 3D archaeology is not yet firmly established in Turkey and that these methods have not yet taken a firm and strong hold in Turkish archaeology.

This thesis evaluates the practicality and potential benefits of 3D scanning concepts and equipment in archaeological contexts, as well as their weaknesses and problematic aspects. In addition, questions such as the suitability of these techniques for different purposes and the extent to which they can contribute are answered. To this end, the 3D studies conducted at Ḫattuša will be used as case studies to provide a framework for their integration into archaeological fieldwork practices and to understand why and how 3D tools have not been deeply integrated into Turkish archaeological research.

Ḫattuša offers very suitable cases for this type of work. First, it is the Anatolian site with the most extensive applications of 3D scanning, and a wide range of tools, research questions, contexts, and disciplines are involved. Second, all this work has been extensively published.

The second chapter of the thesis describes the three most widely used 3D scanning tools in archaeology, particularly the ones preferred for fieldwork, and the working principles of the equipment used for these methods (§§ 2.2.1, 2.2.2, and 2.2.3). The third chapter examines in detail four comprehensive 3D scanning cases that have been conducted at Ḫattuša since 2014, namely Nişantaş and Kammer 2 (§ 3.2.1), Yazılıkaya (§ 3.2.2), the Gorge area (§ 3.2.3), and the Great Temple (§ 3.2.4). These cases will serve as a reminder of the archaeological and historical background of the scanned areas, as well as a review of the methodology and results of the surveys. The fourth chapter provides a comprehensive assessment of the scanning methods and examines the use of the scanning methods at Ḫattuša (§ 4.2), the technical characteristics of the 3D methods themselves (§ 4.3.1), a comparison of their efficiency in the context of archaeological management issues (§ 4.3.2), selected non-3D alternative techniques (§ 4.3.3), and an assessment of the publication and display of post-application data (§ 4.3.4).

1.2. Urban Landscape of Ḫattuša

Ḫattuša (traditionally called *Ḫattuš* for the period before Hittite sovereignty) has a rich history that extends far beyond its role as the capital of the Hittite state. Even prior to its establishment as a city, the vicinity of the area that Ḫattuša would eventually occupy was home to several small settlements (Büyükkaya, Yarıkkaya, and Çamlıbel Tarlası) during the Chalcolithic period (Schachner, 2011: 35; Schachner, 2012; Schoop, 2015). Scholars believe that Ḫattuš was founded sometime during the late 3rd millennium BCE (see Bittel, 1970; Schachner, 2011: 40), and by the early Middle Bronze Age, it had become part of a long-distance exchange network that Assyrian merchants operated. A *karum* (an Old Assyrian trading post) was located in the lower town of Ḫattuša that was used by these merchants (Mielke, 2011: 174; Schachner, 2011: 44-45; Seeher, 2006b: 208).

Despite its early success, Ḫattuš was not immune to conflict. The city was involved in a confrontation with the nearby city of Kanesh and was ultimately destroyed by Anitta around the 1750s BCE. However, it appears that Ḫattuš was soon reoccupied and continued to grow and develop over time. In fact, later, Hattusili I made Ḫattuša the capital of the Hittite state (see Figure 1) (Schachner, 2011: 52-54) and continued with this role until the downfall of the Empire in 1180 BCE, apart from a few years when the royal court was moved to Tarhuntassa (D'Alfonso, 2011; Schachner, 2011: 74), Sapinuwa, or Samuha (Doğan-Alparslan, 2011: 52).

The city was founded in two areas, the Lower City and the Büyükkale, and later expanded to the Upper City in the south around the mid-16th century BCE (Figure 2) (Schachner, 2011: 64). With this expansion, the Upper City was filled mainly with religious and public buildings, such as the Temple Quarter and Yerkapı Gate (Schachner, 2011: 66). The Lower City, on the other hand, is significant both for its older history and because the 3D scanning cases analyzed in this thesis were predominantly conducted in this region.

The elevation of the city area appears to gradually increase from north to south (Schachner, 2011: 33). The Lower Town in the north is bordered on the east and north by the Budaközü river and is adjacent to a valley that opens into suitable agricultural lands along the river basin. The Upper City in the south is a hilly, rugged rocky region, and the altitude becomes more dramatic, especially as one ascends to the southernmost Yerkapı monument (Schachner, 2017: 38).

The city walls are the most significant architectural element of the city, encircling the city to the north and the south and dividing it into districts. The Lower City was divided into four parts by the city walls, including the Büyükkale, the palatial area of the Hittite period. The massive Great Temple complex is one of the most important landmarks in this older half of the city (Bittel, 1976: 67), and it is the focus of the 3D applications discussed in § 3.2.4 to document its grand plan better. To the east of this architecturally complex structure in the northwest is another topographically complex area. The Budaközü stream, critical to the region's landscape, flows northwestward through the valley between Ambarlıkaya and Büyükkaya in this area. Influential to the region's topography, this river is well known for its occasional floods and must have been a natural phenomenon that was taken care of both by the Hittites in the Late Bronze Age and by later inhabitants. So much so that the fortification of the city's north-easternmost edge, across the vast Büyükkaya orographic formation, had to traverse the problematic stream-created topography. There were debates about how Hittite architects and builders overcame this architectural challenge. § 3.2.3 focuses on this particular area and explains how 3D scanning can help to understand this area better.

While Büyükkaya and the Great Temple play critical roles as political and religious centers for the urban landscape of the Lower City of Ḫattuša, other landmarks include the Late Hittite scriptorium, known as the "house on the hillside" (German: *Haus am Hang*), which yielded a large number of tablets during excavations (see Rieken, Schwemer & Torri, 2022), and the silos on the north side of the city walls separating the Lower City from the Upper City.

Although architectural monuments seem to be the significant elements in the city's urban landscape, other equally essential elements are the characteristic orographic formations in the topography of Ḫattuša. Many rocky features, large and small, such as Nişantepe, Sarıkale, Kesikkaya, Yenicekale, and Mihraplıkaya, are integrated with the city's architectural elements in some form or another. This integration can be either through constructions planned directly on the rock or using rock walls as shared walls of the buildings. In examples such as Nişantaş and Yazılıkaya, although the latter is outside the city walls, these rock surfaces were also used for artistic and religious purposes. Both monuments are subject to scrutiny in § 3.2.1 and § 3.2.2, respectively. In this sense, it would be possible to say that the inhabitants of Ḫattuša, especially the Hittites, had an organic use of the city by incorporating the irregularities in the topography into their urban planning as much as possible, trying to turn these conditions into helpful, practical utilizations.

Finally, ponds are noteworthy as urban landscape elements significant to the city. The Eastern Ponds near Nişantepe and the Southern Ponds near the Temple District are two such artificial reservoir complexes. The eastern of these pond complexes is associated with the stone structures known as Chamber 1 and 2, and the latter is another research foci touched upon in § 3.2.1, which is contextually related to Nişantaş. There is debate about whether this pond complex's function was purely practical or cultic (Harmanşah, 2019: 232). The reservoir complex to the south may have been intended for cultic use, given the large amount of ritual pottery found during its excavation and its close location to the Temple Quarter (see Harmanşah, 2019: 235). What is very exciting about both pond complexes, regardless of whether they were cultic or practical, is that the water was not piped in from the springs adjacent to these reservoirs but filled the pools directly from the seasonal upwelling of the aquifers (see Seeher, 2006a; Wittenberg & Schachner, 2012: 318).

1.3. The Italian Expedition at Ḫattuša

The research center "Centro Interistituzionale Euromediterraneo" (CEM) of the University of Suor Orsola Benincasa, in 2014, entered into a collaboration with the Boğazköy team to perform 3D scans of the ancient city under a pact struck with the German Archaeological Institute and the Bogazköy Excavations (Schachner, 2016: 24-25). Since then, the Italian team has maintained a yearly presence at Bogazköy and is presently under the direction of Dr. Leopoldo Repola of the DiSTAR (Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse), University of Naples Federico II.

The Italian team had several main objectives in their work, including creating high-resolution, 3D records of the ancient city of Boğazköy, encompassing its archaeology, architecture, inscriptions, and art history. This was meant to aid scientific research, furnish necessary documentation, and "immortalize" the city's fragile cultural heritage for posterity (Schachner, 2016: 25). The team also sought to devise and employ novel techniques and methods for implementing and displaying 3D studies, aiming to analyze the monuments and seek future developments and simulation procedures in 3D methodologies (Repola, 2016: 607; Repola & Tilia 2020: 359). In keeping with the overall objectives of the study, the project team has an interdisciplinary identity, with the excavation director (A. Schachner), philologists (i.e., M. Marazzi and N. Bolatti-Guzzo), and 3D specialists (L. Repola, originally an architect) working together at every stage. This synergy between archaeologists and specialists will be briefly discussed in §4.4.3.

The instruments used were brought by the Italian expedition, from either the inventory of DiSTAR or the University of Suor Orsola Benincasa, depending on the year when the project was held. In this sense, Ḫattuša excavation has not paid any fee for the equipment. Therefore, the Italian expedition was likely necessary for all the 3D scans mentioned or not mentioned in the case studies.

Although Ḫattuša was reoccupied several times throughout history (including during the Iron Age, Hellenistic period, Roman era, and Seljuk period), much of the focus of the 3D scanning project is on the Late Bronze Age monuments. Throughout the years they have conducted their applications in Boğazköy, the team has concentrated on four main areas. The first of these was the monument of Nişantaş, which had to be studied in an epigraphic context, and the chamber nearby called Kammer 2 (Bolatti Guzzo, Marazzi & Repola, 2017; Repola, 2016; Schachner, 2016). Another area of study was the famous Yazılıkaya open-air sanctuary (Bolatti Guzzo, Marazzi, Repola, Schachner & Tilia, 2017; Repola, Marazzi & Tilia, 2017; Schachner, 2019). Ambarlıkaya, and the gorge separating Ambarlıkaya from Büyükkaya, hosted another survey (Repola, 2020; Schachner, 2022). The famous Great Temple in the Lower City was also a study locale (Marazzi, Pepe, Repola & Schachner, 2020).

In addition to the four cases mentioned above, surveys were also conducted at Lion's Gate, King's Gate, and Yerkapı. Although publications on these three are still in progress, the archaeological survey of the Yerkapı area conducted in 2022 is significant regarding its research questions and the extent of the area surveyed. In this particular case, four people [Leopoldo Repola, Stefano Vitale, Diego di Martire (all three from the University of Naples, Federico II), and the author Yiğit Pekzeren (Bilkent University) as an assistant], under the direction of Leopoldo Repola, carried out the fieldwork for two weeks, using various 3D scanning tools to scan the Sphynx Gate, the Yerkapı ramp and postern, and recently found Luwian hieroglyphic graffitis on the walls of this tunnel.

CHAPTER 2

3D SCANNING TECHNIQUES IN ARCHAEOLOGY

2.1. Introduction

This chapter will examine the instrumental qualities and documentary uses of 3D applications in archaeology, particularly the ones commonly used in fieldwork. The working principles and technological qualities of these 3D scanning methods will be explained while at the same time providing insights into the themes and modes of implementation of the instruments under examination. In this way, two main goals, which are very important for this thesis, will be achieved: firstly, it will provide preliminary information about the functions and tasks of the 3D scanning methods that will be frequently mentioned in the case studies presented in Chapter 3; secondly, it will allow the readers to attribute the 3D tools to the parameters that are critically evaluated in Chapter 4.

2.2. Description of main 3D scanning methods

3D scanning can be defined as the digitization of objects or environments following their shape and appearance. The methodology is implemented by scanning the originals of the objects and environments in question with various instruments and digital software. The techniques, strengths, and weaknesses of these scans vary according to the instruments, technologies, and scientific principles they use. Therefore, in archaeology and other academic or commercial uses, the choices made regarding 3D scanning instruments are based on their strengths and weaknesses. In this respect, different 3D scanning methods and instruments are expected to be used for different contextual uses in archaeology.

There are two main classes of 3D scanning principles used by many different 3D scanning devices and several technologies that can be placed under these classes. These principles, often called contact and non-contact, are simply related to the physical contact of the 3D scanning instrument with the object to be scanned (Cui, Tao & Zhao, 2021: 2).

Devices that make direct contact with the object, such as coordinate-measuring machines (CMM), can give very accurate results despite their simple working mechanisms. These devices record 3D coordinates in x, y, and z format by touching different points on the object's surface to be modeled with their embedded probes (Figure 3). These coordinates are then accumulated, and the resulting point cloud is obtained.

Contact 3D scanners, or the most typical member of this group, CMMs, are, in theory, a technology that can be used to document and measure archaeological finds, but their use is limited to closed working environments, and they are designed to scan solid transportable materials. This means that unlike non-contact instruments, which will be examined in detail in the following sections, they cannot document large surfaces, geographical or architectural features, and landscapes. Their use is often limited to the commercial sector and reverse engineering (see Hocken & Pereira, 2016).

Most 3D scanning work is done with non-contact instruments, where optical technologies are used, and the scanning devices collect the light reflected by the objects. Unlike contact 3D scanning methods, these instruments, thanks to their optical principles, allow the objects and environments that need to be scanned to be recorded from longer distances. This quality of the non-contact scanners makes them suitable for archaeological research, not only because they do not need to disturb archaeological contexts but also because they can scan uneven surfaces and large areas that are technically impossible to scan with contact scanners.

There are three widely popular principles of non-contact scanning that are often used in archaeological research, and therefore three groups of instruments work using these principles: LiDAR, Structured Light Scanning, and Photogrammetry. These groups use different optical and physical infrastructures and technologies. Since all three non-contact scanning methods principally use optics and light, there is a conceptual distinction within them. Regarding their light transmission, these three scanning methods are often classified as active and passive. In this sense, the ones that transmit their own light are considered active, and the ones that collect the environment's light are passive. Consequently, there are considerable differences in the physical characteristics of the instruments, the way they are used during scanning, and the scanning results they provide.

2.2.1. LiDAR

LiDAR (Light detection and ranging) is a technology that delivers laser beams to objects or environments to be scanned and creates "point clouds" by detecting the reflections of these laser beams. LiDAR is considered one of the "active" scanning methods, like other scanning methods that emit their light. The functionality of the mechanism is often based on the physical method called "time-of-flight." Another method known as "phase shift" or "phase-based" is also used by some 3D LiDAR scanners and provides similar results with differences in terms of the use of the light, operational time, and scanning range (Opitz & Cowley, 2013b: 18).

The time-of-flight principle is achieved by sending laser pulses from a light transmitter either inside the 3D scanner or from an external light source integrated with the device, hitting the surface to be scanned and then reflecting to the sensor in the 3D scanner. This triangular movement of light (light source - target surface – sensor) is generally called triangulation, and the time passed during the journey between the light source and the sensor is measured sensitively by the device. Since the speed of light is known precisely, the total time taken for the entire journey of the light is used to calculate how far away the surface the light hits is (Large & Heritage, 2009, 26).

Phase shift scanners work slightly differently. Rather than emitting numbers of laser pulses, phase shift scanners emit one continuous laser beam for each scan. While doing that, the calculations are made by the device regarding the phase shift between the original laser beam and its reflection from the object (Opitz & Cowley, 2013b: 13–14).

To have any meaning, the scanning device's absolute position must be known for the distance data detected by both the time-of-flight and phase shift scanners. Therefore, except for some other exceptional uses, such as local coordinate systems, which can also be used for 3D scanning, the position of the 3D scanner must be known in terms of global coordinate systems, such as WGS 84. On the other hand, the use of local coordinate systems in 3D scanning may require some exceptional processes and introduce new factors that affect the accuracy of the results. This position data, which is in x, y, z format and often originates from GNSS (Global Navigation Satellite System), is calculated together with the distance value obtained after the time-of-flight measurement and some other variables during the measurement of this value (such as physical deflections of the scanner or data on rotational movements) to obtain the actual positions of the points to which the light is sent (Devereux & Amable, 2009: 51–55; Oguchi, Hayakawa & Wasklewicz, 2011: 205). In 3D-scanning instruments using LiDAR technologies, all these optical and geometric operations are performed with extraordinary speed, and within minutes, the locations of countless points in three-dimensional space can be determined. The aforementioned point cloud is the structure in which all these points are displayed together in 3D.

Two sub-branches of LiDAR scanning concepts have been developed for different purposes and are frequently used in archaeological documentation: Airborne Laser Scanning and Terrestrial Laser Scanning.

2.2.1.1. Airborne Laser Scanning

Airborne Laser Scanning is a sub-branch of laser scanning technologies applied to ground-based subjects through aircraft. Mounted on manned aircraft, such as helicopters or airplanes, or unmanned aircraft, such as drones (Figure 4), scanners detect elements on the surface, often using time-of-flight technology (Opitz & Cowley, 2013b: 14).

Widely used in archaeological documentation and research, this remote-sensing technology allows one to record and visualize many different types of data, such as topography, hydrology, vegetation, or architecture, over extensive areas multi-dimensionally (Doneus & Kühteiber, 2013: 33). Recording such landscape and archaeological elements is undoubtedly essential and functional for archaeological interpretation and cultural heritage management.

Understanding topography is often one of the main motivations for Airborne Laser Scanning applications. Topography, which can significantly impact archaeological interpretation, provides an understanding of geographical elements such as elevation, landforms, slopes, and water lines in the surveyed area. This way, practical interpretations of the archaeological theme, society, and historical developments can be created.

Thanks to the Airborne Laser Scanning concept, digital resources such as DEMs (Digital Elevation Model), DSMs (Digital Surface Models), and DTMs (Digital Terrain Models) can be accessed in very high resolution and accuracy (Kokalj, Zakšek & Oštir, 2013: 100; Oguchi, Hayakawa & Wasklewicz, 2011: 208). These data can help to enable widely used GIS analyses, such as Viewshed, Least-Cost Path, or Hydrology analyses (on ArcGIS). These types of calculations may facilitate understanding landscapes and their impacts on the people related to them.

2.2.1.2. Terrestrial Laser Scanning

Terrestrial Laser Scanning uses similar technological principles as Airborne Laser Scanning. However, its uses and motivations often differ from the Airborne Laser Scanning concept. Because it is used on the ground, the angles at which it scans objects and themes are almost always unfavorable to an overhead view like its aerial cousin. This nature of the Terrestrial Laser Scanning concept makes it more useful for place-based scans than for huge topographical ones. Narrow indoor spaces such as inside buildings, caves, and similar enclosed spaces, as well as open areas where unwanted objects or landscape elements do not block scanning positions, are loci where Terrestrial Laser Scanning is most effective.

Terrestrial Laser Scanners are usually mounted on a tripod and rotate around themselves to record scans by transmitting laser beam pulses to their surroundings (Figure 5 and Figure 6) (Opitz, 2013: 17). Since all this scanning activity occurs on the ground, blocking elements not part of the surfaces focused on in terrestrial scans often enter the scan frame. In order to access the surfaces blocked by such elements and to scan the focused surfaces without blind spots, the Terrestrial Laser Scanner needs to use a large number of different positionings. In short, the desired subject must be scanned from every possible direction. To keep this number of scanning positions at reasonable levels, the practitioner must understand the space in which the scanner is being used and develop an appropriate strategy for positioning.

Most of the time, Terrestrial Laser Scanners work with the help of targets placed in the area to be scanned. The location of these targets, which usually have reflective surfaces, is recorded by the device with relative position data calculated according to the Terrestrial Laser Scanner's position. In this way, they become reference points for combining scans made by the scanner at different positions. For this process to be successful, at least three common targets must be seen by the device at different scan positions. Some newer and more advanced scanners do this not by matching reflector targets but by detecting and matching common elements around them.

2.2.2. Structured Light Scanning

Structured Light Scanning is one of the active forms of scanning that emits its light like LiDAR technologies, although it has a different working method than LiDAR technologies. In this method, the scanner sends repeating light patterns consisting of various lines and shapes to the surface to be scanned. One or two cameras embedded in the scanner record these patterns (Figure 7). The distortion of the patterns on the surface during the movement of the scanner allows the device to obtain the depth perception of the surface and generate three-dimensional data (Figure 8) (see Geng, 2011; Opitz & Cowley, 2013b: 18–19).

These devices, which are often considerably lighter and easier to operate, are quite different from LiDAR technologies regarding their operational purpose. First, structured light scanners use projected light patterns instead of amplified laser beams. Therefore, unlike LiDAR methods, they cannot provide adequate service in brightly lit areas, and their range is significantly shorter than that of laser scanners. In addition, this technology's projection and scanning area is also very narrow compared to LiDAR. This prevents them from being able to scan vast landscapes. Instead, they effectively scan smaller objects and narrower surfaces (Opitz, 2013: 19). This means structured light scanners are more suitable for documenting archaeological artifacts, surface finds, and remains, such as reliefs and paintings, than archaeological landscapes.

2.2.3. Photogrammetry

Photogrammetry, or one of its contemporary and widely used sub-branches whose name is sometimes used correspondingly, Structure from Motion (SfM), is an easy and relatively inexpensive 3D remote sensing application widely used in archaeology and cultural heritage (Figure 9). Unlike LiDAR and Structured Light Scanning, it does not require sophisticated instruments of its own. Instead, often just any commercially available camera, even a smartphone camera, a geodata provider (if the scan theme is geographical), and commercial or open-source photogrammetry software to run the digital process are sufficient for SfM applications (see Brandolini, Cremaschi, Zerboni, Esposti, Mariani & Lischi, 2021: 33). As a common method, photogrammetry can be used to model both large landscapes and small objects.

The primary data sources used for photogrammetry are photographs acquired with standard RGB cameras (Lerma, Navarro Cabrelles & Villaverde, 2010: 500). Since RGB cameras do not transmit their own light but instead collect ambient light and convert it into graphic data, photogrammetry applications can be considered passive scanning techniques, unlike LiDAR and Structured Light Scanning.

Just as in the case of LiDAR, to visualize photogrammetric models at their accurate scale and location and accurately document the themes to be represented in the model, it is necessary to have accurate location data, i.e., Ground Control Points (GCPs) (Brandolini *et al.*, 2021: 34; Eltner & Sofia, 2020: 9). This concept is called geo-referencing. Since cameras are used during photogrammetric production, obtaining real-time geographic information during recording is often impossible. This is because GNSS receivers, typical in LiDAR technologies, are either not embedded in the cameras or are simple systems that only detect their own position but are incapable of detecting the direction and viewing angle range the cameras face. Therefore, the GCPs of the models must be recorded externally using other instruments. This is where Total Stations or external GNSS receivers come into the picture (Brandolini *et al.*, 2021: 34). For the application, three or more targets (unlike in LiDAR, these targets do not need to be reflectors) are first distributed over the area to be scanned and then photographed as part of an overarching composition (see Douglass, Lin & Chodoronek, 2015: 138). During post-processing on the computer, the targets appearing in many photographs should be geo-referenced with the coordinates of the GCPs recorded in the field. (In theory, whether the coordinates are recorded before or after the photography does not affect the result.) In this way, photogrammetric data is combined with geolocation and elevation information. This is essential for using photogrammetric models or orthophotos (aerial, ortho-rectified photos commonly used in cartography, eliminating the negative effects of perspective and optical distortions) in geodata processing platforms such as GIS.

The digital elevation models (DEMs) in general, and Digital Surface (DSMs) and Digital Terrain Models (DTMs) in particular, are specifically valuable for fields such as landscape archaeology and Geographic Information System (GIS) studies, and this usefulness makes them widely demanded datasets. Digital Terrain Models (DTMs) include the bare earth surface and typically exclude above-ground objects like buildings and vegetation. On the other hand, Digital Surface Models (DSMs) capture the elevation data of the terrain along with all above-ground objects, including buildings, vegetation, and any other surface features (Figure 10) (Bennet, 2014: 30). It should be noted that aerial photogrammetry is an effective and cost-efficient technique for generating these models, as well as orthophotos, as it allows for acquiring high-resolution imagery from an aerial perspective with the help of commercially available and relatively cheaper aircrafts with embedded RGB cameras. This method facilitates the rapid collection of data over large areas, making it a popular choice for generating DEMs, DSMs, and DTMs. In short, aerial photogrammetry is a valuable tool for generating digital elevation models, offering an affordable and efficient means of acquiring the necessary data.

2.3. Assessing 3D Scanning Methodologies

2.3.1. Previous assessments

Several key parameters are often used to evaluate 3D methods critically (see Douglass *et al*., 2015; Forte, 2014a; Galeazzi, 2016). These parameters can be broadly divided into:

> (a) The quantitative parameters of the 3D methods, such as their resolution, accuracy, precision, or range. These are considered independent of the context in which the 3D scanning methods are used.
>
> (b) Parameters on their usability in the archaeological context.

Quantitative parameters can encompass some outputs that 3D methods can offer in relation to their technical nature, as well as other factors that impact the acquisition of the method. Many specialists offer range, accuracy, precision, and resolution as quantitative parameters of 3D scanning methods (see Hetherington, 2009; Guidi, 2014). In addition to these numerical parameters, some scholars include weather conditions, characteristics of the scanning vehicle components, or other features related to the area to be scanned, which may impact the scanning quality and efficiency of 3D methods (see Charlton, Coveney & McCarthy, 2009).

While the parameters for use in an archaeological context can vary according to many different factors, many scholars prefer to examine different issues such as the time it takes for scan acquisition and post-processing, how much financial resources such work requires, and the labor required (see Murray, Fachard, Knodell, Papangeli, Berenfeld & Svana, 2016).

Many sources on using 3D in archaeology inherently provide examples from various cases. Brandolini *et al.* (2021), Doneus and Kühteiber (2013), Schachner's reports in *Archäologischer Anzeiger* (2016; 2017; 2018; 2019; 2020; 2022), and several other academic studies on 3D scanning either directly describe their cases or illustrate their critical evaluations of 3D archaeology methods through case studies.

2.3.2. Assessment criteria of this study

Considering some of the assessment criteria frequently used in previous literature, some special conditions in Turkish archaeology, and characteristics of the project carried out in Ḫattuša, the assessment criteria of this study for 3D scanning studies were determined as follows:

- **Technical criteria:**
    - ***Field dynamics:*** For many archaeological research questions, 3D scanning may need to be utilized in challenging environments. The nature of the scanning tools can make it either easier or more difficult to work in such harsh conditions, as well as potentially affecting the quality of the 3D data generated (§ 4.3.1.1).
    - ***Acquisition time and accuracy:*** The time spent during scanning applications varies from one tool to another. Variables such as accuracy, precision, range, or size of the scanning area should be considered as they can affect the acquisition time (§ 4.3.1.2).

    - ***Processing time:*** The post-processing time should be examined as it differs according to the needs in addressing research questions and the 3D scanners used (§ 4.3.1.3).
- **Managemental criteria:**
    - ***Cost:*** The cost of 3D scanning is critically important for access to tools and services. Since the total cost of different tools for different research settings is affected by many variables and profoundly impacts the outcome of 3D scanning projects, it must be critically assessed (§ 4.3.2.1).
    - ***Learning and expertise****:* The time and effort needed to gain the expertise required by 3D scanning tools may differ for each tool. Access to experts or appropriate training is essential for a complete understanding of 3D scanning, as it directly affects how 3D scanning studies can be performed (§ 4.3.2.2).
    - ***Legal limitations:*** Various legal restrictions exist for 3D tools in archaeological research. These barriers can prevent 3D research from being conducted for archaeological studies (§ 4.3.2.3).

While these criteria provide a guideline for the review of the Ḫattuša case studies (§ 3.2), which are examined in detail in Chapter 3, the actual assessment of the 3D scanning tools (§ 4.3) is undertaken in Chapter 4. Of course, for a comprehensive assessment of 3D methods in archaeology, it is not enough to consider only what they can and cannot offer technical or what they facilitate and complicate for archaeological research. For this reason, the remainder of Chapter 4 will also present some selected non-3D alternatives (§ 4.3.3). It will also offer conceptual considerations for publishing and exhibiting the results of archaeological research using 3D (§ 4.3.4).

CHAPTER 3

CASE STUDIES FROM ḪATTUŠA

3.1. Introduction

This chapter examines four 3D scanning studies, all conducted by the Italian expedition at Ḫattuša. These four case studies, distinct from each other regarding conceptual and archaeological research questions, represent an integrated use of different 3D scanning tools. Nişantaş and Kammer 2, two monumental structures that are related in terms of their research interests, are examined together and in the first place because they were scanned as part of a single research project and were the first work of the Italian expedition. This case is followed chronologically by the studies from Yazılıkaya, the Gorge Area, and the Great Temple (Figure 11). Through these cases, in which epigraphic, art historical, geoarchaeological, and architectural research questions are attempted to be answered, the contributions of selected 3D scanning tools to answer archaeological research questions are discussed in §3.2.

In addition to the four surveys mentioned in §3.2, the Italian expedition also conducted surveys at the Lion's Gate, King's Gate, and Yerkapı (see § 1.2) within the territory of Ḫattuša. However, these studies have not yet been published extensively enough to be assessed in this thesis.

3.1.1. The Issue of Local Coordinates at Ḫattuša

DAI's excavations at Ḫattuša have spanned more than a century and, over the years, have been accompanied by intensive documentation. Knowing the precise location of artifacts and architectural remains is crucial for documentation and, of course, for archaeological interpretation. For this reason, the Ḫattuša excavations needed a systematic positioning methodology. For this purpose, local coordinate systems were used, the most common and still convenient positioning method before the widespread use of GNSS systems. Throughout the extended excavations at Ḫattuša, local coordinate systems were part of the excavation methodology whenever geolocation data was required. As of 2022, the local coordinate system and the Total Station devices that serve by this system are still in active use at Ḫattuša during the planning and implementation of excavation works. This particular case resulting from the research methodology is an essential issue as it affects factors such as the accuracy and cost of 3D scanning studies and is discussed in the following sections.

Under normal circumstances, using local coordinates does not cause any disadvantage in data quality for conventional archaeological documentation (provided that the location data are produced by experienced survey personnel). However, most aerial and terrestrial laser scanners and most professional UAVs are equipped with GNSS receivers that are not compatible with local coordinate systems and, by default, calibrate the 3D scan data according to their position in the GNSS network. As a result, additional procedures need to be implemented in the scanning process to visualize the 3D scanning data from Ḫattuša in harmony with the other archaeological records from the city.

The main one of these extra procedures is geo-referencing targets within the scan areas. In passive scanning, such as photogrammetry, distinctive, often high-contrast targets are placed at various intervals in the area to be scanned, and geo-location data is collected from these targets. The reflective targets mentioned in § 2.2.1.2 are used for laser scanners, and the geo-referencing process is performed using these reflectors.

3.2. Case studies

3.2.1. Nişantaş and Kammer 2

3.2.1.1. Background

Nişantaş and Kammer 2 are two Late Bronze Age remains located in the vicinity of Nişantepe and Südburg, in a relatively central position considering the city plan (Figure 11). Kammer 2 is an approximately 8 m^2 chamber covered by a parabolic vault with an open entrance. The presence of supporting walls on the left and right sides of the structure suggests that an artificial hill may have covered it. The stone walls of Kammer 2 are engraved with reliefs attributed to the Great King

Suppiluliuma (whether he is the first of his name or the second will be discussed later) and the Sun God, as well as Luwian hieroglyphs, suggesting that it should probably have been built to house an underground cult (Neve, 1990: 36-40). On the other hand, Nişantaş is an epigraphic inscription in Luwian hieroglyphs carved on the side of a rocky cliff in the west of this chamber (Figure 12).

The two monuments have different exploration and research backgrounds and were in contrasting conditions when initially found. Kammer 2 (Figure 13 and Figure 14) was discovered when Peter Neve was the head of the excavations in Ḫattuša. Following the discovery, Peter Neve invited the British archaeologist David Hawkins to Boğazköy in 1989 to analyze the inscriptions, and Hawkins' translation of the inscriptions was published in *Archäologischer Anzeiger* in 1990. Based on these studies and the stratigraphic observation of the structure, it is thought that it probably dates to the reign of Suppiluliuma II, the last emperor of the dynasty (Hawkins, 1995: 13; Neve, 1990: 39).

Nişantaş, known from a much earlier time, was not as fortunate in its state of preservation as Kammer 2. This large Luwian epigraph, found on the face of a rocky cliff, was severely exposed to the weather and, except for the initial introductory genealogy at the text's opening, is illegible to the unaided eye. Nonetheless, the typology of the inscription suggested that it was most likely to date to the last three dynastic generations of the Hittite royal house (the brothers Muwatalli II and Hattusili III, Tudhaliya IV or Suppiluliuma II) (Hawkins, 1995: 13). Thanks to one of the very few readable fragments of the epigraph, the genealogy, according to Neve (1990: 39), the Nişantaş text stemmed from Suppiluliuma II. However, the rest of the text remained undeciphered for a long time. Hence, further research needed to be undertaken to uncover the archaeological theme and context of the epigraph.

The area between Nişantepe and Südburg was a major challenge for the Italian mission, perhaps not in terms of 3D scanning studies but in philological analysis and archaeological dating. Although Nişantaş was poorly preserved, it was safely dated to Suppiluliuma II (see Laroche, 1969-1970). Kammer 2, on the other hand, was well preserved and was certainly traceable to the "Great King Suppiluliuma," but for some, questions remained as to whether this was Suppiluliuma I or Suppiluliuma II (see Weeden, 2020). Therefore, the fundamental motivations of the delegation were not only to document the Nişantaş monument and Kammer 2 but also to utilize various 3D scanning methods to enhance the illegible text at Nişantaş to make it as readable as possible. Meanwhile, they were to collect data that may help minimize the question marks, especially about Kammer 2.

3.2.1.2. Methodology

The first work in the Nişantaş and Südburg area was geo-referenced 3D scanning with a time-of-flight laser scanner. (Schachner, 2016: 26) The results of these scans correlated with the area's existing topographic plan to create up-to-date and high-quality topographic models. This paved the way for a holistic study of the site and its archaeological and architectural elements.

Kammer 2 and the monumental hieroglyphic inscription of Nişantaş were scanned using a variety of different methods in order to create detailed and accurate digital models of the inscriptions. These methods included using a handmade stereoscopic scanning device (Scubalibre Stereoscopic Scanner) and two structured light scanners (Artec Eva, a pulsed light scanner, and Scanprobe LT). (Schachner, 2016: 27; Bolatti Guzzo *et al.*, 2017: 315; Repola & Tilia, 2020: 363) The stereoscopic device in question is a product produced by the NOP SINAPSIS project of the CEM, which integrates two action cameras to take videos of the same theme and create models using the software created specifically for it, with a principle similar to photogrammetry. (Repola, 2016: 607; Schachner, 2016: 26) In addition to these scanning methods, the entire inscription area was subjected to a detailed photogrammetry scan using Agisoft PhotoScan (the predecessor of Agisoft's Metashape). By combining these scanning methods, researchers could create highly detailed and accurate digital models of the hieroglyphic inscriptions at Kammer 2 and Nişantaş (Repola & Tilia, 2020: 364).

The models resulting from all these applications were combined into a common interpolation model to evaluate them in an integrated framework. In this way, models covering larger areas (such as the TOF laser scanning model) can be shown within models covering smaller areas (such as the structured light scanning or stereoscopic models), which appear in their actual places with their actual features (Repola, 2016: 607). This method is critical for accurately assessing specific cultural heritage elements in the overall landscape of the site.

In order to provide a solution to the problem of the illegibility of Nişantaş, the hieroglyphic inscriptions were divided into blocks and lines during the scanning process. Narrow vertical fragments (blocks) of three lines each, and then longitudinally recorded lines, were reconstructed for further interpretation by linguists. This way, the relatively smaller chunks could be visually manipulated to improve readability. Thanks to these mathematical manipulations, some of the outlines of the inscription have been refined, and some of the hieroglyphic characters can be graphically visualized in a way that allows them to be easily identified (Figure 15*a, b, and c*) (Bolatti Guzzo *et al.*, 2017: 30; Schachner, 2016: 28).

3.2.1.3. Results

Thanks to 3D scanning, the legibility has been improved, even for the very badly preserved parts of the Nişantaş inscriptions (Schachner, 2018: 65). Firstly, the negative effects of the mineral texture of the stone (patina), which makes it more challenging to comprehend the eroded stone surface, can be minimized due to 3D scanning. Secondly, factors affecting vision, such as cracks and chips, were similarly eliminated during 3D visualization. Finally, to precisely understand the structure of the epigraph in 3D space and distinguish faint engravings, the scanning minimizes the possible perceptual errors that the human eye or problematic conditions may cause during illumination (Bolatti Guzzo *et al.*, 2017: 32). It may be possible to exemplify some of the linguistic elements of the Nişantaş inscription that 3D scans have reportedly contributed positively to its reading (Bolatti Guzzo *et al.*, 2017: 35-39):

- Introductory sequence EGO-*wa/i-mi-a* (Figure 15*a*) (Bolatti Guzzo *et al.*, 2017: 35; Schachner, 2016: 31)
- The sign L 196 = *HATTI / HATTUSA* in the sequence *HATTI*(REGIO) REX (Figure 15*b*) (Bolatti Guzzo *et al.*, 2017: 36; Schachner, 2016: 31)
- Historical narrative referring to Tudhalija IV, Suppiluliuma II's father:
    - Starting formula of *mi-sa-a tá-ti* MONS.*TU* MAGNUS.REX = "my father T. the Great King" (Bolatti Guzzo *et al.*, 2017: 35)
    - The sequence DEUS-*ni-ti á-zi/a-mi [s]a-tá-a* = "was loved by the gods" (Figure 15*c*)

    - An element previously read as ^{D}*Sarruma* is read as (DEUS)SOL.SOL+*RA/I* = “Sun goddess of Arinna” (Bolatti Guzzo *et al.*, 2017: 36)
    - Section ending *wa/i-na-a [wa/]i-[s] à-ti [u]-[n]i-[t]á* = (can be possibly translated as) “and (the deity) looked at / recognized him with favor/goodness” (Bolatti Guzzo *et al.*, 2017: 36)
- The text continues from the second line onwards with a narrative of Suppiluliuma II's conquests. According to Schachner (2016: 34), this narrative contains many recurring toponyms that appear together with Determinatives REGIO and URBS.

As a result of the increased legibility of Nişantaş, it was possible to find some shared expressions and linguistic components between Kammer 2 and Nişantaş. Following the new findings, it is noted that a toponym found at Nişantaş (the name of the city of *Tamina*) appears in both monumental structures, whereas it does not appear in other known sources. Therefore, according to Weeden (2020: 489), referring to both Hawkins’ and Project Ḫattuša’s findings, it is very likely that both of these epigraphs could be parts of the same narrative. Therefore, these results suggest that the two monuments are most likely contemporaneous and that their dating to the Suppiluliuma II period can be confirmed. In addition to improving the legibility of the text at Nişantaş thanks to 3D studies, Hawkins' strengthening of his previous findings on Nişantaş using traditional approaches also played a decisive role in the proper validation of the 3D scan results (Weeden, 2020: 480).

The 3D scanning studies in Nişantaş and Kammer 2 confirmed Hawkins' opinions regarding their outcomes and resolved many lingering uncertainties on a larger scale. At this point, it is possible to discuss a common conclusion reached within the scope of two studies carried out independently. First, a working group led by Marazzi and Bolatti Guzzo analyzed and dated Kammer 2 and Nişantaş using 3D scanning materials. The second is Hawkins' new revision, in which he updates his earlier research from the 1990s and reaches more or less similar conclusions. Both of these studies, consistent with each other and with Hawkins' earlier findings, conclude that both Nişantaş and Kammer 2 (or at least the inscriptions at Kammer 2) were built during the reign of Suppiluliuma II (Weeden, 2020: 489).

3.2.2. Yazılıkaya

3.2.2.1. Background

Yazılıkaya is a rock-hewn open-air temple site located about 2 kilometers northeast of Ḫattuša. Based on the numerous reliefs and Luwian inscriptions found inside, it appears to be partly dated to Tudhaliya IV and partly after him. The sanctuary of Yazılıkaya has a plan with two chambers, traditionally called Kammer A and Kammer B. The entrances to these chambers were used in the Late Bronze Age and joined with an architectural temple structure. In other words, the access to Yazılıkaya was presumably through a temple where some ritual activities occurred (see Schachner 2011; Seeher, 2011a).

Although Kammer A is the section thought to have been the first to be completed in terms of its art historical elements during the reign of Tudhaliya IV, the ritual use of this chamber was initiated even before, possibly from the 16th century BCE onwards (see Seeher, 2011a). There are many reliefs in this area (68 so far identified), some of which are associated with hieroglyphic inscriptions (Figure 16). This area is entirely open to the elements, so the reliefs and inscriptions are generally poorly preserved.

On the other hand, Kammer B is located southeast of Kammer A and is a narrower and more enclosed room. This room was probably a closed natural space, but its entrance was opened and incorporated into the temple complex following the initial construction of the Yazılıkaya sanctuary. In addition, the typology of the reliefs in the chamber suggests that it was designed as a mausoleum for King Tudhaliya IV after his death (see Schachner, 2011; Seeher, 2011a).

In the '70s and '80s, prior scholars, Güterbock and Masson, had independently made readings of the hieroglyphic inscriptions at Yazılıkaya. Some of these readings were inconsistent with each other. Some natural rock textures were interpreted as possible hieroglyphs due to poor preservation, especially at Kammer A, or some signs were not agreed upon (see Güterbock, 1975 & 1982; Masson, 1981).

Against this background, 3D scanning appeared to be a practical option, not only to provide a detailed and very high-quality record of epigraphic and art historical elements that were already exposed to the natural conditions and increasingly in danger of being wholly erased, but also to help confirm or debunk the findings discussed in previous contributions. In the summer of 2015, the Italian expedition began its work at Yazılıkaya with a strategy similar to that of Nişantepe and Südburg.

3.2.2.2. Methodology

The methodology of the scanning work at Yazılıkaya is similar in texture to work at Nişantaş and Kammer 2. Just as in Nişantaş and Kammer 2, a scanning strategy that goes from the general landscape to the specific art historical elements was followed at Yazılıkaya, and the 3D scanning technology and equipment used during these processes were preferred accordingly. In other words, instruments with a broader scan range were used initially, and instruments with narrower focal areas were used subsequently.

The aim was to accurately record the three-dimensional spatial relationship of Yazılıkaya with Ḫattuša and the surrounding topography. To this end, a Terrestrial Laser Scanner (Riegl LMSi 420), which works on the TOF principle (see § 2.2.1 in this article) as in the Südburg examples, was used to perform a comprehensive territorial scan of the site. The Laser Scanner scans were followed by scanning more specific small-scale surface areas. For this process, as in Nişantaş and Kammer 2, the Artec Eva structured (pulse) light scanner, the older and more cumbersome to handle Scanprobe LT structured light scanner, the Scubalibre Stereoscopic Scanner of the NOP SINAPSIS project, and PhotoScan procedures for photogrammetric scanning were used (Bolatti Guzzo *et al.*, 2017: 21-23; Repola *et al.*, 2017: 397; Schachner 2016: 30). This allowed the scans to cover the overall topographic structure of Yazılıkaya and to access hieroglyphic inscriptions and reliefs that require detailed scanning (Figure 17). It is safe to say that this diverse perspective can be found to a large extent in all of the team's scanning operations.

Related to the local coordinate use in the site, in the specific case of Yazılıkaya, the positioning had to be done with Total Station instruments following the methodology followed in the excavations at Ḫattuša. Therefore, the Total Station had to be calibrated for Yazılıkaya, about 2 km from the city. Since at least three previously known geographical reference points had to be known for the calibration process (see §2.2.3 and § 3.1.3), the survey team took the three points from Büyükkaya, which is the most clearly seen area from Yazılıkaya (Repola, Marazzi & Tilia, 2017: 398). After the calibration of the Total Station, the reflector and non-reflector targets within the scan area were geo-referenced, allowing the new data to be integrated with the cumulative Ḫattuša data, as well as allowing different scan chunks (TOF laser scanning, structured light scanning, or photogrammetry) to be combined. Using Total Station systems for positioning is essential for addressing issues such as the cost and accuracy of 3D scanning. These issues are discussed in § 4.3.

3.2.2.3. Results

The 3D scanning studies conducted at Yazılıkaya considerably improved the legibility of the hieroglyphic inscriptions identifying the figures in almost all the reliefs (Bolatti Guzzo *et al.*, 2017: 40). The high effectiveness in this regard allows for testing hieroglyphic readings from previous literature, notably the work of Güterbock and Masson. Thanks to the 3D scanning results, it is possible to say that Güterbock was correct in some readings and Masson was correct in others. For example, it was observed that deity groups 18-22 at Kammer A have no hieroglyphic qualifiers, and Güterbock's 1975 study and the 1982 revision of the same study reached the correct conclusion in this regard, and Masson's reading was not correct. In another example, focusing on hieroglyphs associated with deities 13-15, Masson's 1981 reading was confirmed (Bolatti Guzzo *et al.*, 2017: 40-41). Table 1 shows whether the 3D scan results confirm some of the assessments made by Güterbock and Masson.

The work at Yazılıkaya has served as a fruitful benchmark for academic disagreements arising from the conventional reading method and different readings, especially for epigraphic problems, and has contributed positively to the correct understanding of the texts. For new finds, Bolatti Guzzo *et al.* suggested that plaster casts from the 19th and 20th centuries from the Pergamon Museum in Berlin, which are copies or replicas of some of the Yazılıkaya reliefs and inscriptions, should also be examined so that the accuracy of the results of the 3D studies can also be confirmed (2017: 44).

For Schachner, the Yazılıkaya studies (possibly in conjunction with the Nişantaş and Südburg studies conducted in the previous season) raised an important question, which is also part of the subject of this thesis. This question is related to the fact that despite the many advantages that 3D studies offer, they have not yet been transformed into a suitable form for academic publishing, especially for printed publications (Schachner, 2016: 43). According to Schachner, the question of appropriate media needs to be put forward for 3D studies to be published in literary form. Possible solutions will be evaluated in the following sections (§§ 4.3.4.1 and 4.3.4.2).

Hieroglyphic Identification	Güterbock	Masson	Comments
Gods 13-15	-	Confirmed	-
God 16	Confirmed	-	-
God 16a	Confirmed	-	-
God 17	Confirmed*	Confirmed	*Güterbock partially accepts Masson's reading.
Gods 18-22	-	Not applicable	The readings presented by Masson were not applicable since the themes do not contain his proposed elements.
Gods 23-24	-	Not applicable	
God 25	Uncertain		Scholars agreed with each other, but the models could not confirm them.
God 40		Confirmed	-
Bulls 42a and 43a	Confirmed	-	-
Goddesses 45-46	Confirmed	-	-
Goddess 51	Confirmed	-	-
Goddess 60	Not applicable		-
Gods 65-66	Confirmed	Confirmed	Each scholar has been partially confirmed

Table 1: A table on the re-evaluation of prior scholars' readings shared in Schachner 2016.

3.2.3. The Gorge Area

3.2.3.1. Background

The Budaközü river, which is one of the significant influences on the landscape of Ḫattuša, and the valleys and gorges (Figure 18 and Figure 19) formed by this stream and its tributaries are home to some archaeologically valuable contexts. In particular, the section of the riverbed between the orographic formations called Büyükkaya and Ambarlıkaya (Figure 20) on the north-eastern borders of the city hosts essential data in terms of Ḫattuša's defense organization and water management. This area is home to multiple archaeological and architectural remains that have been subject to 3D scanning, but it is also a complex landscape in its own right and has undergone a long and challenging survey process. In scanning the site, some key archaeological finds were prioritized and emphasized. The most focused of these can be listed as follows (see Repola, 2020):

- The north-eastern part of the fortification walls
- An unfinished tunnel in the southern slope of Büyükkaya (Figure 21)
- Cave at the southern slope of Ambarlıkaya (Figure 22)
- Dowel holes and other marks around the gorge

In the landscape of the region, where the river flows on an east-west axis, there is Büyükkaya to the north and Ambarlıkaya to the south, and between the two large rock formations is a smaller rocky structure called Minarekaya after its shape (Figure 23). The riverbed normally flows between Ambarlikaya and Minarekaya. Minarekaya is of particular significance as it is the only natural formation in the region that would have allowed Ambarlıkaya and Büyükkaya to be connected by architectural elements. The importance of this rock, especially concerning the construction of the city's defensive walls on the north side of the flow, was noted by previous researchers in Ḫattuša, and former DAI co-directors Neve and Naumann conducted studies in this area and recorded the architectural presence of the walls in the area (see Repola, 2020: 181).

In Büyükkaya, north of the canyon area, some cavities cut the rock formation on a north-south axis and are considered entrances to an unfinished tunnel structure. Although the northern one was excavated approximately 16 meters long and the southern one approximately 24 meters long, it is thought that the construction was abandoned before the two cavities were joined in the middle (Schachner, 2018: 53). The possible function of the tunnel was not identified prior to the survey. However, the structure has a context that allows for the speculation that it may have been designed concerning the hydrology of the complex landscape and the architectural elements in the area.

Another focal element is the hollow on the southern slope of the Ambarlıkaya orographic formation, which is probably natural in origin but has been subsequently re-worked. For instance, a staircase has been carved into the entrance of this cavity, while a passage leading to the hill plateau of Ambarlıkaya is likely entirely artificial.

This cavity is considered noteworthy and has been interpreted as a possible cult site (Figure 22) (Schachner, 2022: 62-64).

The last of the major focal points are the small dowel holes in the area (most of them supporting the stones of the wall at Minarekaya) and the rock-cut holes concentrated on the Ambarlıkaya side of the valley, possibly associated with the beams of a wooden platform. The holes at Minarekaya were presumably made to increase the stabilization of the architectural elements, possibly a bridge passing over the rock formation, according to Naumann (1963: 24). Neve (1978: 67-68) takes this idea a step further, suggesting that the structure here may not have been a bridge but rather a structure that crossed the river while retaining the shape of the city wall (see Seeher, 2007). Such a structure would have been strategically important for connecting the Büyükkaya area to the city center, as it was crucial for the city's defense and housed many granaries. As for the holes found on the surface of Ambarlıkaya, Neve suggests that they may have been holes carrying galleries running along the wall and were probably made with iron tools long after the Hittite imperial period (1978: 69-70).

3.2.3.2. Methodology

For all these archaeological features, which have very different characteristics, different methodological approaches were proposed by the Italian expedition to enable the analysis of each of them. Since all of these archaeological elements, apart from their structural characteristics, were evaluated and recorded according to different needs and conditions due to their context within the terrain, we see that alternative methods were sometimes used, going beyond the ideal. Nevertheless, as in the previous case studies, a survey strategy that focuses from the general to the specific has been developed in the case of the gorge (see § 3.2.1.2 and § 3.2.2.2).

As in the Yazılıkaya and Nişantaş-Südburg case studies, a comprehensive topographic survey of the area was first undertaken (Figure 23), including all of Ambarlıkaya and part of Büyükkaya. Although this scanning was carried out using a TOF-laser scanner, which is suitable for large landscapes, unlike the other case studies, high-quality non-UAV photogrammetry was also used for topographic scanning since the area is a deep canyon, the river flows continuously and is often at a depth and flow rate that limits mobility in the area, and the heavy terrestrial laser scanner set-up (Riegl LMS-Z420i) cannot be taken to every desired area (Repola & Tilia, 2020: 364). In the gorge case, the GoPro Hero Black Edition action camera was mainly used for photogrammetric photography, although a standard Nikon DSLR camera was also used (Repola, 2020: 181-184; Schachner, 2018: 46). Due to the vastness of the area, the final topographic 3D models consisted of many scan chunks combined in the post-processing phase, and these chunks were obtained by two different methods (laser scanning and photogrammetry). The geo-referencing of the models, as in the previous studies (see § 3.1.3), was achieved by using the local coordinate system and total station devices (Leica TCR405 for this specific example) (Repola, 2020: 181).

Apart from the general topographic survey, some of the specific surveys in the area (such as the building elements at Minarekaya, Ambarlıkaya, and the holes for construction purposes) were predominantly photogrammetric. In contrast, a commercial stereoscopic scanner (Sense) working on a similar principle to photogrammetry (see § 3.2.1.2 for another stereoscopic scanner example) was used for some elements, notably the construction holes carved into the high surfaces of the walls of Ambarlıkaya. On the other hand, the tunnel entrances were scanned with a laser scanner due to their larger area and the conditions allowing, and the architectural relationships between the two tunnel entrances were analyzed in detail by geo-referencing the models.

3.2.3.3. Results

Many natural and artificial elements have been recorded, and topographic models of the area have been obtained during the work in the gorge. Besides, some specific conclusions have also been reached for specific focal points. One of the most striking of these is the tunnel's axis, which leads one to believe that the two ends of the tunnel, even if they did not meet in the middle, were built in a planned architectural line. Repola said such an alignment would have required designers capable of trigonometric calculations (2020: 195). In addition, given the height of the plan of the fortification line connecting Ambarlıkaya to Büyükkaya via Minarekaya, it is speculated that both the fortifications (Figure 24) and the tunnel (Figure 25) may have been designed, taking into account the level of water rising during possible river floods and that the tunnel was, therefore, most likely dug to drain the rising water (Repola, 2020: 195-196). According to Repola's elevation measurements obtained through 3D analysis, the southeastern entrance of the tunnel is 22.7 meters above the current river surface, and the northwestern exit is 12 meters above the current river surface (2020: 189). Although these are pretty high elevations, the tunnel is still estimated to have been located below the presumed top surface of the fortification walls (Repola, 2020: 196).

Apart from the tunnel, another contribution of the 3D data is the relatively more precise information on the trajectory of the fortification line. The interpretation of the fortification fragment, of which only parts of the plan and some stone blocks are visible today, has been possible thanks to the scanning and survey work. During the survey, some large stone blocks were found in the river basin, similar to those found at other gates in the city (such as the Lion's Gate or the King's Gate), which are thought to have been cut for the construction of vaults. According to Repola, these blocks suggest that the fortification architecture here may have crossed the river through a stone arch, which would have been more robust than the other possible alternative, wooden construction (2020: 197). The possible evidence of an arched structure some 20~ meters above the modern river surface and connecting two rock formations could be the product of one of Anatolia's most ambitious engineering efforts at the time and, if proven, would be a sensation.

Finally, the scans confirmed that the dowel holes on the northeastern wall of Ambarlıkaya were probably made later than the Hittite period, as they were made with a different method than those at Minarekaya and compared to the Hittite dowel carving techniques published by Seeher in his 2005 article. These holes were carved with metal chisels and had a shape more suitable for supporting cantilever beams (Repola, 2020: 195; Seeher, 2005). Thus, these particular holes were probably unrelated to the Hittite fortification walls, although further research is needed to understand their exact purpose.

3.2.4. The Great Temple

3.2.4.1. Background

The Great Temple is a building complex in the Lower City of Ḫattuša and the most prominent structure within the city wall. The temple complex has a large and intricate plan surrounded by numerous storerooms. Although the two cult chambers dedicated to the storm god Teshub and the sun goddess Hebat had led to the temple being erroneously dated to the late 14th or 13th century, the latest stratigraphic data from excavations at the site indicate that the temple was built in the 15th century (Schachner, 2011: 83). Although precise dating of the building cannot be made, this structure appears to be a sacred complex excavated in the early stages of the Ḫattuša excavations and whose plan was utterly unearthed.

The fact that the building complex is composed of large blocks of stone, that the floor plan is relatively well preserved, and that it has an essentially regular plan may be considered a factor that facilitates the archaeological documentation of the site. Nevertheless, in 2018, a new project was designed to expand the 3D scans of the Lower City, aiming to scan areas that had been excluded from the Italian expedition's previous scanning project, which covered Büyükkaya, Ambarlıkaya and the gorge (Schachner, 2019: 97; Schachner, 2020: 49). The main research interest in this study centered around the Great Temple (more specifically, Temple 1), the most significant Hittite landmark in the area. The primary objective was to create a series of 3D models of very high resolution, interpolated models of the whole site, capable of showing the whole planimetric development of the structures and simultaneously the specific construction features of individual elements, such as foundations and elevations, sills, or drainage/collecting systems (Marazzi, Pepe, Repola & Schachner, 2020: 80-81). However, the completion of the work at this site was initially postponed until 2022 (Schachner, 2022: 76), but with the discovery of the hieroglyphs in the Yerkapı postern in 2022 (see § 1.2), the 3D scanning work was shifted to the Yerkapı area and the final analysis of the work at the Great Temple has not yet been completed.

3.2.4.2. Methodology

The methodology for the 3D scanning of the site has been largely straightforward. The relatively flat, uncomplicated terrain and foundation plans that are neither too high nor too low made using broader topographic and planimetric scans possible and practical. What methodologically distinguished The Great Temple area and Temple 1 in the center from other areas previously scanned in 3D was that this large area was very suitable for aerial scanning. Thus, UAV-based photogrammetric models were also planned, and two drones, a DJI Phantom 4 Advanced, and a DJI Spark, were used in this study (Marazzi *et al.*, 2020: 83). Besides, two TOF terrestrial laser scanners (Riegl LMS-Z420i and Riegl VZ400i) and a phase-shift laser scanner (FARO Focus S350) were used to scan the area. In addition to the comprehensive topographical scanning, some building elements with traces of use were scanned via structured light scanners, and some (see § 3.2.4.1) were photogrammetrically modeled for greater detail (Marazzi *et al.*, 2020: 86; Schachner, 2019: 102).

The work at the site of the Great Temple was a large survey area where many instruments were used, and therefore a significant amount of 3D data was acquired (Figure 26). The general scanning approach was similar to previous studies, starting with larger topographic scans, moving to medium-scale architectural plan scans, and then to small-scale scans of archaeological elements (such as hieroglyphic inscriptions, reliefs, or small-scale architectural components). As in previous studies, this 3D data was recorded in a local coordinate system and integrated with Total Station instruments to match it with Ḫattuša's geolocated archaeological data, GIS databases, and cartographic records. For this reason, Ground Control Points were used for most of the scans (see Marazzi *et al.*, 2020).

3.2.4.3. Results

The work in this region has involved extensive topography and object scanning, intending to help to find clear answers to the archaeological, architectural, and stratigraphic questions that are likely to arise. Furthermore, a large amount of scanning has been carried out, with the potential to serve one of the main objectives of the Italian survey: to use as many different 3D scanning tools as possible and to contribute to the theory and methodology of these tools (see § 1.2). In addition to the documentation already obtained, the highly detailed scans can help answer archaeological questions likely to be asked later in the project, such as Hittite construction techniques, use of building elements, and architectural dating (Marazzi *et al.*, 2020: 88).

CHAPTER 4

DISCUSSION

4.1. Introduction

As the Results sections of the Ḫattuša case studies (§ 3.2) make clear, the 3D methods used have enabled the research team working at the site to successfully solve some research problems that would have been difficult, if not impossible, to solve using traditional methods. In particular, the epigraphic problems at Kammer 2 and Nişantaş (§ 3.2.1.3); the research questions at Yazılıkaya based on epigraphic and art historical concerns and the need for confirmation of previous literature (§ 3.2.2.3); and the archaeological character of the gorge area, which was challenging to understand due to its complex topographic/orographic structure (§ 3.2.3.3), have all been clarified by 3D methods. In addition to these three positive contributions, the documentation of the Great Temple (§3.2.4.3) does not yet seem to have helped solve a specific problem as in the other three case studies. This is because, in addition to the fact that the scans conducted at this particular site have not yet been thoroughly analyzed, it is a building complex in which many architectural elements and archaeological contexts coexist. A complete understanding of this site will probably take a long time, even with the best 3D scanning results, as it will require a holistic analysis of the numerous objects scanned. Nevertheless, it is possible to say that the Great Temple has been captured in 3D in exceptionally high quality and immortalized as a cultural heritage landmark.

Although 3D scanning methodology can provide further functional analyses for archaeological themes in terms of its results, researchers may have to pay some inherent trade-offs to apply these methods at Ḫattuša or any other archaeological site. To better understand the impact of such requirements on the efficiency of 3D scanning methods in archaeology and to be able to put them in context with the examples at Ḫattuša, it is necessary first to make some observations about the peculiarities and dynamics of 3D applications at Ḫattuša (§ 4.2). Then, based on the observations made about the site, general evaluations of 3D scanning applications in archaeology will find their place in this chapter (§ 4.3). The section on general considerations of the very nature of the 3D scanning itself is divided into four sub-categories: technical evaluations of 3D methods, evaluations of administrative issues during the implementation of archaeological projects, non-3D alternatives to solve some archaeological problems mentioned above, and finally, reflections on the publication and demonstration of 3D scanning results. The chapter concludes with some final remarks on 3D studies for particular research questions and the relevance of 3D studies to the ancillary sciences of archaeology (§ 4.4).

4.2. Observations and Assessments on 3D Studies at Ḫattuša

3D scans seem to have successfully answered most of the research questions posed for the case studies in Ḫattuša. The contribution of 3D scans to clear research questions, such as the problematic state of legibility at Nişantaş, the analysis of complex elements in the gorge area, and the investigation of previous literature for Yazılıkaya, cannot be overlooked. In addition, archaeological and cultural heritage elements have been adequately recorded in all these cases, including the Great Temple.

The techniques currently used to document and analyze large archaeological sites, such as the large-scale survey of Yazılıkaya and the Südburg region, seem ideal. In this case, imagining a more convenient way to holistically study these specific sites' topography, reliefs, and inscriptions is not easy.

For a case like Nişantaş, where the main problem is readability, the survey conducted to answer the research question is already very successful. However, another widely used tool, Reflectance Transformation Imaging (RTI), could also have provided promising results to answer the question. (For more information on RTI, see §4.3.3.2). It should be noted, though, that the data obtained with RTI could not be integrated into the overall Ḫattuša survey.

For the gorge area and the Great Temple, 3D scanning tools are not necessarily irreplaceable, especially for topographic recording, and conventional methods can and have been used there, although they would require much more physical effort (see Bittel, 1976). In contrast, the complex archaeological elements in the gorge area, especially the tunnel, seem too complex to be recorded by conventional methods. The steep walls of the cliffs and the impossibility of surveying or even walking in many parts of the gorge area make 3D scanning tools very useful, if not for the topographic recording of this area, then for the recording of the archaeological elements within it.

It is essential to remember that most of the tools used in Project Ḫattuša are too expensive for most archaeological research projects and not accessible to most researchers. Even Ḫattuša - an extensive archaeological excavation that is very well funded compared to many others - would probably not have been able to incorporate these methods into its research without the international cooperation between Germany, Italy, and Turkey. General considerations on the price of 3D scanning tools are discussed in more detail in § 4.3.2.1.

Another observation relates to the minimal use of UAV-based 3D scanning during the period of the 3D scanning surveys, and in the cases where it was used, it was not LiDAR-equipped drones but drones with cameras suitable for airborne photogrammetry (see § 3.2.4.2). The following sections discuss why airborne LiDAR, which would have been suitable for all of the case studies, especially The Great Temple and the gorge area, may not have been used, even though it is a swift and very reliable tool for scanning archaeological landscapes (§§ 4.3.1, and 4.3.2).

Although not directly related to the Italian expedition and Project Ḫattuša, a final observation is that the Ḫattuša excavations favor traditional drawing techniques as the primary method of day-to-day archaeological documentation. 3D scanning tools and orthophotos/orthomosaics are often auxiliary methods at Ḫattuša. More on this will be discussed in § 4.4.2.

4.3. Assessments on 3D Scanning Studies

Rather than dealing directly with Ḫattuša, this section evaluates the 3D tools used at the site and their advantages and limitations for archaeological applications more broadly. The assessments are based not only on the published case studies of Ḫattuša but also on the author's own field experience there (§§ 4.3.1 and 4.3.2). It also briefly examines some non-3D digital methods that may be preferable to 3D scanning tools in some cases (§ 4.3.3). Finally, it discusses the publication and exhibition of 3D scanning results (§ 4.3.4).

4.3.1. Technical Assessments

4.3.1.1. Field dynamics

Field Dynamics includes ground conditions such as bulkiness of technical equipment, weather, light, and reflections that affect the usability of 3D technologies. For instance, Terrestrial LiDAR scanners are mounted on a tripod and may require an external power supply. In addition, they are heavy to transport in the field since the "head" alone, which performs the scanning operation, is around 15-20 kg, while together with the tripod, power supply, laptop, and camera, if necessary, this weight can exceed 40 kg (Charlton, Coveney & McCarthy, 2009: 40). This weight can become a slowing and tiring factor for the surveyor, especially in field conditions, and often results in the work not being carried out by one person alone.

Weather conditions also significantly impact both Airborne and Terrestrial LiDAR applications. Especially in airborne scanning operations, wind and precipitation can directly impact flight. Terrestrial laser scanning can similarly be affected by weather conditions. For example, heavy fog, rain that creates puddles on the ground (which has a negative effect on the reflectance of the laser beams), or rain that soaks the scanner glass can cause errors in the scan result (Charlton *et al.*, 2009).

Lighting is more critical for structured light scanning than terrain conditions. Very sunny or well-lit environments make it difficult for the cameras to detect the light patterns projected by the structured light scanner. Consequently, errors in the scan results are likely to be encountered. Therefore, when using these instruments, working in dim or dark environments, or even at night, can help to achieve effective results (Opitz & Cowley, 2013b: 19).

Photogrammetry is a method that is relatively unaffected by terrain and external elements, except in wet environments that can cause glares. Digital cameras used for photogrammetry are often lightweight and rugged, do not require external power sources, and are operated by only one person. Photogrammetry, on the other hand, requires a slightly illuminated environment. In the case of under-exposure, the cameras have difficulty taking clear pictures suitable for data processing. Moreover, the long exposure method that can be used to avoid this will result in camera shakes and noisy or problematic images. It is, therefore, important that the photogrammetry environment is sufficiently bright for the subsequent data processing. Nevertheless, too bright light and the resulting contrasted shadows may be disturbing for some in terms of the overall quality of the photogrammetric model. For this reason, soft light (such as in cloudy weather or conditions just before sunrise or just after sunset) can be seen as ideal lighting during photogrammetric practice.

4.3.1.2. Acquisition time and accuracy

Time spent in the field while applying the scan methods can be named the acquisition time. Still, it is difficult to compare methods in terms of acquisition time in the field, as it depends on many factors such as the experience of the user, the size of the area to be scanned, the number of scan positions required to scan the theme in the case of LiDAR thoroughly, and environmental changes during the application (weather conditions, differences in lighting, whether the archaeological site is open to the public, and if people or animals are roaming the area, etc.).

Accuracy, on the other hand, like resolution, is related to both spatial scale and acquisition time. For example, the higher you fly a UAV doing photogrammetric scanning, the faster it goes, the fewer photos it takes in the same area, and the lower the point accuracy and resolution. To increase accuracy, you have to fly lower, which means more photos at higher resolution and much more time to acquire and process them. A similar balance is true for all of the scanning methods discussed here.

Moreover, in most cases, the scanning techniques to be applied will be determined by the needs of the research project, including the need for higher or lower quality or resolution in the scan, and these needs directly impact the acquisition time.

For a project where the purpose of scanning is to obtain a substantial topographic record, the area to be scanned will affect the operating time of the airborne scanners. If the same area is scanned with a terrestrial laser scanner, this time will increase significantly and even multiply. If such a large area is scanned with aerial photogrammetry, although a similar amount of time is spent with airborne LiDAR, the scan results and details will significantly lose clarity.

In a different hypothesis, let us imagine a scenario where we scan the interior walls of a chapel with frescoes on the surface. In such an environment, photogrammetric modeling can be applied by taking only a few tens of photographs of the interior façade with a DSLR camera equipped with a wide-angle lens. In this process, the acquisition time will be reasonably short. However, although relatively slower, the structured laser scanner will give more accurate results with fewer possible errors in post-processing.

In any case, it can be commented that the accuracy of the 3D photogrammetry concept is, overall, lower than the other two methods. For 3D scans and point clouds, the accuracy can be measured by observing the possible errors. LiDAR provides millimetric accuracy with less than 10 mm point error for an up to 100 meters range TOF scanner (Hetherington, 2009: 90). Although for significantly shorter ranges and narrower scanning areas, Structured Light Scanners generally provide even more accurate scans with less than 1 mm of error (Piedra-Cascón *et al.*, 2020: 573). These numbers are generally around one or two centimeters for photogrammetry, which is multiple times less accurate than the other two methods (Brandolini *et al.*, 2021: 35).

Besides its relatively lower accuracy, there are other concerns about SfM photogrammetry, its precision, and its realism. Since it is a passive method, it can develop errors, although not significant, depending on the state of light and shadows. Especially when integrated with geolocation data, some errors can be observed, such as unwanted distortions. These problematic surface distortions due to geolocation errors can also be found in other georeferenced survey results. For example, manual georeferencing of GCP points (also used in some TLS models) to match local coordinate systems can result in similar distortions or alignment errors due to possible calibration errors associated with the total stations or their users. However, unless SfM is done with perfect selections of a large number of photographs - and even those cannot be said to be absolutely accurate due to wind movement of vegetation, changes in shadows, blind spots that cannot be captured in the camera shot, differences in lighting - it is likely to have problems with millimetric, if not centimetric, accuracy. In addition, the level of realism may be compromised (such as the appearance of blurred vegetation or high-contrast shading in the 3D model) due to these unwanted causes. How such problems can be corrected or how photogrammetry can be improved and made more efficient as a cheaper and more readily applicable method is discussed in more detail in § 4.4.2.

While there is limited quantitative information from Ḫattuša about how much time its 3D survey acquisitions have taken, at least some papers examine photogrammetry studies and conventional drawings regarding how long they take. In a study by Murray *et al.* (2016: 7) comparing both photogrammetry and conventional drawing methods in terms of time, the total labor time required to draw a building with a wall perimeter of approximately 200 meters stone-by-stone and record it with photogrammetry - all procedures such as site clearing, geodata collection, data processing, and drawing detailing were taken into account for both methods - was estimated (Figure 27). From the observations and calculations, it was concluded that even in the scenario where conventional drawing is the fastest and experienced illustrators manage the process, it is twice as slow as photogrammetry (about 1 meter per hour for drawing and about 2 meters per hour for photogrammetry). This result can be up to four times slower in a setup where students draw instead of experienced illustrators (drawing: about 0.5 meters, photogrammetry: about 2 meters).

4.3.1.3. Processing time

The processing time for 3D scanning methods can vary depending on several factors, including the type of scan, the hardware used, the size of the area being scanned, the level of processing during acquisition, and the practitioner's expertise. As a result, it is difficult to predict exact post-processing times. However, post-processing high-resolution point clouds will take longer than processing low-resolution point clouds.

In a scenario involving scans of comparable size and quality, LiDAR and Structured Light Scanning offer the most efficient post-processing methods. LiDAR generates point clouds during acquisition, so post-processing primarily involves aligning the point clouds obtained from different scanning positions. Structured light scanning similarly captures surfaces using light patterns, and the resulting distortion in the patterns is recorded concurrently, making post-processing relatively brief. Conversely, photogrammetry demands significant computational power to convert two-dimensional photographs into a three-dimensional depth map and point cloud (Westoby, Brasington, Glasser, Hambrey & Reynolds, 2012: 303). This means that post-processing photogrammetric data in three-dimensional space is a crucial aspect of photogrammetry, and it may take hours or even days to produce high-quality photogrammetric models of extensive areas.

4.3.2. 3D Scanning Management

4.3.2.1. Cost

The prices of devices used for 3D scanning are highly dependent on many factors, such as the quality of the devices, extra hardware, software features, and so forth. Nevertheless, devices belonging to the scanning categories mentioned above can be compared with each other in terms of price. Of course, various hardware differences may lead to exceptional pricing and falsify the generalized price ranges presented here.

Photogrammetry is the cheapest 3D scanning and application method mentioned, which does not require special equipment. Simple photography with the help of commercially available cameras is often within reach of many. The software required for post-processing photogrammetry is often either relatively inexpensive (e.g., Agisoft Metashape, Autodesk ReCap, 3DF Zephyr, RealityCapture) or entirely open-source and free of charge (e.g., Meshroom, Regard3D).

	Terrestrial Laser Scanners	**Structured Light Scanners**
Beginner level devices	FARO Focus S 70 $35,000	Artec Eva Lite $9,800
Medium level devices	Artec Ray $60,000	Artec Eva $19,800
High-end devices	RIEGL VZ-400i $120,000	Hexagon AICON PrimeScan $35,000

Table 2: Example prices for TLS and SLS instruments.

*All prices are from aniwaa.com, August 4th,2023.

**Airborne laser scanning and SfM prices are not presented in this table since the final prices change depending on the set-up. (LiDAR sensors and aircraft for ALS; and cameras, lenses, and software for photogrammetry are typically customized by users according to their needs).

One of the main factors that can significantly increase the cost of operation for photogrammetry is the positioning systems required to geo-reference the SfM models made for land recording. Total station or GNSS systems are often available for several tens of thousands of dollars. However, positioning systems are long-term investments for many excavation projects, and it can be misleading to associate the cost of these systems with the overall cost of photogrammetry applications.

The situation for structured laser scanning devices is different from photogrammetry. Since this method requires its particular scanner instrument, it is considerably more expensive. Structured Light Scanners are often sold for over ten thousand dollars (see www.artec3d.com). Moreover, most of these scanners are designed for scanning medium and small-sized objects and surfaces and are seldom used for geographic scans (see Jecić & Drvar, 2003: 244).

LiDAR scanners are the costliest of the scanners mentioned, with some models, such as an industrial RIEGL scanner, costing more than a hundred thousand dollars (www.aniwaa.com, retrieved in August 2023). In Airborne LiDAR, LiDAR systems and the aircraft and its operation process must be afforded. On the other hand, Terrestrial Laser Scanners often require external power supplies at an extra cost, and they are costly instruments standing alone.

4.3.2.2. Learning and expertise

To utilize these applications effectively, researchers require trained surveyors who understand these methods proficiently. Both students and professionals may utilize various scanning techniques for research purposes. In the field of 3D scanning in archaeology, considerations of the learning curve, transfer of expertise, and cost of training are essential. On the one hand, specific techniques, such as Structure from Motion (SfM), can be acquired quickly and at no cost due to the abundance of freely available resources and open-source software. However, other techniques, such as Terrestrial Laser Scanning (TLS) and Airborne Laser Scanning (ALS), typically require specialized courses or learning materials, often at considerable cost. Second, the time required to master these techniques varies widely, with some requiring only a few hours to learn and others requiring weeks or even months to master. Finally, the accessibility of the technology is influenced by the level of expertise required. Inexperienced researchers can easily engage with certain techniques, while others require the involvement of trained specialists, severely limiting access to many archaeological projects.

Of the various scanning methods available, photogrammetry proves to be the most accessible and easy to learn. The swiftness of the learning process can be attributed to the widespread familiarity with cameras, as opposed to the more complex instruments required for alternative methods. In the author’s experience, this technique can be mastered in as little as a week with appropriate instruction and can be utilized in archaeology for daily documentation. However, it should be noted that the more complex application of photogrammetry, involving the merger of various models and the generation of new data, may necessitate expert knowledge and prolonged study.

Access to these instruments must be provided to initiate the learning process for LiDAR and Structured Light Scanning. Acquiring such equipment, particularly in the case of LiDAR, can prove to be challenging due to the high cost of these instruments.

On the other hand, airborne applications necessitate a distinct set of skills. In addition to training in archaeology and 3D scanning, the operation of an aircraft requires extensive instruction. Charlton *et al.* (2009) report that it took them approximately six months to attain proficiency in Terrestrial Laser Scanning. It can be inferred that a similar amount of time may be required to master airborne scanning. In the case of LiDAR scanning alone, it may be plausible to assume that the airborne method may be easier to learn than TLS due to the superficial nature of the scans. However, it should be noted that piloting an aircraft requires significant practical experience and effort.

4.3.2.3. Legal Limitations

The Republic of Turkey heavily regulates aerial activities through several authorities, one of the key pillars of 3D scanning efforts. Article 144 of the Turkish Civil Aviation Law No. 2920, dated 14/10/1983, stipulates that unmanned aerial vehicles must be registered to the Directorate General of Civil Aviation. In addition, the areas where these UAVs can fly are determined by the Ministry of Transport, Maritime Affairs, and Communications in accordance with this law, so there are restrictions on some areas. Furthermore, other parameters, such as the maximum weight of the drones in question and the maximum height they can rise to, are also determined by the relevant articles of law and legislation. Apart from all these regulations, drones must obtain official permission from the Directorate General of Civil Aviation to record video/image footage. Besides, aerial recordings of areas such as cultural sites for scientific research must be declared in the Excavation Research Plan and approved by the Ministry of Culture or the relevant Provincial Directorate of Culture. The drone pilot must have a piloting license, and the type of certificate (UAV-0, UAV-1, UAV-2, or UAV-3) must be appropriate to the drone's characteristics. Turkish and foreign drone users in Turkey must comply with all relevant laws, regulations, and instructions.

Given that the requirements and regulations are relatively complex and difficult, especially for non-Turkish researchers, obtaining permission to use heavy UAVs equipped with powerful sensors can be an obstacle. This may be one of the main reasons why industrial drones equipped with LiDAR were not used in the surveys at Ḫattuša. For this reason, it is possible to say that such regulations, examples of which are found in many countries and which aim to ensure flight safety and prevent espionage activities, are one of the significant disadvantages of aerial 3D scanning operations.

4.3.3. Evaluating Non-3D Scanning

Other methods may be more suitable than 3D scanning technologies depending on the intended use. Satellite-based remote sensing applications can be healthy substitutes for airborne scanning and TLS to answer research questions requiring extensive topographical surveys. On the other hand, Reflective Transformation Imaging (RTI) is often preferred by archaeologists and philologists for archaeological questions such as vanishing reliefs and inscriptions.

In some ideal circumstances, such a tool change can reduce the time or cost of research and overcome obstacles caused by a lack of 3D expertise and equipment in the research team or by legal restrictions.

4.3.3.1. Satellite-based remote-sensing

Many satellite image providers are actively updating imagery, and many are free of charge. There are also commercial satellite imagery providers that charge different fees for higher image resolution. Some of the satellite service providers may be able to provide elevation data to their customers, although the accuracy and precision may be questionable. In this way, datasets such as DEMs or DTMs, often used for landscape archaeological studies, can be produced by experts and used for archaeological interpretation or documentation. Of course, one significant consideration when using satellite imagery is the cost. Custom high-resolution DTMs, which may be required for capturing fine details, can result in substantial expense as they typically require coverage of extensive areas, ranging from 500-1000 km^2 or more, at a rate of $5-10 per km^2.

Furthermore, the highest available resolution for commercial DTMs may be limited in certain regions, such as Turkey, where it may be constrained to 5-meter resolution (ALOS 3D World), which is far away from not being optimal for detailed analysis of intricate features, such as the Ḫattuša gorge. Similarly, older satellite scans, like the CORONA satellite imagery or its successor HEXAGON KH-9, can be handy for recognizing traces of archaeological landscapes (such as hollow paths or urban plans), as they were taken before the industrial and urban boom of the second half of the 20th century. It is important to note that the availability of CORONA satellite imagery may be limited to specific regions, such as south-eastern Turkey, and its successor, HEXAGON, may offer higher resolution but may still fall short of capturing fine details in landscapes, with a resolution typically ranging from 4-6 feet, corresponding to 8-12 feet of DTM resolution. In short, almost any satellite-based DTM will not be as detailed in its resolution as a high-quality aerial survey [up to centimeter resolution, depending on various parameters such as flight altitude and speed, laser emission frequency, etc., while most commercial satellite services provide metric resolution, such as ALOS with max. 5m in Turkey, and Quickbird (panchromatic) with max. 61 cm (see Karan, Sivakumar, Irizarry & Guhathakurta, 2014).

4.3.3.2. Reflective Transformation Imaging (RTI)

Reflective Transformation Imaging (RTI) is a non-3D, computational photographic method that allows for the digital enhancement of subjects that are difficult to read or recognize, such as inscriptions, reliefs, carvings, and incisions (Figure 28) (Cultural Heritage Imaging 2023). It is typically applied by taking a large number of photographs of a fixed surface with a fixed camera, illuminating the surface from different angles for each photograph (Lech, Matera & Zakrzewski, 2021). In this way, the way the object's surface reflects the light is recorded and can be dynamically modified in the RTIViewer program. The software required to implement this method (RTIBuilder and RTIViewer) is entirely open-source and free of charge. For practical use, a light dome prepared for RTI provides ideal conditions, but a simple DSLR and suitable light sources often provide satisfactory results (see Durusu-Tanrıöver, 2020).

RTI is a very inexpensive method, and, despite its simplicity, it can provide very efficient results, making it a very suitable method for solving some epigraphic and archaeological problems. For this reason, it is used in many archaeological projects, including those in Turkey.

4.3.4. Assessments on Research and Publishing

4.3.4.1. Publishing 3D research data

Above, it is mentioned that one of the biggest problems with 3D scan results, in general, is that they do not conform to traditional scientific publishing methods. Certainly, altering the entire publishing tradition is not a realistic plan to deal with this problem. Recent developments in both hardware-based and internet-based data storage technologies over the last decades, such as the dramatic improvement in the ability to store data such as vast amounts of photos, and the widespread availability of high-operating-capacity computers that make it easier to play sophisticated graphics, have strengthened the potential of 3D data in the virtual world (see Hoffmeister, 2018; Oguchi, Hayakawa & Wasklewicz, 2011: 197).

In archaeology, many excavation projects, including Ḫattuša, are already attempting to make their 3D recordings available to interested audiences in some way, for example, through links in articles, QR codes, or physical displays (see Schachner, 2019: 110). Online or face-to-face display methods are increasingly dominant in the emerging new research environment. So perhaps it would help to update contemporary archaeology without leaving anyone behind if today's academy gradually became more proactive about how new mediums can improve it rather than engaging in vicious debates about whether these methods are traditionally correctly academic. Online resources that publish archaeological data as open-source and have been editorially overseen to become genuine academic journals have started to be launched. The *Journal of Open Archaeology Data* (https://openarchaeologydata.metajnl.com) is a good example of this, making the data that researchers think might be useful to others available through various online repositories. Similarly, there are various other portals where archaeological research projects store and indirectly share their meta-data online (e.g., https://archaeologydataservice.ac.uk/).

With purely digital publication methods, as we have already mentioned, some phenomena can potentially create problems regarding the quality and detail of the content. The first of the two most important are the data transfer rate and the large data size. This is critical for 3D scans, and while 3D data shared online often requires a few tens of megabytes of storage for low-resolution non-photorealistic models, high-resolution models can often be several hundred megabytes or even several gigabytes, depending on their content. Moreover, raw point clouds covering large areas, as produced in LiDAR scans, often require at least several gigabytes of storage, depending on the scan density. The second possible problem, on the other hand, is the hardware power required for a smooth display of 3D recording content such as point clouds and meshes, which is generally directly related to the viewers' devices, and can only be improved by having stronger devices. It is possible to discuss potential solutions for these two problematic phenomena.

The problem of high data sizes and the resulting problems with internet download/upload speeds can be solved from two perspectives. The first one is to reduce the data size, and this can be achieved mainly by reducing the granularity of the recordings by the expert (who may well be an archaeologist) taking the recordings or processing the data. The second option could be a scenario in which the data transportation and data storage qualities of the internet are changed as a macro-scale external factor that is entirely independent of the nature of the 3D records and the Web 3.0 phenomenon, which has the potential to help in this regard, promises a digital environment that transfers data directly between users without passing it through centralized repositories, but through the semantic network it creates (see Gan, Ye, Wan & Yu, 2023). While some work is being done commercially, this is only a proposal for archaeological use.

In any case, transferring 3D records to the viewer seems to require a paradigm shift. Regardless of Web 3.0 or alternative data transportation facilitators, evaluating the "data minimization" way that is currently available to us is necessary. It is a fact that the sharing of 3D data in an archaeological context must necessarily carry an archaeological interpretation since the question of what precisely archaeological representations (even if they are photorealistic 3D models) mean is necessarily understood by adhering to the archaeological context. This context is not merely the material appearance that 3D models can convey. Without the interpretative analyses of trained archaeologists, considering all factors, 3D models would be nothing more than fancy graphic reproductions. As such, it is open to question the importance of the "detail" carried by 3D models and in which situations. In other words, except for the aforementioned examples, such as Nişantaş or Yazılıkaya, not every 3D model representation has to be of maximum graphic quality and detail. For instance, an online publication that focuses solely on the archaeological plan of the Great Temple may not need to include all the architectural elements of the building in great detail.

The DAI's iDAI.objects portal (https://arachne.dainst.org/) offers a service that fits this concept and, at least for Ḫattuša, allows viewing small, non-bulky 3D models. In this portal, some scans (including the scans from Yazılıkaya, Nişantaş, the Great Temple, etc.) can be viewed online with substantial identification, such as who produced the models and which academic source they are published, and the viewer can download these low-resolution non-photorealistic models. For institutions with budgets, such as the DAI, publishing 3D models through their web repositories can be pretty functional. Indeed, a similar approach could be adopted by independent archaeological research projects. Of course, this requires adequate and sustainable funding. This is because web portals for archaeological excavations and surveys, which are often designed to be temporary, depend on this funding to continue storing large amounts of data long after the projects have ended.

4.3.4.2. Exhibiting digital cultural heritage

In addition to the academic publication of 3D data, there may be other opportunities to share 3D data with the public or to use methods commonly used for entertainment to create academic content and visual aids. This section briefly summarizes the digital methods considered helpful for the exhibition of archaeology and all kinds of cultural property. Three innovative approaches for showcasing 3D scans of cultural heritage, i.e., Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR); Video Mapping; and Video Games, are the most common 3D exhibition concepts.

4.3.4.2.1. VR, AR, and MR

Virtual, Augmented, and Mixed Reality concepts stand out as prevalent and sensational ways of exhibiting 3D archaeological insights with the viewer experience, taking the possibilities offered by screen-oriented data-sharing platforms created to "show" 3D data one step further (see Forte, 2014b). It is possible to get inside the replicated 3D scan results, such as the extensive landscape and architectural scans at Ḫattuša, through VR and travel through these sites to experience them in true-to-life realism. Augmented Reality contributes to understanding archaeological sites by overlaying informational data and markers on actual images differently, but it is not a suitable method for sharing 3D scan data. The intriguing Mixed Reality (MR) concept, on the other hand, is both important and promising in terms of creating exciting virtual atmospheres where 3D models (such as models designed by analyzing the archaeological context in line with archaeological investigation and research), rather than actual 3D scans, are simultaneously superimposed on authentic images of real sites and presented to the viewer. This way, the MR can show the audience not just what is there but also what is not there.

Considering these, VR is the perfect concept for sharing 3D scan results with the audience as they are, and it allows sharing of raw scan results (primarily environmental records) without the need for any creative process in the scan results. MR, as a slightly different concept, is an exhibition method that provides predictions rather than reports since it displays innovative modeling products in real environments. In any case, both concepts have the potential to be influential in the future paradigm of academic publishing.

4.3.4.2.2. Video mapping

The near-virtual concept of video mapping is very effective as it highlights a range of details that can be visualized more clearly through models, even if they are not models themselves. In this concept, light projections can be projected onto the original surfaces or 3D plastic replicas of these surfaces to visualize hard-to-see or archaeologically discovered finds in their original locations. For example, Repola (2016: 611) explains in an earlier article that after the obscure inscriptions on the reliefs of Nişantaş were understood through a series of manipulations using 3D methods, inscriptions and textures close to the original were projected onto a 3D-printed replica of the monument. Of course, video mapping is a concept that needs to be supported by a well-prepared museological and curatorial background (see Pescarin, 2014).

4.3.4.2.3. Video games

The concept of video games, or simulations in more general terms, has made great strides in recent years and has the potential to be a very viable source for bringing archaeological sites and data to interested people. This concept not only allows the "player" to experience the original 3D survey records by "traveling" through them but also to experience the realistic and largely historically accurate and interpretive fictional environments created through archaeological research (Forte, 2014b: 117).

4.4. Final Remarks

4.4.1. Optimality of 3D techniques used at Ḫattuša

The Ḫattuša cases present some typical archaeological challenges that can be found in many other archaeological projects. It seems that some specific 3D scanning tools are closer to being optimal for solving such typical problems than others, given the evaluation criteria shared in §4.3. Of course, the “best 3D scanning tool” is not absolute. Instead, it is relative and depends on many factors, such as the research question, time, funding, or instrumentation.

LiDAR scans provide the most reliable results in small landscape surveys such as the gorge area, especially in the presence of dynamic geographic elements such as vegetation and watercourses. In the case of the gorge, the topography is highly complex and steep, making airborne methods unsuitable for scanning narrow, hidden areas (such as tunnels or caves). Although logistically challenging due to the landscape conditions, the most successful topographic scanning was achieved using terrestrial laser scanners.

Structured Light Scanning could be a viable method for solving the epigraphic problem in the Nişantaş case. Although it costs several thousand dollars, its high accuracy and ease of use make it an outstanding tool. Photogrammetry, on the other hand, although typically offering relatively low accuracy, is always preferable in an epigraphic context because it is a low-cost method. Finally, although not a 3D tool, RTI is one of the more commonly preferred methods in the field, both in terms of cost and data clarity, and is certainly an option for inscriptions and reliefs in settings such as Nişantaş or Yazılıkaya.

It is fair to say that airborne methods are better suited to scanning large architectural plans like the Great Temple. However, I believe that airborne LiDAR is too expensive and difficult to access for this type of work, despite the slightly higher level of detail and quality it offers. In addition, this particular tool requires overcoming severe legal challenges in order to be implemented in Turkey. Instead, aerial photogrammetry would be sufficient to capture the overall architectural plan.

There are, of course, good reasons for the Italian expedition to have used a wide range of tools for all these archaeological problems, and not all problems can be expected to be solved using only the most ideal method. Archaeological research areas almost always consist of more than one archaeological element, and naturally, each element needs to be analyzed using different methods.

4.4.2. Maximizing the Potential of Photogrammetry in Archaeological Documentation

It is currently impossible to reduce the price of Laser Scanning (LiDAR) or Structured Light Scanning (SLS), which provide great detail and fast and efficient results, or to reduce the rental costs for archaeological research projects. However, improving the accuracy and detail of inexpensive photogrammetry methods is technically possible and relatively straightforward. In this respect, it is possible to maximize the efficiency of SfM with some simple field and post-processing procedures that need to be focused on, and it is possible to evolve it not only to standalone models but also to multi-layered 3D documentation works that work integrated.

The main question is the nature of the archaeological feature to be documented. In the case of Ḫattuša, documenting specific problems or monumental/artistic remains with SfM would naturally require a high level of detail. In such a case, the quality of the recordings taken in the field is crucial. The ideal quality of many factors, such as how "soft" or "hard" the ambient light is in terms of its contrast, the condition of the vegetation or other environmental factors, the camera equipment used, the positional accuracy of the GCP points, etc. will significantly improve the quality of the model. However, the use of SfM in archaeological research is not limited to such specific problems; as a broader and more effective methodological concept, SfM is often preferred in daily archaeological record-keeping. GIS-based software such as Esri® ArcScene are well suited to presenting 3D meshes produced by photogrammetry programs such as Agisoft Metashape in three-dimensional space and can provide extraordinarily efficient stratigraphic observation, especially in conjunction with general archaeological artifact information during everyday field archaeological recording. Although presenting stratigraphic information in post-processing can be very time-consuming and specialized, systems such as the Locus-Lot System (see Gates, 2020) or comparable documentation systems used in most archaeological excavations can provide an environment in which the archaeological components and units of excavation sites can be documented instantaneously with 3D photogrammetry, at least during fieldwork. Daily documentation through 3D SfM, together with, of course, the recording of artifacts encountered during excavation and common bulk materials such as sherds and bones, is a method that facilitates archaeological documentation, regardless of whether or not the highest quality graphical records are obtained. Regardless of the details of its appearance, multi-chunk SfM models not only visualize the archaeological conjuncture at the excavation site more accurately but also provide a comprehensive stratigraphic understanding that can be considered as 4D rather than 3D since they are efficient resources in terms of representing the chronological information. By planning the chunks according to the archaeological units, such as loci/lots or contexts (depending on the excavation methodology), archaeologists can integrate the daily 3D records with the archaeological find and observation data. Furthermore, these applications have been used as the primary documentation method in many archaeological excavation projects in recent years. Some projects have taken this understanding even further. The number of 'paperless' excavations, where the methodology of excavation documentation is based entirely on SfM and where no conventional drawing methods are used, is growing by the day (see Scott *et al.*, 2021).

It is a fact that photogrammetric models must be of high graphic quality in situations where readability or comprehensibility is an issue; otherwise, the method is likely unhelpful. It is precisely this need for very great detail that is the main reason why Structured Light Scanning is often used, as in the case of Nişantaş or Yazılıkaya, where the intention is to read faint reliefs on very complex surfaces. On the other hand, SfM photogrammetry is much more suitable for daily field archaeological recording due to many factors such as ease of use, regularity, lack of need for a very high level of detail, and low cost. Because the frequent, daily documentation of excavation sites, which often have more than one trench, does not require bulky, large, and expensive laser scanners. At this point, it is essential to acknowledge that the minor weaknesses in detail, accuracy (often millimetric errors), or precision that SfM can cause should not lead to the assumption that it is an impractical method. In any case, for this kind of day-to-day documentation, it is enough to ensure that the basic parameters and requirements are meticulously met, and there is no need to shoot a rabbit with an elephant gun for much greater detail.

4.4.3. The synergy between technologists, archaeologists, and others

Campana (2014: 11) shares his opinion that technicians applying 3D methods in an archaeological context should have a basic knowledge of archaeology, even if they are not archaeologists. I would go one step further and say that the archaeologist needs to know enough about digital documentation methods to guide the research questions and the chosen methodology, and the 3D specialist needs to understand the research questions in detail. Moreover, again in Campana's view, 3D scanning and other similar scientific/technological methods should be applied based on archaeological questions and motivations, and the central position of the archaeologist should be maintained during the implementation of these methods by specialists. Furthermore, the scope of this necessary synergy is not limited to archaeologists and technologists. As we have seen in the two primary case studies in this thesis (Nişantaş and Kammer 2; and Yazılıkaya), the alignment of disciplines such as epigraphy and paleography with 3D scanning methodologists is critical for solving specific archaeological problems. In this specific case, for example, for Nişantaş or Yazılıkaya, philologists like M. Marazzi or N. Bolatti Guzzo play pivotal roles.

Similarly, although outside the scope of this thesis, the geology and geomorphology of the gorge area are natural and integrated research subjects, as the team conducting the 3D scans comes from DiSTAR, an earth sciences department. Such an interdisciplinary environment also fosters academic collaboration, creates a research environment where different experts from different perspectives learn from each other, stimulates new project ideas and innovation, and boosts knowledge transfer

(Siart *et al*., 2018: vi). Of course, an archaeologist is needed at the center to make all these elements archaeologically meaningful, as Campana suggests. Because whether an epigrapher, a geologist, or an architect is involved, only an archaeologist can holistically construct the ultimate archaeological interpretation.

CHAPTER 5

CONCLUSION

This thesis examined the strengths and weaknesses of using 3D scanning in archaeology regarding the methods used at Ḫattuša. In this way, issues such as price, implementation time, ease of use, clarity of results, learning curve, and legal barriers, which strongly influence the use of 3D methods and their potential contribution, were evaluated. In addition, some ways to improve 3D scanning studies, alternatives that can be used for various specific situations, and their publication were discussed.

3D scanning methods already seem to be indispensable for the future of archaeology. While we have already seen some of the problem-solving possibilities provided by scanning methods in the Ḫattuša cases in this thesis, 3D scanning methods can potentially solve many other problems. In challenging terrain where conventional archaeological documentation methods have limited contribution, 3D scans could be used to read complex and ambiguous epigraphic artifacts, perform comprehensive architectural surveys, and digitally record valuable cultural assets and archaeology items. In addition, other themes, such as the documentation of vast landscapes or the scanning of archaeological objects and art historical elements covering small areas, are also fields where 3D scanning methods are particularly strong.

Nevertheless, some challenges must be overcome for these scanning methods to deliver the desired outcomes in archaeological research. Due to the high cost of LiDAR and Structured Light Scanning, the requirement that they must be practiced by specialists, or because of some legal constraints, researchers may prefer cheaper, more straightforward, or less strictly regulated methods such as photogrammetry. While it is possible to improve the output of this specific method, which is not free of its weaknesses, in some cases, those drawbacks may be neglected in favor of the advantages provided by the method. Of course, the necessity of such an attitude must be wisely judged according to the enquirer's research questions, the research theme, the time or budget allocated for the study, and the instruments at hand.

The publishing or exhibition stage, where 3D scans ultimately acquire meaning, is at least as important as the answers to archaeological questions and should be discussed. This thesis reflects on how 3D scans can be published and experienced well by interested audiences without losing their three-dimensional quality.

All the insights and arguments presented in this research finally lead to some less difficult-to-predict observations for Turkish archaeology. The first of these is the resistance of Turkish archaeology to 3D applications due to several non-archaeological constraints, and the primary reason for this is undoubtedly the high cost of advanced 3D scanning equipment and services. Secondarily, this high cost may lead to a shortage of 3D specialists or a lack of training due to a lack of equipment. Thus, the intrinsic efficiency dynamics of 3D methods will be less critical for archaeologists outside of research projects like Ḫattuša that are fortunate enough to have such equipment and specialists. Relatively inexpensive applications such as photogrammetry are often the only viable option for those projects that, for some reason, dare to undertake 3D studies.

Nevertheless, archaeology's engagement with digital concepts is still in its infancy and has great potential for the future. In particular, the emerging trend of 3D archaeology will be brought to a broader audience through the development of 3D data sharing and publishing. In that regard, one could say that the importance of 3D data publishing has never been more critical. Archaeologists and data scientists should improve 3D data publishing by focusing on this aspect shortly. In this way, they will inevitably make a significant contribution to the completion of the development of 3D archaeology.

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FIGURES

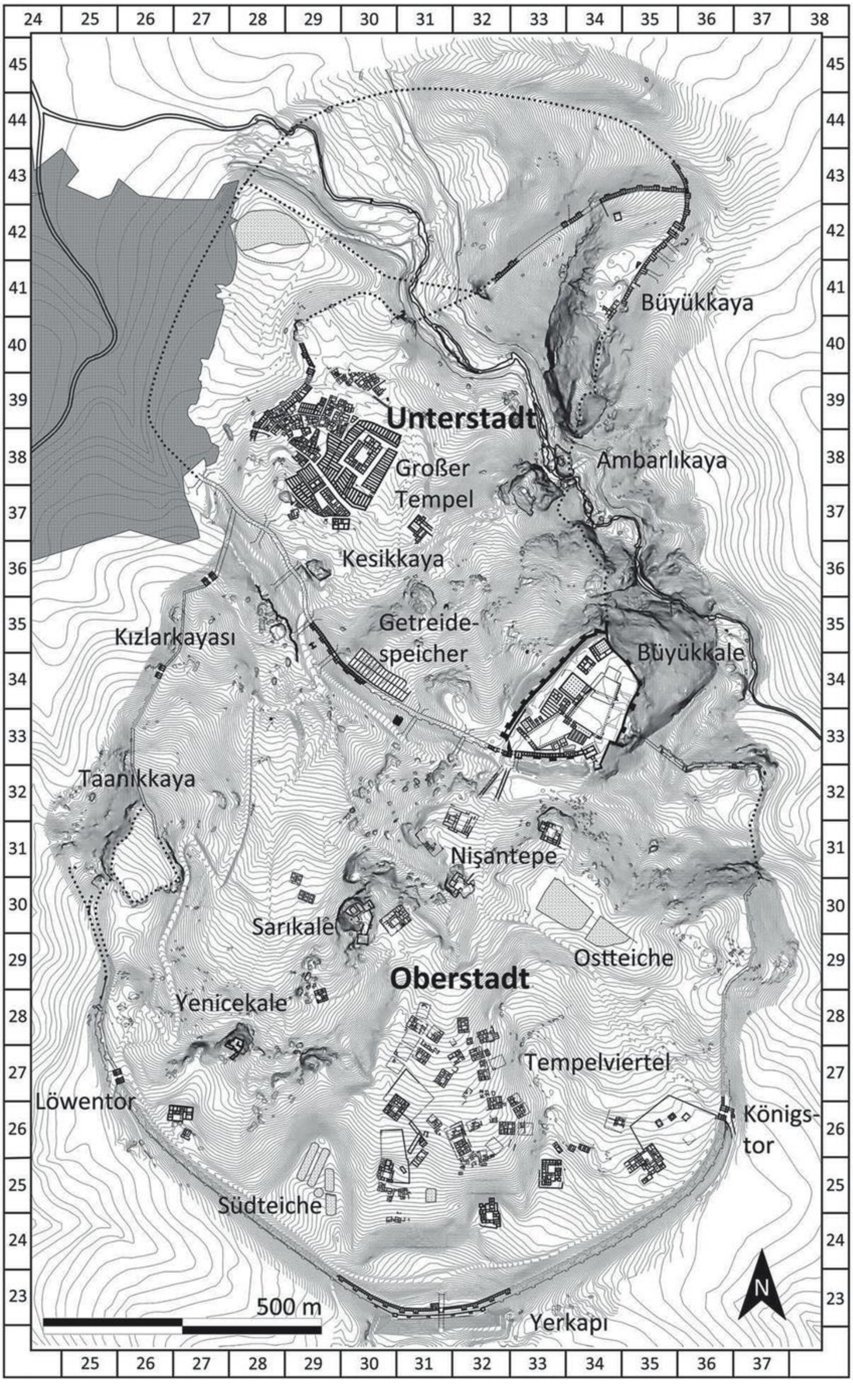
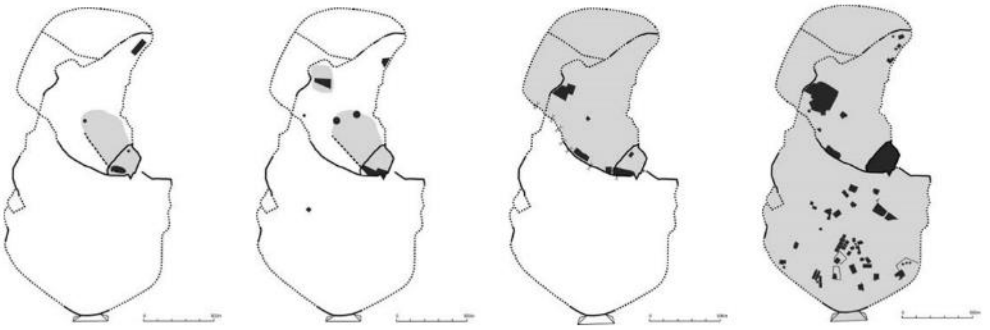


Figure 1 Plan of Ḫattuša (Harmanşah, 2019, with reference to the courtesy of German Archaeological Institute. Image: Dominique Krüger)



Late 3rd millennium BCE

Early 2nd millennium BCE (MBA)

17th and early 16th centuries BCE

From the 2nd half of the 16th century to early 12th century BCE

Figure 2 Development of Hattus(a) (maps: Schachner, 2011)

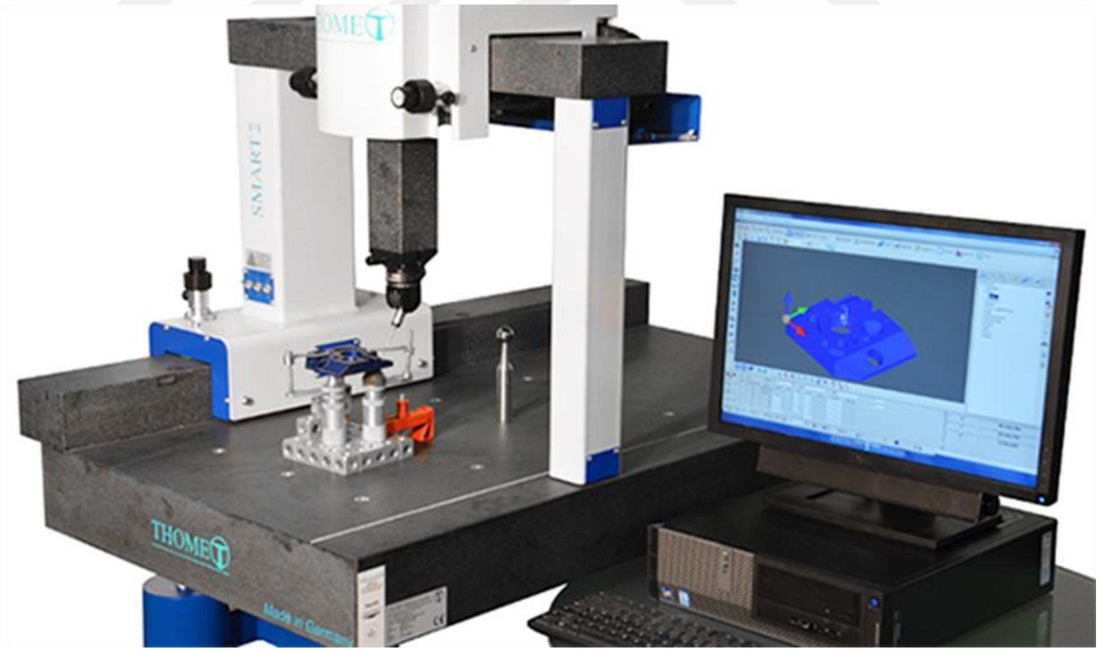


Figure 3 Coordinate Measuring Machine (https://www.thome-precision.com/manual-cmm-coordinate-measuring-machine-smart-thome.html)

Figure 4 A drone with DJI Zenmuse L1 LiDAR scanner mounted (https://www.dji.com/zenmuse-l1)

Figure 5 Riegl LMS-Z 420i Terrestrial time-of-flight laser scanner on Ambarlıkaya (Repola & Tilia, 2020)

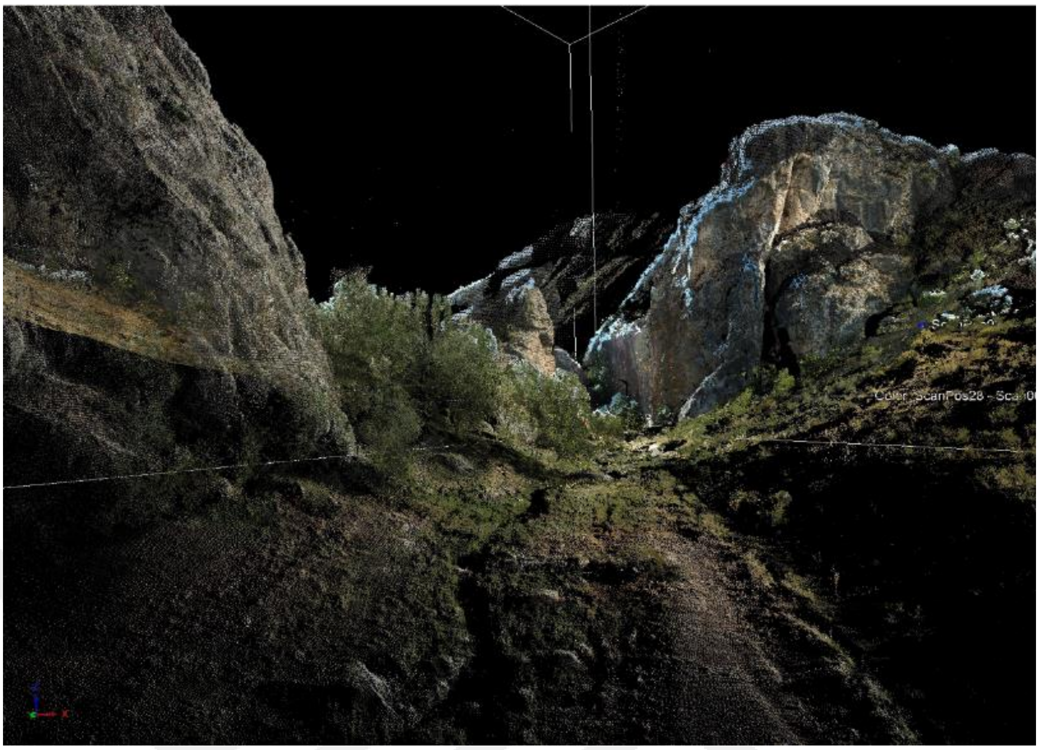


Figure 6 Point cloud from Ḫattuša Gorge, obtained with a time-of-flight Terrestrial Laser Scanner (Repola, 2020)

Figure 7 Artec EVA structured light scanner (https://www.artec3d.com/portable-3d-scanners/artec-eva)

Figure 8 A collage of structured light scanning acquisition, data processing, and its result (https://www.artec3d.com/portable-3d-scanners/artec-eva)

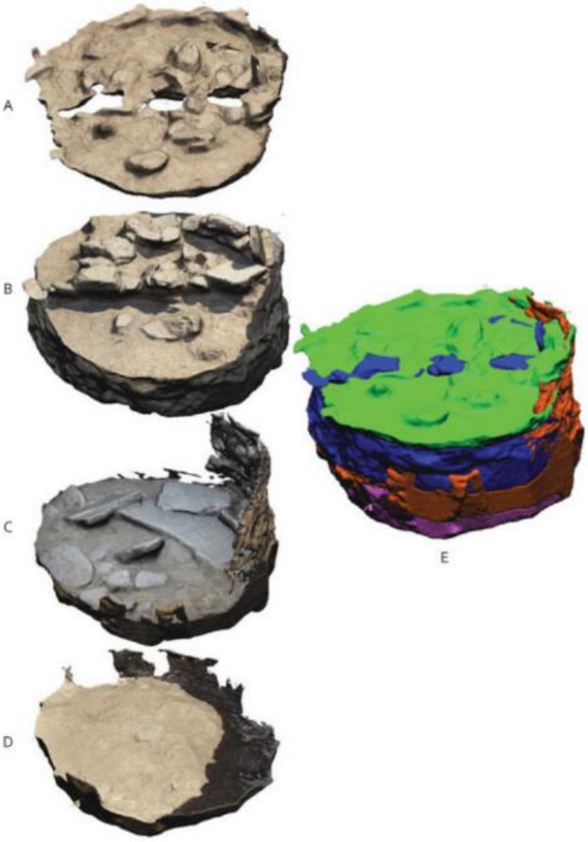


Figure 9 Volumetrically reconstructed photogrammetric models from Kaymakçı excavation contexts (Roosevelt et al., 2015: 338)

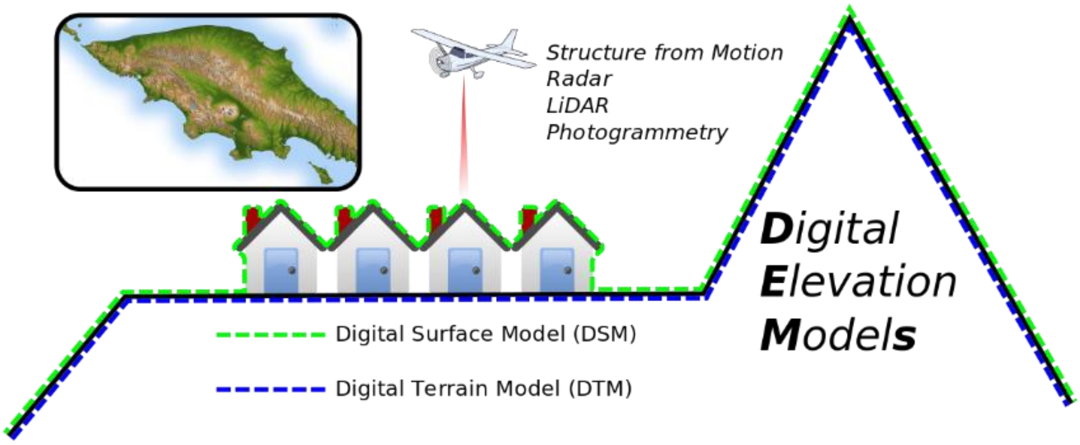


Figure 10 Graphic definitions of DSMs and DTMs [https://commons.wikimedia.org/wiki/File:The_difference_between_Digital_Surface_Model_(DSM)_and_Digital_Terrain_Models_(DTM)_when_talking_about_Digital_Elevation_models_(DEM).svg]

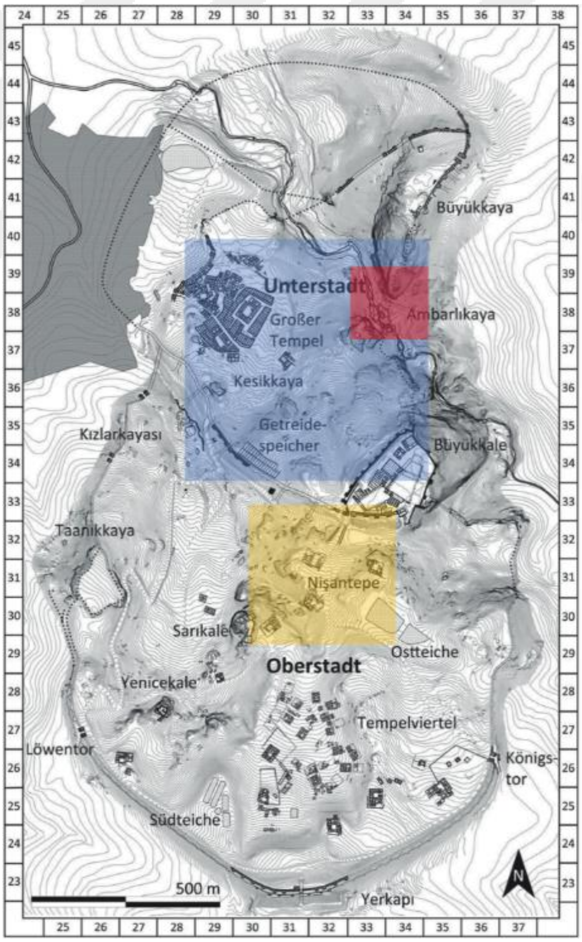
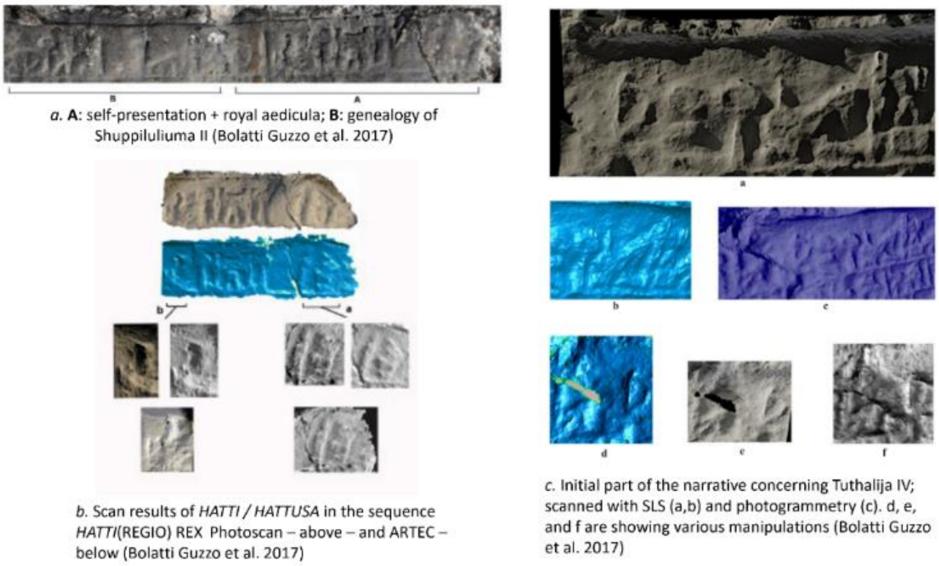


Figure 11 Approximate coverage areas of 3D scanning cases within the city walls of Ḫattuša. Red: the gorge area, Blue: The Great Temple, Yellow: Nişantaş and Südburg. (Original map from Harmanşah, 2019, symbolic case area markers were placed by Yiğit Pekzeren, based on Marazzi et al., 2020)

Figure 12 Nişantaş inscriptions (Repola & Tilia, 2020)

Figure 13 Inscriptions in Kammer 2 (http://www.reiseinfo-tuerkei.de/Interessante_Orte/Hattuscha.htm)

Figure 14 3D scan from Kammer 2 (Bolatti Guzzo et al., 2017)



a. **A**: self-presentation + royal aedicula; **B**: genealogy of Shuppiluliuma II (Bolatti Guzzo et al. 2017)

b. Scan results of *HATTI / HATTUSA* in the sequence *HATTI*(REGIO) REX Photoscan – above – and ARTEC – below (Bolatti Guzzo et al. 2017)

c. Initial part of the narrative concerning Tuthalija IV; scanned with SLS (a,b) and photogrammetry (c). d, e, and f are showing various manipulations (Bolatti Guzzo et al. 2017)

Figure 15 Scans mentioned in § 3.2.1.3 from Nişantaş (all from Bolatti Guzzo et al., 2017)

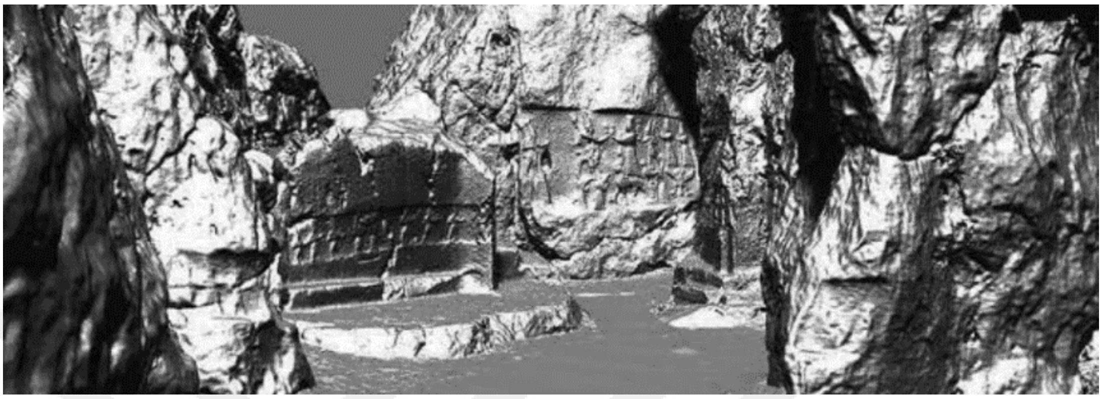


Figure 16 3D model from Yazılıkaya: Chamber A (Schachner, 2018)

Figure 17 Photo from Yazılıkaya: Chamber A
(https://www.kulturportali.gov.tr/turkiye/corum/gezilecekyer/yazilikaya-acikhava-tapinagi)

Figure 18 The gorge between Büyükkaya and Ambarlıkaya (Repola, 2020)

Figure 19 Budaközü River passing next to Minarekaya (Repola, 2020)

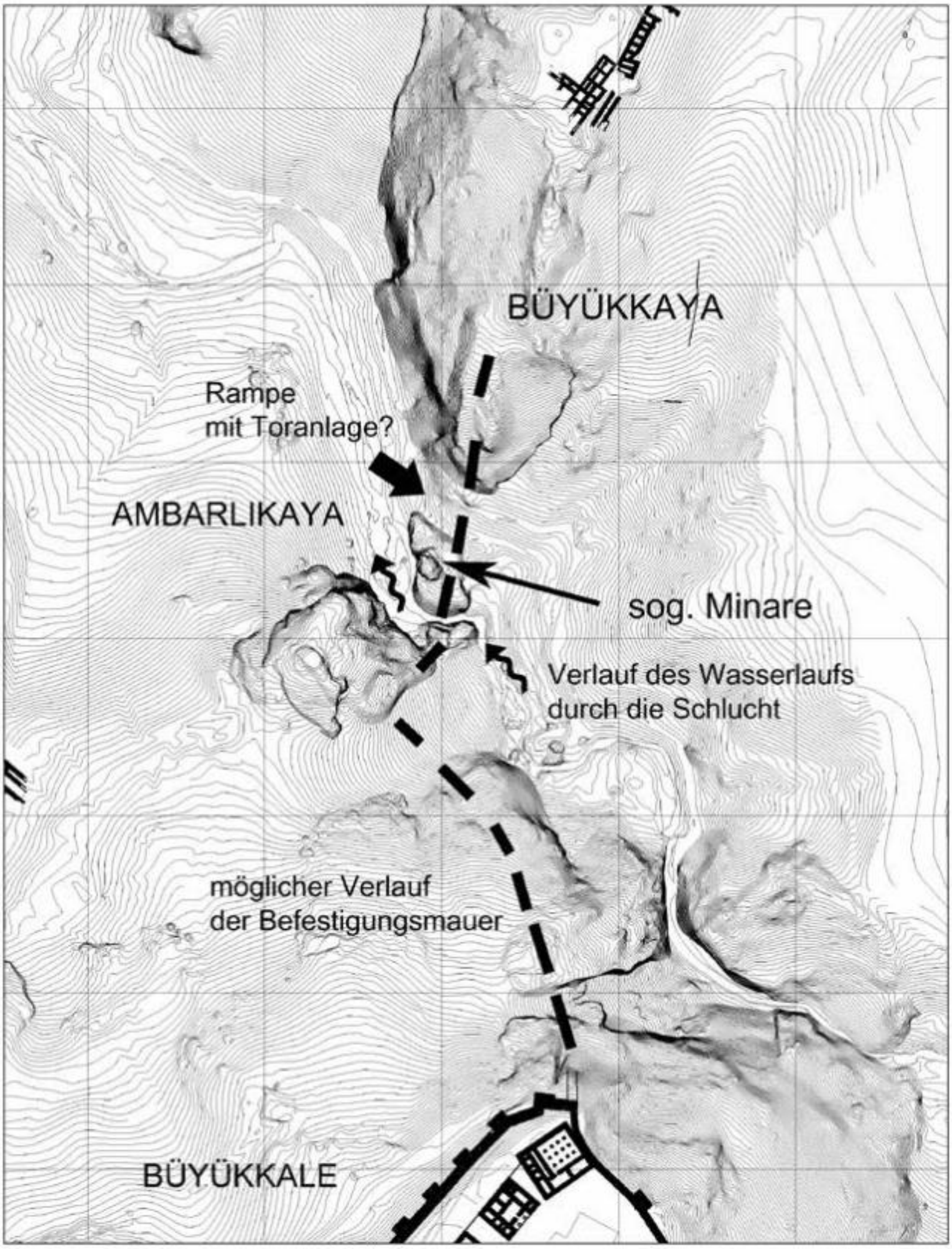


Figure 20 A map of the gorge area (Schachner, 2019).

Figure 21 The unfinished tunnel in Büyükkaya (Repola, 2020)

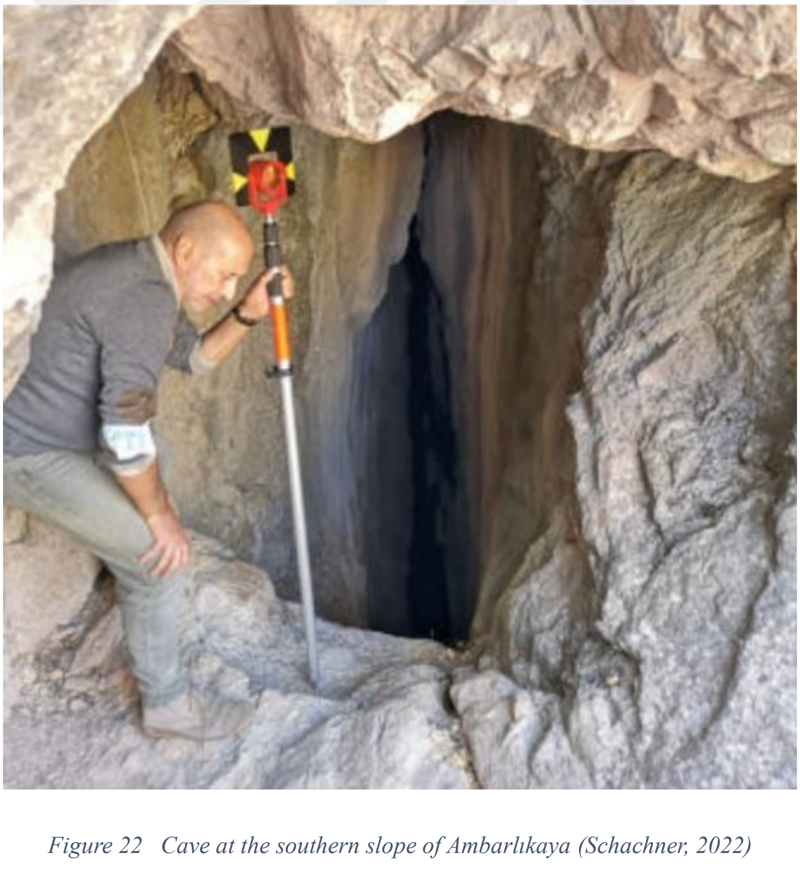


Figure 22   Cave at the southern slope of Ambarlıkaya (Schachner, 2022)

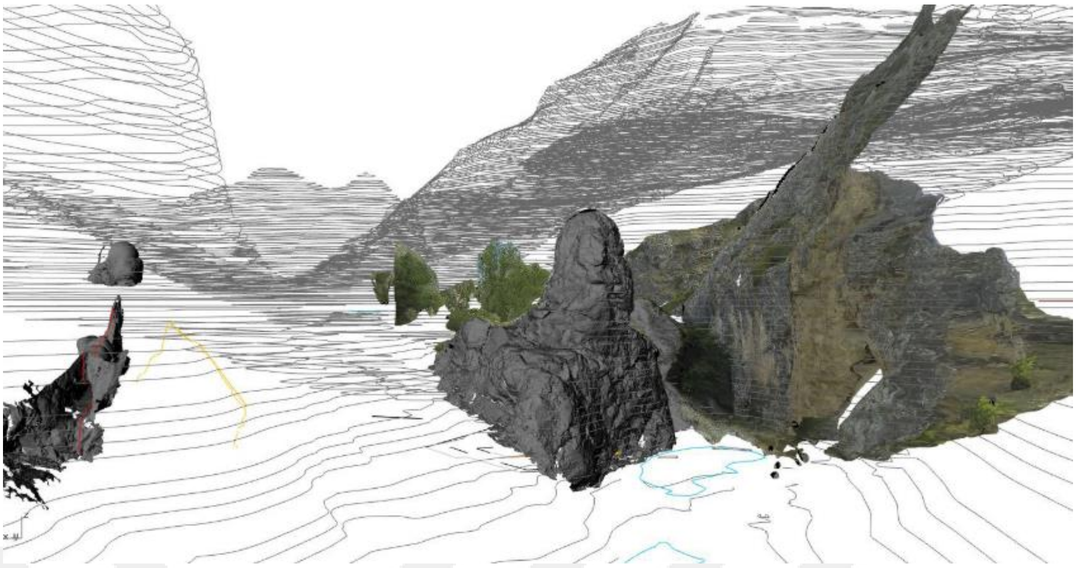


Figure 23 Topographic 3D scan of the gorge area (Repola, 2020)

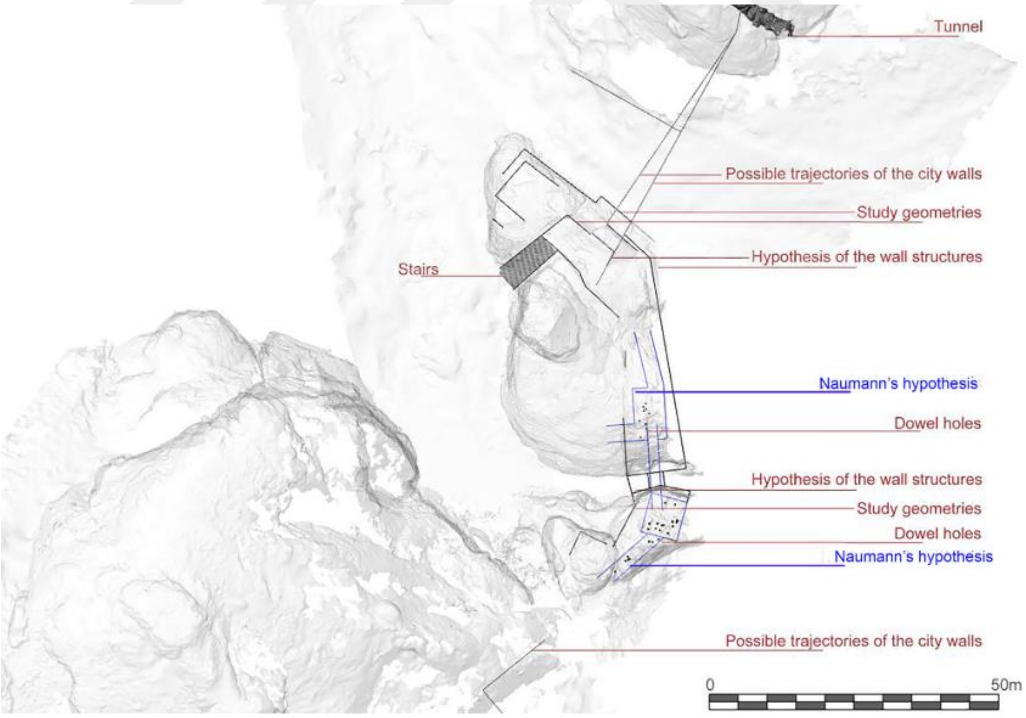


Figure 24 Hypothetical plan of the city walls passing over Minarekaya (Repola, 2020)

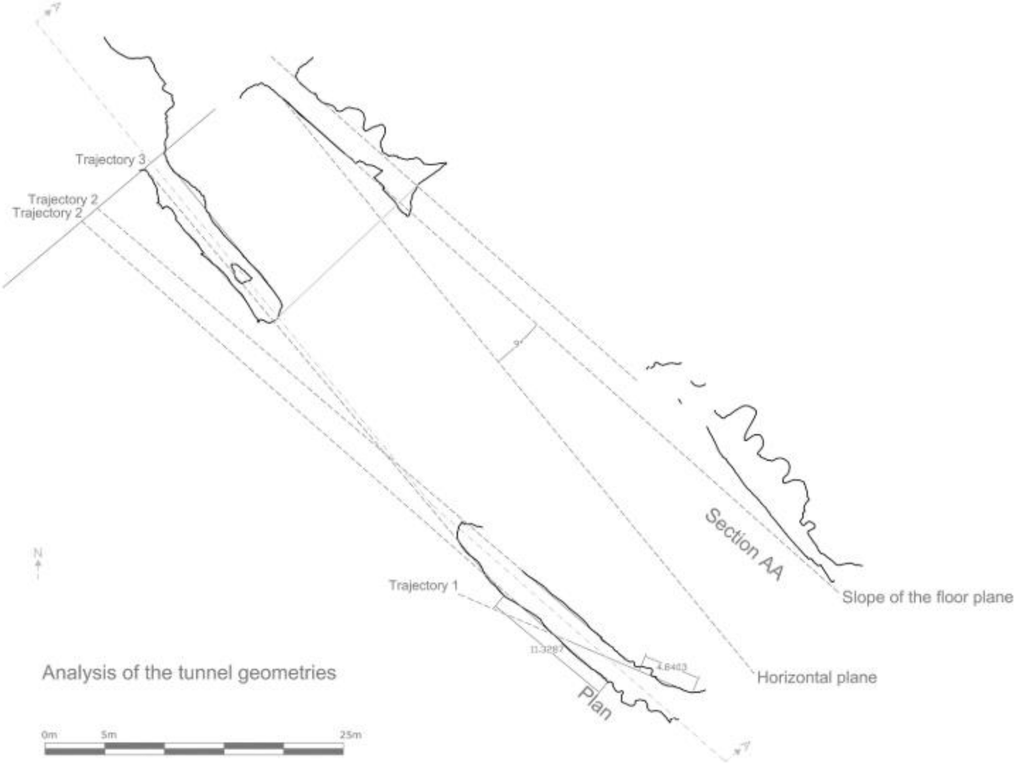
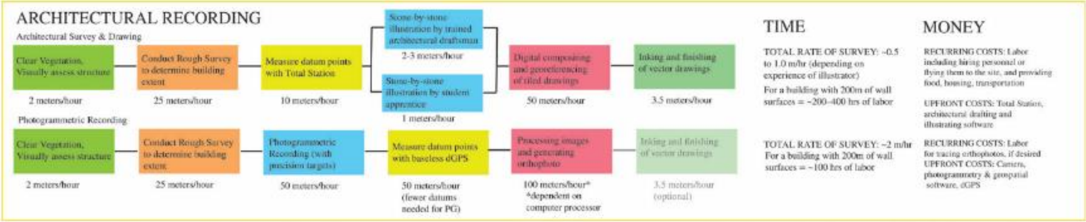


Figure 25 Cross-sections of the Büyükkaya tunnel (Repola, 2020)

Figure 26 Point cloud from the Great Temple 3D scanning survey. Obtained by using a Riegl LMS-Z420i terrestrial laser scanner (Marazzi et al., 2020).



TOTAL RATE OF SURVEY: ~0.5 to 1.0 m/hr (depending on experience of illustrator)
For a building with 200m of wall surfaces = ~200-400 hrs of labor

RECURRING COSTS: Labor including hiring personnel or flying them to the site, and providing food, housing, transportation

UPFRONT COSTS: Total Station, architectural drafting and illustrating software

TOTAL RATE OF SURVEY: ~2 m/hr
For a building with 200m of wall surfaces = ~100 hrs of labor

RECURRING COSTS: Labor for tracing orthophotos, if desired
UPFRONT COSTS: Camera, photogrammetry & geospatial software, dGPS

Figure 27 Schema from Murray et al., 2016; comparing conventional architectural drawing and photogrammetry in terms of time and money.

Figure 28 A photo (left-top) and three various RTI images of a stamp (Lech et al., 2021)