TECHNISCHE UNIVERSITÄT WIEN

DIPLOMARBEIT

Immersive Experience of Ancient Architectural Heritage and Related Historical Events

Reconstruction and Visualization of the Fire Incident at the Tomb of First Dynasty Egyptian Queen Meret-Neith in Abydos

carried out for the purpose of obtaining the degree
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Wien, am

abstract

This thesis examines how to communicate remote ancient architectural heritage and related significant historical events compelling the visitors to deal with the past actively, developing their own opinion on the subject, and preventing them from falling into the role of mere spectators.
The development of a VR experience, characterized by the great sense of presence offered by Virtual Reality, firstly proposes a solution to the availability issues helping broader remote accessibility, and secondly, enables the visitors to immerse into the past in the first person.
The Metaverse, meant as the evolution of the internet, as a virtual shared space accessible to all, represents a promising place to host such virtual realities. Connecting the real and the virtual, the Metaverse lends itself to creating experiences that surpass space and time, placing the users in the main character role.
The direct study of this thesis is the digitalization, reconstruction, and development of the VR experience of the tomb of Meret-Neith in Umm El Qa'ab, the cemetery of the First Dynasty Kings in Abydos, Egypt.
Through photogrammetry, it has been possible to create an accurate digital equivalent of the tomb. The VR experience "The Queen's Tomb Fire" featuring the virtual tomb as a subject aims to transmit the heritage contextualized in its environment and explore the origin of its burning. "The Queen's Tomb Fire" allows the visitors to freely explore the grave and engages them in a forensic fire investigation by visualizing three different hypotheses regarding the fire causes, enabling a direct comparison and creating an actual common starting point to initiate a discussion on the topic, attempting to overcome physical, cultural and temporal distance.

kurzfassung

Forschungsinhalt dieser Arbeit ist die Frage, ob und inwiefern eine VR-Experience dazu beitragen kann, geschichtlichen Kontext im virtuellen Raum darzustellen und zu beurteilen. Dabei nimmt auch das Medium des Metaverse eine entscheidende Rolle ein und dient als erweiterter digitaler 3D-Raum, der keine physischen Grenzen kennt und unsere gewohnten Raum-Zeit-Beziehungen neu definiert. Ein virtueller Ort, der für jeden zu jeder Zeit und an jedem Ort verfügbar und zugänglich ist. Durch die enge Verstrickung von Realem und Virtuellem kann zudem eine vollkommen neue Perspektive eingenommen werden, die dabei hilft, sich als Protagonist aktiv im scheinbaren Raum zu bewegen. Das Metaverse unterstützt also einerseits die permanente und ortsunabhängige Verfügbarkeit einer vermeintlichen Wirklichkeit, andererseits bietet sie die Chance einer individuellen Erlebnisgestaltung – Vergangenes kann ebenso erfahren werden wie Abstraktes oder Fiktives.

Als Grundlage hierzu dienen zum einen die Digitalisierung und Rekonstruktion des Grabes von Meret-Neith in Umm El Qa'ab, dem Friedhof der Könige der ersten Dynastie in Abydos, Ägypten sowie weiterführend die Entwicklung einer VR-Experience mithilfe dieser Basisdaten.

Durch die Methodik der Photogrammetrie konnte ein genaues digitales Äquivalent des Grabes erstellt werden, welches - eingesetzt in die VR-Experience "The Queen's Tomb Fire" - das historische Erbe in seiner damaligen Umgebung darstellt und die Gründe für die Zerstörung der Grabstätte untersucht.

„The Queen's Tomb Fire" ermöglicht es den Besuchern vor Ort, das Grab frei zu erkunden und konfrontiert sie mit möglichen vergangenen Szenarien. Die Besucher sind Teil forensischer Branduntersuchungen, indem drei verschiedene Hypothesen über die Brandursachen visualisiert und von ihnen digital nachempfunden werden können. Diese fiktiven Bilder ermöglichen einen direkten Vergleich und einen gemeinsamen Ausgangspunkt für eine offene Diskussion über die damaligen Ereignisse.

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1 visualizing architectural heritage and related events

The concept of architecture includes not only the final construction but also the thinking process that led to the design of that space. Architecture, in fact, represents the values and needs of the culture it was designed for as much as the coexistence with its inhabitants.

The space and its organization, the connection between different areas, the circulation, the chosen location, and orientation are examples of various aspects that depict its users' pragmatic needs, habits, and beliefs.

Analyzing space and its damage helps us to understand the relationship between the structure, the culture, and the events characterizing a specific period. Civilizations leave traces of their values, priorities, problems, and solutions through their architecture.

To actively visit such spaces is of priceless value, both for research purposes and for enabling visitors to establish an emotional connection with other cultures. It is, unfortunately, not always possible due to their remote location or the fragility of their construction materials. In fact, numerous external factors can endanger our cultural heritage, and most of them can not be prevented. Weather like rain, humidity, extreme heat, sun exposure, natural disasters like earthquakes, and human-driven factors like war or vandalism, can destroy any construction over time.

Additionally, the Covid-19 pandemic made the issue of accessibility tangible for everyone; many activities had to be carried out remotely, most of them virtually; the physical presence suddenly became surpassed. The inability to personally reach particular structures imposes the search for new solutions. The digital reconstruction of remote architectural heritage represents an attempt to overcome such accessibility issues, contributing simultaneously as a means of documentation.

Creating a digital copy raises the question of how to communicate its essence, peculiarities, and history to the audience. This thesis examines how to transmit remote ancient architectural heritage and related significant historical events adapting to the ongoing digital revolution, exploring the actual media of Virtual Reality in its possibilities and limitations. Creating a virtual experience should immerse the visitors in the past, compelling them to actively form their opinion on the subject by participating in it in the first person. The sense of presence enabled by Virtual Reality allows the visitors to be the protagonists, freely moving around and interacting with the displayed objects rather than making spectators out of them.

Creating a digital copy enables buildings to exist in the virtual world, allowing a broader audience to visit and interact with them. Clearly, virtually stepping into the digital copy of a building will not replace the natural act of stepping into an authentic historic one.

A virtual visit does not need to copy a real one but, on the contrary, presents new strategies to display and explain specific concepts, offering different exploration levels. The visitors can immerse themselves in different historical periods, participate in significant events, even tragedies, characterize a particular culture, and create an emotional connection with them.

The Metaverse, meant as the evolution of the internet, as a virtual shared place that exceeds place and time, represents a promising place to host such virtual realities. A digital version of the real world becomes accessible to anyone at any time. In this case, the process starts by digitalizing reality. Photogrammetry represents one of the various strategies to create digital reality copies, also called Mirror Worlds, making them available for virtual analysis and exhibitions. The remote access to cultural heritage in the Metaverse, meant as an enhanced virtual experience, creates numerous possibilities in education and information mediation. The structure, existing in a virtual place, becomes more readily available for analysis as evidence of historical events.

The direct study of this thesis is the reconstruction of early dynastic Egyptian archaeological structures with the example of the tomb of Queen Meret-Neith, located in Umm el Qa'ab, the royal cemetery of the First Dynasty Kings in Abydos, Egypt dating back to 2950 BC.

Due to the fragility of its structure, built of mudbricks, the tomb was excavated, analyzed, and eventually filled with sand to preserve it since covering the building with sand proved an excellent strategy for preserving ancient architecture.

Today, the tomb lies under the sand and in a highly remote location, making it impossible to reach. Thanks to photogrammetry, it was possible to reconstruct an accurate digital copy of the tomb suitable for later archaeological analysis and virtual exhibitions.

It is not easy to understand and interpret a civilization that lived so far away in the past compared to our own. However, some events are still clearly recognizable: the tomb shows signs of burning. Why and when it burned is still unclear.

The creation of the VR experience "The Queen's Tomb Fire" visualize the tomb of Meret-Neith in its context, the low Sahara desert, surrounded by its high mountains, engaging the visitors in a forensic fire investigation exploring three different hypotheses over later analysis on the cause of the burning. The envisioning of the different theories should make a direct comparison and a common starting point possible to initiate a debate on the case. Visualizing events that occurred so far away in the past involves exploring methods that transmit a clear statement about what is real and what is just supposition, avoiding the imposition of a truth, which is not entirely sure. In any case, actively taking part in the burning of Meret-Neith's tomb should help the visitors visualize the event in its whole complexity, enabling them to deal with the past actively.

1.1 related work

The digitalization of remote architectural and cultural heritage allows virtual access to otherwise unreachable locations. Virtual exhibitions have the potential to create an emotional connection between the visitor and the displayed object, but overall to revolutionize the experience and communication of cultural heritage in, among others, educational and entertainment fields.

Many recent studies and projects have focused on virtualizing heritage pieces, creating multisensorial and interactive exhibitions that reach a deep level of immersion, trying to give the visitor the possibility to explore the environment as he would in reality, free from devices and mediums. While there has been much research on the virtualization of heritage to enhance museum exhibitions, few projects have considered the creation of an entirely virtual exhibition. Most of the analyzed projects expect the user to visit the museum or cultural institution to visit the exhibition physically. Virtual reality devices, such as head-mounted displays (HMD) or gesture-based interaction sensors, are still not widespread among the common population. Although the number of VR and AR users is growing exponentially, according to Statista (2021), the number of augmented reality and virtual reality devices shipped worldwide in 2021 reached 9.86 million units, and forecasts suggest that it will probably rise to 14.19 million units in 2022.

Pietroni and Adami (2014) present the award-winning Etruscanning European Project in the Culture 2007, which focused on virtual reconstruction and developing a virtual exhibition of two Etruscan tombs in Cerveteri and Veii. The project's goals were: digital acquisition, digital restoration and 3D representation of the tombs, communication during exhibitions, and supporting cultural heritage institutions to create and exchange digital 3D reconstruction. The (second version) application about the Regolini Galassi Tomb in Cerveteri allows users to visit the Etruscan tomb virtually and learn about their funeral rites. The 3D reconstruction of the grave via a laser scanner, digital photos, and photogrammetry portrays it with its funerary goods in its original state. The visitors, featuring a torchlight, can take a gesture-based virtual tour of the tomb; by approaching the objects, they listen to the buried princess and warrior telling stories about themselves and their belongings. The user takes the role of the main character in the scene by actively interacting with the environment around him, creating a deep, immersive emotional experience. A full HD screen displays the 3D reconstruction, and the Kinect for Windows detects the gestures. Concerning this process, Pietroni and Adami(2014) state: "it is necessary to design not only for the contents of virtual applications but also the communicative approach. We cannot focus only on the scientific aspects if we want the results to be widespread with the general public." and conclude: "the user is not a spectator, but the protagonist of his or her process of knowledge."

Reunanen et al. (2015) reconstructed a virtual model of the Dutch shipwreck Vrouw Maria, an 18th-century merchant ship that sank near Nauvo, Finland, in 1771, to enable visitors of the Maritime Museum in Kotka in 2012 to have an immersive virtual tour of the ship, which still lies underwater. The project's main features were: real-scale graphics, immersive stereoscopic display, 3D goggles, gesture-based interaction, immersive soundscape, and info spots offering further details. It resulted from the

Fig. 1. Interface and viewport of the second version of th Etruscanning application by Pietroni

collaboration among several domain experts, such as archaeologists, scuba divers, and visual artists, discussing the main narrative, including critical historical events and the different camera views and their content. To create the 3D model, the team combined multiple data sources like sonar scanned depth measurements, laser scanning of miniature models, drawings, photos, and underwater footage shots. All the elements were then assembled in Unity. With the gestural interaction based on Microsoft Kinect, the visitor can freely explore the virtual wreck, displayed in real scale, reaching an excellent level of immersion thanks to the implementation of underwater soundscape through loudspeakers and learning about its history approximating the info spots. A user evaluation reported severe problems with the gesture tracking because of the Kinect driver, which was still experimental at the time, and problems with vertical navigation, stopping and exiting the cargo since the hatches were hard to find. The visitor got easily lost when far from the ship, although the screen showed a miniature map. The visitor seemed impatient to start navigating and intolerant to the introduction showing the ship's history, which had to be shortened. However, almost all the users enjoyed the installation.

The non-profit organization CyArk is dedicated to spreading cultural heritage to a broader audience

through digital media, or, in their words: "CyArk strives to connect new audiences to heritage through digital documentation and the creation of place-based web, mobile and immersive experience that inspire reflection, conversation and imagination"(2022). Their VR experience of Balcony House, resulting from the Resonant project, features a digital copy of Balcony House at Mesa Verde National Park, reconstructed through photogrammetry and LIDAR and "provides a unique opportunity to interact with stories of a place in ways that would otherwise be difficult to visualize or embody" (CyArk, 2020). The player, guided by walkie talkie and a virtual notebook, walks through the reconstructed structure, explores different stories of the site by completing missions, "moving through the site with stories that transport you across time and cultures"(CyArk, 2020).

Concerning a more specific representation of fire, the Museum of London, in partnership with London Metropolitan Archives, Guildhall Art Gallery, and the Monument, created an interactive informational website to commemorate the 350th anniversary of the Fire of London in 2016. The Dutch studio Fabrique, responsible for the concept and design of the website, developed an interactive story or, in their words, "a complete educational experience for all ages" (Museum of London | Fabrique, n.d.). The

Fig. 2. Reconstructed model of the Dutch shipwreck Vrouw Maria, Reunanen et al.

Fig. 3. Balcony House, VR Experience by CyArk

style was inspired by 17th-century art, especially woodcuts, typography, and literature. The structure, navigation, typography, and illustration aim to create "an authoritative and distinctive site that tells the story of the fire in different ways for different types of user" (Museum of London | Fabrique, n. d.). The narration of the Great Fire of 1666 is separated into four storylines: The Fire, Society and Politics, Streets and Buildings, and People's Lives. The story follows a linear flow, showing stunning illustrations alternating with original maps of London in 1666, where the starting and progression of the fire are progressively pictured. Small pop-up windows offer a brief and concise explanation of the events, allowing users to get deeper information by clicking on the expand icon. Indeed it is up to the users to decide how deep and detailed they want to experience the story. The user experience (UX) Director calls the users to "get lost through the different layers of the site. Immerse yourself in the historical objects and stories" (Sanwikarja as cited in Museum of London | Fabrique, n.d.). The website, developed by the Dutch firm Logirix following the general concept created by Fabrique, seeks to "bring the story of the Great Fire of London back to life using an interactive timeline on which both the events and the fire are visible" (Fire of London - Interactive web application - Logirix, 20).

This project effectively transmits the tragic story; the linear narration is engaging, letting the users enjoy the illustrations by getting clear, concise information about the happening. The stylized style depicting the spreading of the fire manages to transmit a clear impression of the event without imponing a visual truth, which is not proved.
The British Museum displayed 2013 an exhibition about the tragedy in Pompeii, directly comparing videos of reconstructed scenes of the city and its inhabitants to pictures of what remains of them. This project follows a different approach than The Great Fire of London Project, favoring an actual reconstruction of the object.
An exhibition about the burning of the Notre Dame cathedral in 2019 is currently on display in the National Museum Building of Washington DC, USA. Notre Dame de Paris: The Augmented Exhibition enables visitors to choose their own in-depth experience in an immersive, interactive experience transporting them through time (Notre-Dame de Paris: The Augmented Exhibition | National Building Museum, 2022). The augmented level can be reached through a HistoPad, "a virtual reality touch-screen tablet technology developed by [the French startup] Histovery" (Notre-Dame de Paris: The Augmented Exhibition | National

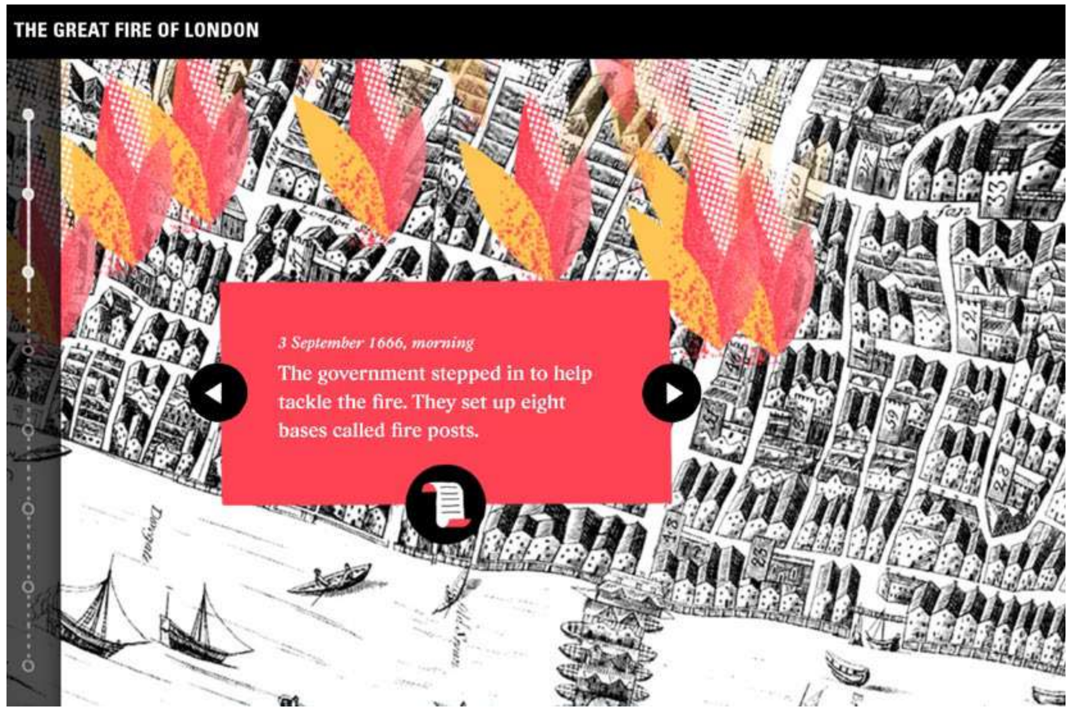

Fig. 4. Interactive informational website commemorating the Great Fire of London of 1666, Museum of London

Building Museum, 2022). The exhibition traces the 850-year history displaying many important events. The President and Executive Director of the National Building Museum, Aileen Fuchs, states: "Visitors will experience first-hand how technology can contribute to our understanding of buildings. The unique and immersive virtual nature of the exhibition provides a window into this World Heritage site" (STIRworld, 2022). Reconstructed replicas of the cathedral and 3D installations create the immersive physical setting providing visual cues for the augmented exploration (STIRworld, 2022), reaching a reconstructed Notre Dame populated by animated characters, showing memories of coronations, architectural details, and even the burning and the reconstruction works in progress. The exhibition also features a scavenger hunt for children. This exhibition chose a mix of actual and 3D reconstructed elements to achieve an immersive and engaging way to communicate information.

Peter Matejowsky, in his master thesis "Visualisierung der räumlich-zeitlichen Entwicklung des Temples der Satet auf Elephantine" published in 2006 at the Vienna University of Technology, investigates how to present archaeological structures easily and interactively, creating a 3D model of

Fig. 5. Notre Dame de Paris, the Augmented Exhibition, National Building Museum

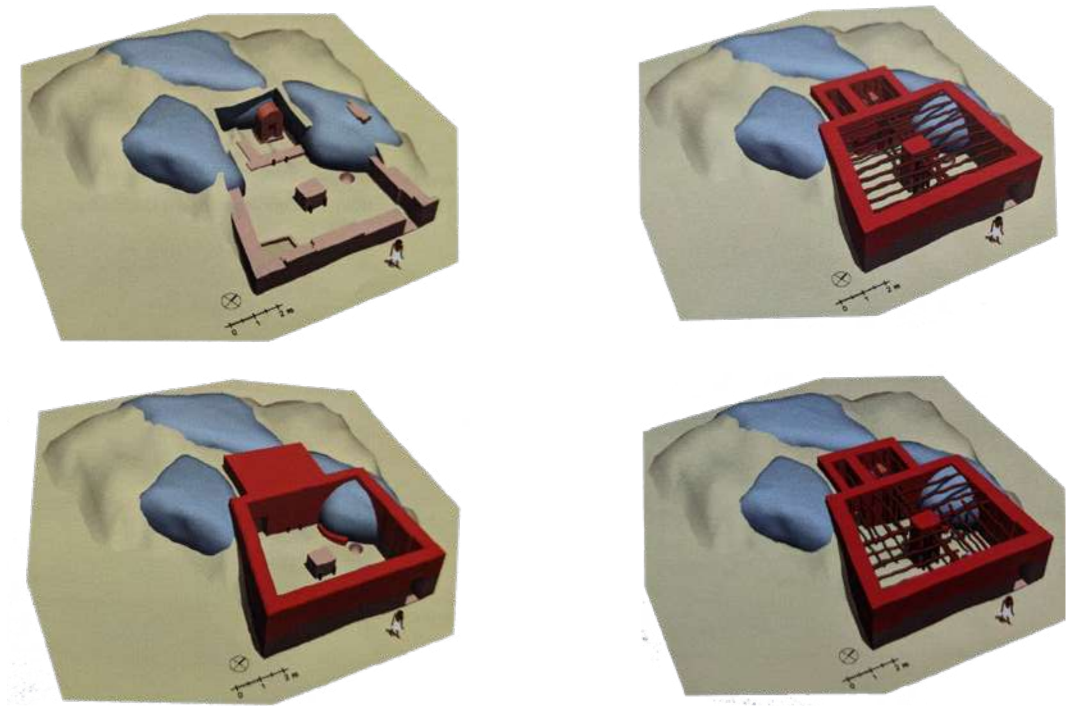

Fig. 6. Visualization of the different hypotheses of the reconstruction of the Satet temple of the early 6. Dynasty Peter Matejowsky,

each building period. The digital models show the temple abstractly, clearly differentiating the physical reconstruction from the virtual one and avoiding photorealistic details. The archaeological rests do not always deliver consistent testimonies about the exact original structure's appearance, so it is necessary to visualize different variants of the same object. Matejowsky approach to the problem was to place the different visualizations next to each other, evidently distinguishing the found parts, depicted in brown, from the digitally reconstructed ones, in red. This style allows a direct comparison between the variants. More concretely, the findings of the Satet temple dating back to the early 6. Dynasty (2250 BC) show the rest of an enclosure wall and a square brick construction in the middle, which can be interpreted as a base structure for an altar or a column supporting a roof (Matejowsky, 2006).

Soraya Field Fiorio used a similar approach in her video, "How did they build the Great Pyramid of Giza?" (2022) for TED-Ed. Here Field Fiorio shows three different hypotheses on the appearance of ramps, assumably used to transport the stones to build the pyramid of Pharaoh Khufu; "[...] the actual construction process remains mysterious. Most experts agree that limestone ramps were used to move

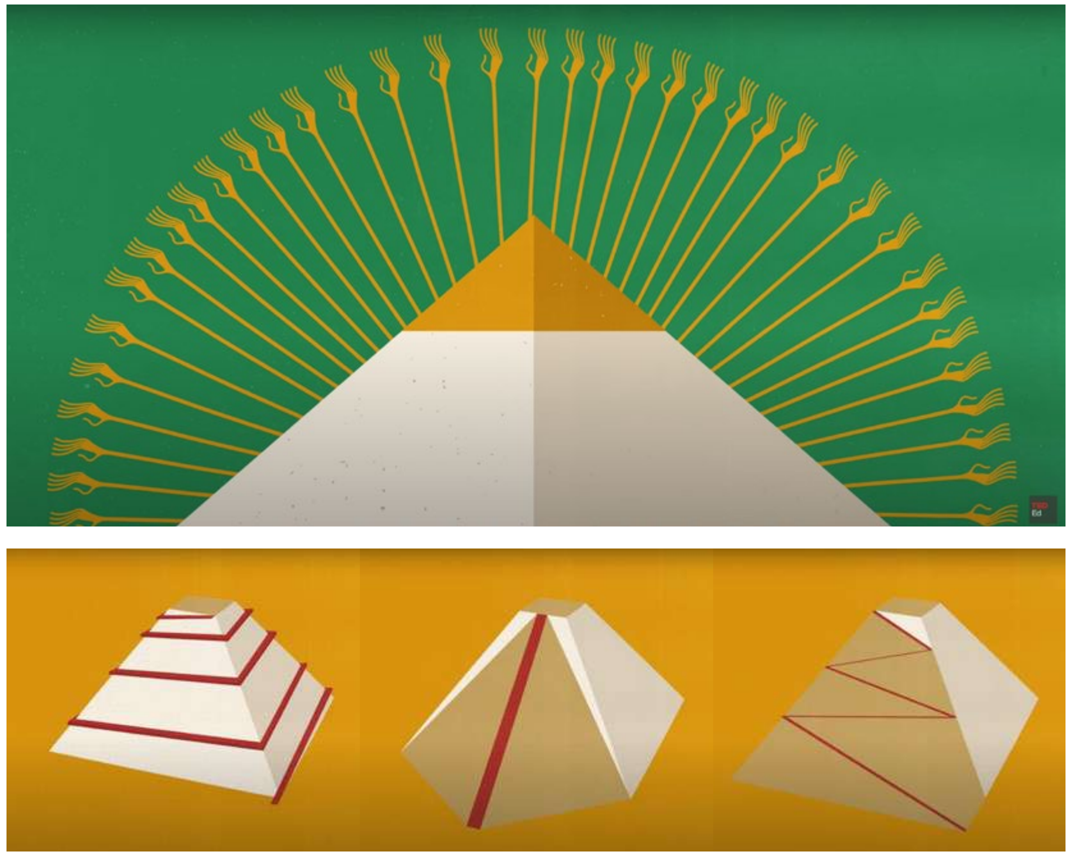

Fig. 7. Visualization of the three hypotheses of the construction of the ramp, TED-Ed, Soraya FIeld Fiorio

the stones into place, but there are many theories on the number of ramps and their locations" (Field Fiorio, 2022). The three variants are displayed successively, depicted in an abstract style, with the pyramid as a constant element in bright yellow and the ramps in red, allowing a clear differentiation between reality and supposition.

Many projects feature the virtual reconstruction of remote heritage, choosing a narrative means to communicate the history. Most exhibitions are meant to be visited within a museum rather than thoroughly remotely enjoyable.

2 historical relevance

Defining the historical importance and interest of a specific building structure or site is essential to determine its monument status.

Many historians contributed to the coining of the term monument; the Austrian art historian Alois Riegl states in his essay "The Modern Cult of Monuments: Its Character and Its Origin" published in 1903: "A monument in its oldest and most original sense is a human creation, erected for the specific purpose of keeping single human deeds or vents (or a combination thereof) alive in the minds of future generations" (Riegl, 1903). Such monuments are clarified as intentional monuments; Riegel, in fact, defines specific values according to which it is possible to analyze monuments: Commemorative and Contemporary values. Commemorative values include historical (unintentional), age, and intentional values.

By historical value is meant "Everything that has been and is no longer we call historical, in accordance with the modern notion that what has been can never be again, and that everything that has been constitutes an irreplaceable and irremovable link in a chain of development" (Riegl, 1903).

The age values include monuments that transmit a religious, commemorative feeling; "These monuments are nothing more than indispensable catalysts which trigger in the beholder a sense of the life cycle, of the emergence of the particular from the general and its gradual but inevitable dissolution back into the general. This immediate emotional effect depends on neither scholarly knowledge nor historical education for its satisfaction, since it is evoked by mere sensory perception" (Riegl, 1903). Contemporary values include utility value and art value. The utility value involves keeping a monument in use and ensuring maintenance and restoration where necessary (Bacher, 1995). The art value should be defined in two different ways: "depending on whether one adopts the earlier or the modern point of view. According to the former, a work of art possesses art-value insofar as it corresponds to a supposedly objective but never satisfactorily defined aesthetic" (Riegl, 1903).

In the modern view, the art-value of a monument is established by the requirements of the modern Kunstwollen but these requirements are even less well defined and in the strictest sense can never be defined because they vary from subject to subject and moment to moment" (Riegl, 1903). Riegl continues by stating that "according to current notions, there can be no absolute but only a relative modern art-value." With the term Kunstwollen, Riegl means the characteristics and the limits of the aesthetic design of an epoch and the its inner creative drive

Monuments represent an essential element of human history and development; it is necessary to document such heritage to conserve for future generations and communicate it to the current one.

2.1 documentation and digitalization

Documentation of Cultural Heritage includes "the capture of information regarding monuments, buildings, and sites, including their physical characteristics, history, and problems; and the process of organizing, interpreting, and managing that information. Reasons for engaging in documentation include:
assessing the values and significance of the heritage in question;

- guiding the process of conservation;
- providing a tool for monitoring and managing
- heritage while creating an essential record; and
- communicating the character and importance of heritage" (LeBlanc and Eppich, n.d.).

Documenting relevant historical heritage follows, in fact, not only the purpose of the record but also the transmission of knowledge.
The Venice Charter of 1964 set the international standard of conservation and restoration of historic buildings aiming, as defined in article 3., "to safeguard them no less as works of art than historical evidence"(Venice Charter, 2021). It follows, in article 7. declaring that "A monument is inseparable from

Fig. 8. Master Works: Journey through History in Virtual Reality, CyArk

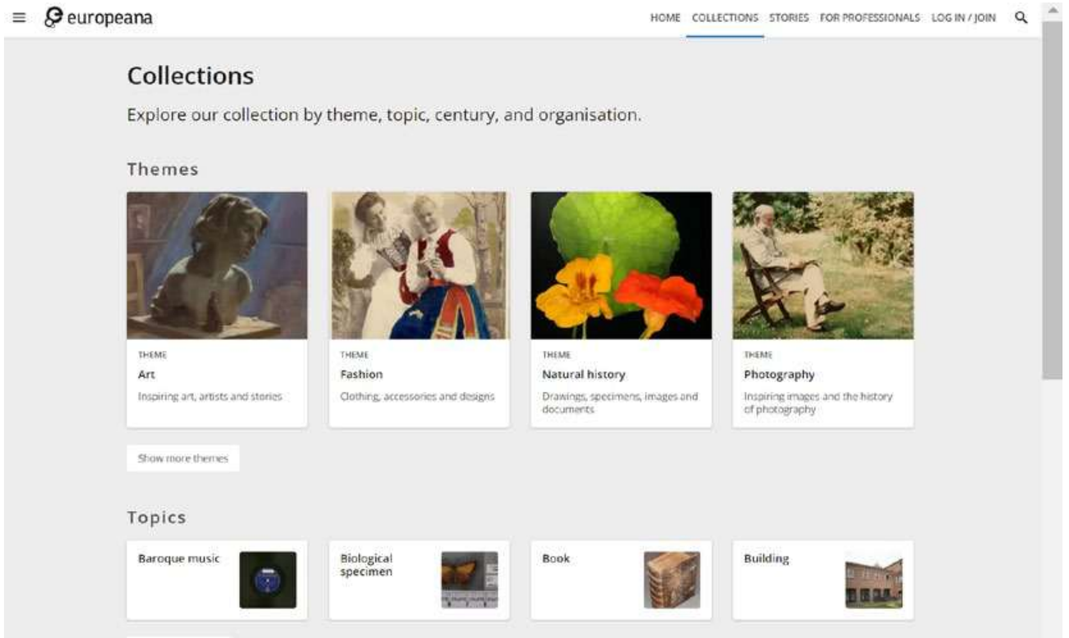

Fig. 9. Europeana, screenshot of the official website

the history to which it bears witness and from the setting in which it occurs. [...]" (Venice Charter, 2021).
The object, in fact, defines its meaning not only by its original purpose but also by becoming a witness of happenings.
The Venice Charter states in article 2. that "The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage" (Venice Charter, 2021).
The digitalization of historical heritage represents the conservation method appropriated to the current time. The development of technologies such as laser scanning and photogrammetry proved to be of significant impact on the documentation discipline, allowing the creation of digital copies available for further analysis and the possibility of making them accessible to a broader audience.
Many cultural institutions are moving toward offering online exhibitions on their websites; furthermore, 3D models or point clouds of heritage are available on webpages like Sketchfab. Many are ongoing projects aiming at the digitalization of cultural heritage, like, for example, the Europeana project or the non-profit organization CyArk dedicated to creating connections with historical places.

2.2 photogrammetry

"Photogrammetry is the science of obtaining reliable information about the properties of surfaces and objects without physical contact with the objects, and of measuring and interpreting this information" (Schenk, 2005). The word photogrammetry derives from the Greeks; phos or phot, meaning light, gramma, meaning letter or something drawn, and metrein, the noun used to indicate measure (Schenk, 2005).
The French inventor Aimé Laussedat officially invented photogrammetry. He began investigating mapping methods by using the newly invented camera in 1851. Terrestrial photogrammetry was successfully used before World War I as a mapping technique. During the war, aerial photogrammetry proved helpful for military purposes (Enciclopaedia Britannica, 2016). In fact, "Photography is today the principal method of making maps, especially of inaccessible areas, and is also heavily used in ecological studies and in forestry" (Enciclopaedia Britannica, 2016).
Photogrammetry is nowadays widely used, representing a fast, effective method for the digital reproduction of reality. Some of the fields in which photogrammetry is confirmed to be incredibly valuable are:

- Architecture: the photogrammetric reconstruction of a particular building or site is helpful in the aim of reaching photorealism in 3D visualizations
- Game: Photogrammetry represents a scalable medium, permitting the reconstruction from small objects to whole environments. Such a fast method of 3D model creation enables the enhancement of virtual environments.
- Cultural heritage: Cultural heritage is constantly endangered by factors like weather, natural disasters, vandalism, wars, and many others. Many historical places are not always accessible due to their remote location or the fragile nature of their structural materials. A photogrammetric reconstruction enables the preservation and documentation of such heritage, making it available for further utilization, for example, as virtual exhibitions or virtual tours, "as a fast and accurate method of transferring the real world into a virtual one" (Capturing Reality, n.d.). Photogrammetry is particularly suitable for cultural heritage reconstruction because of its scalable nature, making the reconstruction from small objects to whole sites possible.

The process starts with the acquisition of reliable data in the form of pictures. The object is, in fact, photographed from different angles and different distances; this strategy needs to follow the rules imposed by photogrammetry strictly. Schenk (2005) states: "Data acquisition in photogrammetry is concerned with obtaining reliable information about the properties of surfaces and objects". According to Schenk (2005), the gathered data can be arranged into four different categories:

- "Geometric information involves the spatial position and shape of objects. It is the most important information source in photogrammetry.
- Physical information refers to properties of electromagnetic radiation, e.g., radiant energy, wavelength, and polarization.
- Semantic information is related to the meaning of an image. It is usually obtained by interpreting the recorded data.
- Temporal information is related to the change of an object in time, usually obtained by comparing several images recorded at different times."

The photogrammetric software identifies the position of the object points in three-dimensional space, following different algorithms, enabling the orientation of the images in their corresponding position. All the images are aligned, creating a point cloud, meshed to a 3D model, and eventually textured.
A detailed insight into the photogrammetric process was investigated in Hanspeter Kals "Bauaufnahme und Echtzeitvisualisierung historischer Gebäude, Angewandte Photogrammetrie und Virtual Reality am Beispiel von Schloss Waldenfels"(TU Wien, 2019), and Cheng Shi "Application of Photogrammetry and Virtual Reality at building redevelopment in existing contexts" (TU Wien, 2019).

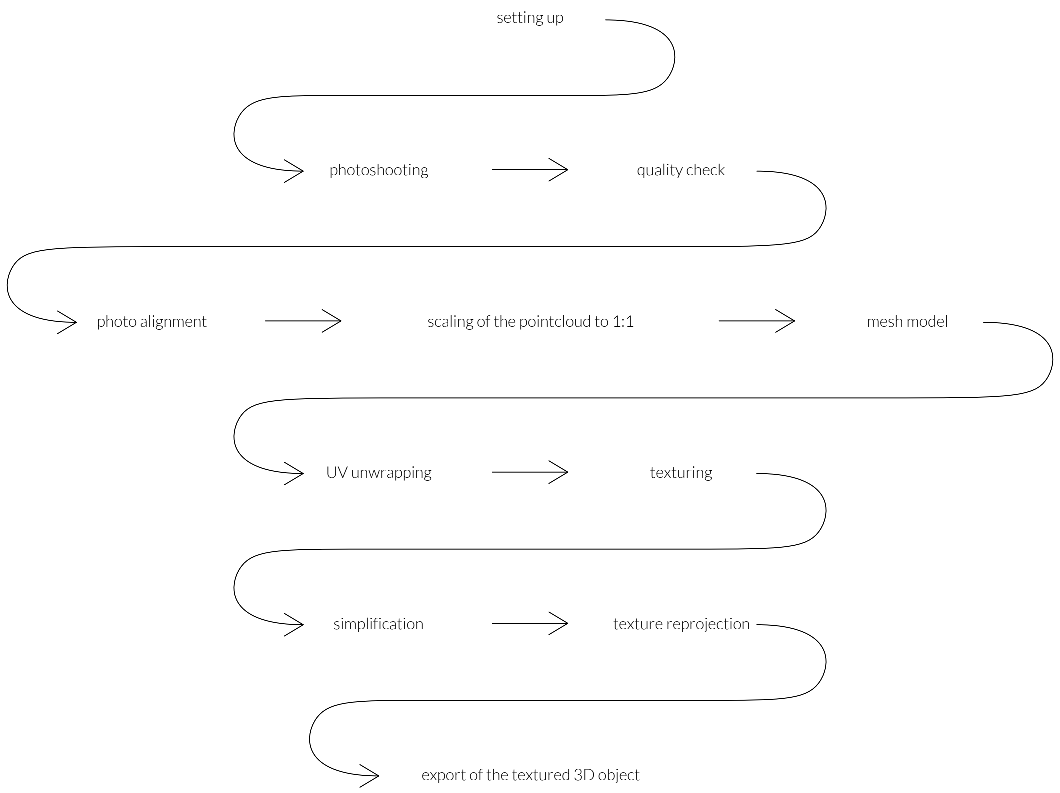

Fig. 10. Photogrammetric workflow

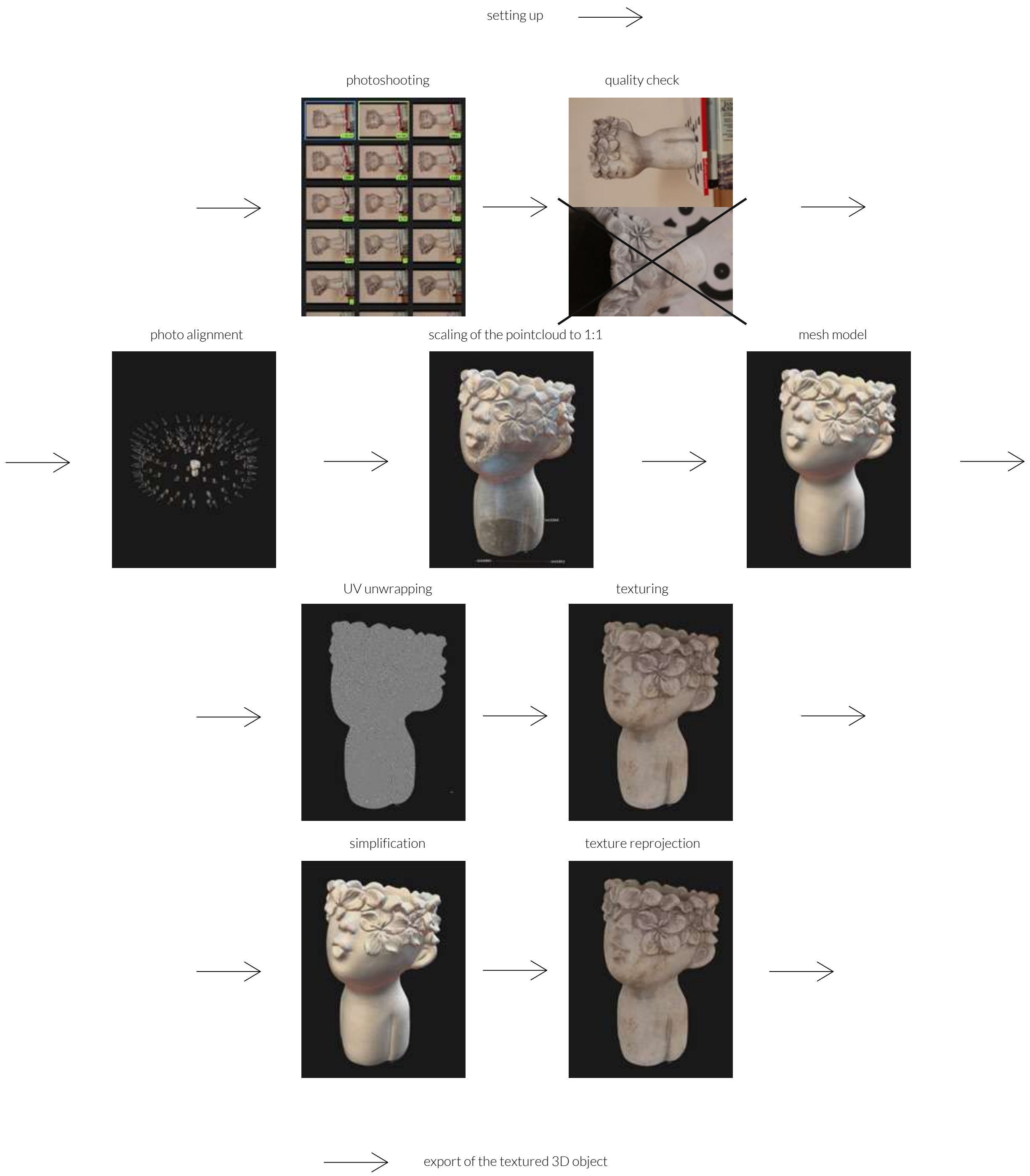

Fig. 11. Photogrammetric workflow by the example of a vase reconstruction

For a photogrammetric reconstruction, it is first necessary to set up the shooting stage creating a diffuse light situation, or to wait for a cloudy day if the object is placed outside. Markes or other measuring references should be put near the object for the correct scaling of the digital copy.

The shooting proceeds with photographing the object from different heights, angles, and distances paying attention to the ISO and Depth of Field (DOF) camera settings. Every picture should be, in fact, possibly completely sharp; blurry images would compromise the result and must be deleted. The image set, accurately selected, can be imported into the software and aligned to create a point cloud. The point cloud must be then scaled to its actual measurements and meshed to a 3D model. After examining the 3D model and removing any errors, the mesh can be first unwrapped and then textured. The mesh can be optimized by reducing its polycount without any detail loss, thanks to the possibility of baking the detail of the high poly mesh to the low poly one. The reduced 3D model can eventually be exported as a 3D object.

The photogrammetric process and the concepts of unwrapping and baking are explained more extensively in chapter 5.2 Reconstruction of the tomb.

Fig. 12. 3D model of a photogrammetric reconsructed vase, wireframe and textured

3 communication

Once the digital copy of relevant historic architecture has been created, the problem of how to communicate it arises. The certainty of self-explaining ancient heritage can not be taken for granted since cultural heritage is relevant not only for archaeologists and historians but also for touristic purposes.
Communication, in this case, is about overcoming distances and facilitating emotional connection to other cultures, places, and times. It is, in fact, not easy to empathize with faraway civilizations and locations, especially if they are additionally situated in remote ages, clearly different from our current one.
The visualization method must be carefully studied since it will deliver a message; a clear differentiation needs to be kept between reality and supposition, avoiding imposing a visual truth that is not entirely true. The spectators should be put in the protagonist role, living emotionally important historical events themselves in the first person. Envisioning critical historical events characterizing a specific period could help establish a connection.
There are many methods to deliver a message; storytelling, as a method to educate and pass on culture and experiences, characterized human history, proving to be an effective communication instrument of easy comprehension.
Technological evolution provides access to new media, which offers further possibilities to help connect the past and the present throughout humans.

3.1 storytelling

Historic buildings and generally cultural heritage are not of immediate understanding. The narration of specific circumstances is an essential medium to win insights and better comprehend the unfolding of critical historical events. Nowadays is possible to recreate such occurrences virtually to understand or compare complex happenings. In this case, the virtual representation aims to tell a piece of history rather than defining a new investigation tool to analyze a specific artifact and its materiality (Pietroni, 2019).
The scientific reliability of a digital reconstruction, with the possibility of an interactive representation at different scales structured on multiple exploration/ semantic levels, and the integration of analysis tools is essential (Pietroni, 2019). It is, however, "not a sufficient characteristic to transmit culture to the public in an engaging way and, above all, to convey a complete cultural message," states Pietroni (2019). Pietroni continues remarking that "Aspects such as symbolic and intangible value, function and use of a spaces, social behaviours, lifestyle (which justify the architectonic shape, or the appearance of a landscape), are closely interrelated to the heritage meaning" remarking that they need to be communicated by "sophisticated

forms of representation, content structuring and storytelling".
According to Katifori et al., digital storytelling was recognized as an effective strategy in the field of cultural heritage interpretation and communication, and "mobile guides offering different forms of digital narratives are often employed to enhance the visitor experience" (Katifori et al., 2020).
Storytelling, as a means of cultural preservation and education, has accompanied human history, continuously adapting to the evolving available tools. Stories were initially orally narrated, then drawn, carved into stones and pottery, sung, and took life in a theater piece. The evolution of writing and printing enables further documenting and sharing of stories, evolving these days to animated visual media.
A meaningful example is located right in Abydos; scenes of the Battle of Kadesh are depicted on the west wall of the Ramesses II temple.
Virtual Reality enables the creation of an immersive experience in which the environment becomes alive, interacting with the user. The user can take part in specific historical events firsthand.
Rizvic et al. (2020) state that "VR, AR, and MR are more effective in conveying heritage information if accompanied with storytelling. The visitor of the museum and CH sites are interested to find out "the story behind" the cultural monuments and get acquainted with the characters and events from their history."
According to the California State University Chico (as cited in Rizvic et al., 2020), digital stories need to:

- Include a compelling narration of the story
- Provide a meaningful context for understanding the story being told
- Use images to capture and/or expand upon emotions found in the narrative
- Employ music and other sound effects to reinforce ideas
- Invite thoughtful reflection from their audience(s)

According to Pietroni (2019), the narration needs to catch the meaning "of the cultural message, avoiding useless descriptions repeating what is already evident when looking at the objects." "The objects become occasional points in which the story coagulates, creating an emotional involvement and an expectation in the visitors, that throw a bridge between past and present" (Pietroni, 2019), transforming the experience into a journey. It is also essential to find a way to guide the visitors (Pietroni, 2019) subtly, accompanying them through the adventure.
A virtual environment meant as "a performative space, immediately generates in the visitor the impression of being involved in a playful situation" (Pietroni, 2019).
Storytelling is a powerful means to help cultural institutions inform and clarify visitors about specific historical events, visualizing the context, which is otherwise challenging to picture, especially regarding cultures lived far away in the past.

3.2 fire simulation in architecture

Fire plays an essential role in the evolution of architecture. Vitruvius states, "The beginning of association among human beings, their meeting and living together, thus came into being because of the discovery of fire" (Vitruvius, 30 - 20 BC in Zografos, 2019). Architectural historians assume that the primitive hut was erected around the fire, setting the starting point of the evolution of architecture (Zografos, 2019). The area warmed up by fire becomes the central space for community and gathering, representing the most important room of the building.

However, fire is an ongoing threat to architecture (Zografos, 2019). The process of combustion, defining the starting of the fire, requires the simultaneous presence of oxygen, combustible material, and a specific temperature level (Zografos, 2019). At least one of these components must be annulled to stop the burning.

According to Zografos (2019), the combustion process unfolds into four stages:

The smoldering sage: a non-flaming process characterized by incandescence and emission of smoke

- The appearance of smoke: meaning the beginning of combustion, reaching temperatures of 80 - 100°
- The incandescence stage: a glowing heat
- The flaming stage: producing a temperature of 1500K (1200°C) to 2500K (2200°C).

The fire can quickly spread to the many combustible materials in buildings, such as furniture, fabrics, carpets, and curtains. The construction materials may represent a fire threat; in fact, "The resistance of materials to ignition is dependent upon their chemical composition and the surface area that is exposed to air" (Zografos, 2019).

Fire protection represents a crucial part of the design process itself. Active or passive fire protection systems are, nowadays, part of the standard equipment of a building. An active fire protection system indicates "objects or methods that respond actively to certain changes in the condition of close environments" (Zografos, 2019), like sprinklers, smoke detectors, and fire extinguishers aiming for the safety of the building and its inhabitants. A passive fire protection system "deals with the overall design approach of a building with regard to fire and the appropriateness of the materials used for its construction" (Zografos, 2019), like fire compartmentation and fire escapes. Fire safety regulations accompany the planning of a building "from the conception of a design to the construction and maintenance of the building" (Zografos, 2019). Fire plays an essential role in defining architecture's shape and appearance.

Nowadays, it is possible to simulate fire and smoke thanks to Computational Fluid Dynamics to understand their behavior. An example of such software is Autodesk CFD, employed to predict how liquids and gases perform, evaluating smoke spread and temperature distribution.

A simulation is an integral part of the digital prototyping process (Autodesk Simulation, 2016). Tests and validations can be computed thanks to a 3D CAD model, answering critical questions like what happens when the temperature changes, how do [products] parts interact, and when will [products] fail (Autodesk

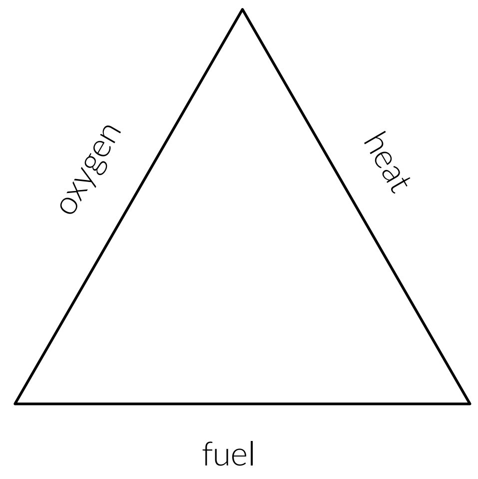

Fig. 13. Fire triangle representing the three components needed to have a fire

Simulation, 2016). Today it is possible to run such simulations in a virtual environment instead of building an actual prototype, saving resources. Simulations lead to an optimization of materials and design, fostering higher quality products and encouraging innovation since the exploration of different what-if scenarios is more readily tested (Autodesk Simulation, 2016). Computational Fluid Dynamics studies the flow of liquids and gasses in and around solid objects (Autodesk Simulation, 2016).

After a CFD analysis, the user will get information about smoke movement, temperature distribution, and airflow field (Munirajulu, 2017), helping the designer make decisions while the product is still developing. Although CFD simulations are not perfect yet, they are extraordinarily useful since the prior distribution of smoke and air velocities is unknown, and the prescriptive codes provide only guidance (Munirajulu, 2017). CFD simulations are often paired with evacuation simulations based on crowd dynamics and pedestrian motion using muli-Agent Systems. Crowd simulations in specific emergencies are incredibly beneficial since they allow the study of crowd behavior, avoiding exposing real people to a dangerous environment (Almeida et al., 2013). Multi-Agent Systems (MAS) allow for recreating real-world interaction among humans, modeling each individual related to the surrounding persons (Almeida et al., 2013). In a MAS

model, "Human individuals are modeled as autonomous agents who interact with a virtual environment and other agents according to the individual's characteristics" (Almeida et al., 2013). Such models can even be implemented using the BDI technique, which refers to Beliefs, Desires, and Intentions driving the agents (Almeida et al., 2013). Examples of MAS models are Exodus, Simulex, and PedGO.
These kinds of simulations even if they are not perfect, these kinds of simulations provide references for better decision-making, providing a visual scenario of particularly complex and dangerous situations.

3.3 forensic fire in architecture

Architectural techniques and technologies may also be used to investigate events and violations. Architectural forensics refers to " the investigation of the built environment, whether that be in relation to crime and injustice or an investigative process to discover the root cause and deterioration in buildings" (Leete, 2022). Forensic Architecture, the non-governmental, non-profit association based at Goldsmiths, University of London, founded in Berlin in 2021, is the perfect example of how spatial and visual investigation, and time-based 3D reconstruction, can be employed in producing evidence. Among the various methodologies used by the multidisciplinary research group are:

- 3D modeling considered more than representations of real-world locations, functioning as analytic or operative devices, giving a fuller picture of how much is known or not about the incident they are studying (Forensic Architecture, n.d.).
- Fluid dynamics, utilized to analyze the motion of particles through space (Forensic Architecture, n.d.)
- Photogrammetry
- Virtual reality, helpful in simulating the witnesses' perspective at the moment of the happening, provides a natural sense of vision concerning moving objects, allowing the wearer to examine an event or space virtually freely. This immersive experience analyzes and cross-references different memories against known physical facts (Forensic Architecture, n.d.).

Regarding the case of the Grenfell tower fire on the 14th of June 2017, Forensic Architecture collected hundreds of videos of the fire captured by many witnesses creating a continuous 3D. This freely available video represents a powerful resource to analyze and better understand the events of that night (The Grenfell Tower Fire, 2018).
A fire investigation involves, in fact, "the examination of all fire-related incidents," monitoring the whole interested scene to establish the origin and, eventually, the cause of the fire (Fire Investigation – The Forensics Library, n.d.).
The primary pursuit is establishing the fire's origin and cause and determining if its nature was accidental or deliberate (Fire Investigation – The Forensics Library, n.d.). Like in a crime scene, the investigator examines the whole set, generally beginning with the inspection of

Fig. 14. Visualization of the Grenfell Tower Fire, Forensic Architecture

the external area and following "with the area of least damage, allowing investigators to backtrack to the seat of the fire, which will typically be found in a more damaged region" (Fire Investigation – The Forensics Library, n.d.).
The starting spot of the fire is generally recognized as the worst damaged part since the fire burnt for a more extended period than the rest of the area.
Since the fire tends to burn in an upwards direction, the origin of the fire may be found at a lower point; but the presence of particularly fuel elements allows the fire to spread in a downwards direction, too (Fire Investigation – The Forensics Library, n.d.).
Not only does the presence of ignitable materials need to be considered, but external factors like weather or the presence of possible burning sources such as candles play an essential role in the fire investigation. Analyzing all the evidence related to the fire, if lucky, may lead to precise identification of the fuel sources and incendiary devices. The application of architectural techniques in forensic investigations aims the purpose of creating evidence as a visual starting point to narrate a story and open a discussion.

4 the Metaverse

The Metaverse, meant as the evolution of the internet as a virtual shared space accessible to all in which people can engage in socio-economic activities, has lately gained exponential attention. The concept of a Metaverse emerged in 1992 in Neal Stephenson's novel Snow Crash. It described an immersive virtual environment that included interactions between the real and the virtual worlds. This new paradigm undoubtedly has the potential to profoundly transform many aspects of our future daily life, like how we communicate, shop, travel, learn, and so on, generating tremendous excitement. We hear of real estate investors buying increasingly expensive digital property; large corporations currently face an intense race to construct the infrastructure and virtual ecosystem that will govern the Metaverse. Still, the lack of a conceptual foundation and a precise idea of what the Metaverse will look like creates confusion.

4.1 definition of the Metaverse

The term Metaverse is compounded by the prefix meta, from the Greek after or beyond, and the word universe, as it follows, can be described as ''a post-reality universe, a perpetual and persistent multiuser environment merging physical reality and digital virtuality'' (Mystakidis, 2022).
Go et al. defined the Metaverse as "a 3D-based virtual reality in which daily activities and economic life are conducted through avatars representing the real themselves".
Lee stated, "metaverse means a world in which virtual and reality interact and co-evolve, and social, economic, and cultural activities are carried out to create value" (Bokyoung, 2021). Reality and virtuality will grow together, interacting and compensating for one other, becoming a unified model. Van der Merwe, at the 3rd World Conference on Research in Social Sciences in Vienna, states: "The metaverse is something of a paradox, both an inhabited and enacted space as well as an impermanent interface between the digital and the physical realms - an expression called "phygital" in the contemporary investigation into experience design (Gaggioli, 2017, as cited in van der Merwe, 2021), and continues "it is becoming more evident that the metaverse is rather a mixed reality we inhabit - where digital and physical immersive experiences are overlaid to occur concurrently." Matthew Sparks describes a Metaverse as a shared online space incorporating 3D graphics on a screen or virtual reality (2021). In his famous talk on the 28th of October 2021, Mark Zuckerberg described the Metaverse as a new immersive platform and medium. He pictures: "An embodied internet where you are in the experience, not just looking at it,"; a place to get together with friends and family, work, learn, play, shop, and create new experiences that don't fit how we think about computers or phones today. Marc Petit defines the Metaverse as the internet, as a (hopefully) open platform

that features many different shared experiences in real-time 3D. It does not need to be immersive but, in any case, interactive and customizable, where the user is part of the experience and becomes from watcher to creator (Bloomberg Intelligence, 2021). Matthew Ball (2022) defines the Metaverse as: "a massively scaled and interoperable network of real-time rendered 3D virtual worlds that can be experienced synchronously and persistently by an effectively unlimited number of users with an individual sense of presence and with continuity of data, such as identity, history, entitlements, objects, communications, and payments". There still is not an official definition of the Metaverse, of the apparent fact that the way it will look is still unclear. However, all the theorists picture it as a shared 3D virtual world in which it is possible to actively perform daily life activities that will exist alongside what we now define as reality.

4.2 visions

On the 28th of October, 2021, Mark Zuckerberg announced, at Connect 2021, its annual conference, to share ideas regarding the evolution of AR/VR and bring developers and creators together, he changed his company's name from Facebook to Facebook Meta, becoming a metaverse company.

The announcement video "The Metaverse and How We'll Build It Together - Connect 2021," published on Youtube, reached, until today, almost 7 million views. Precisely because of this video, the concept of the Metaverse gained for the first time mainstream interest.

In his visualization, Zuckerberg pictures his concept of the Metaverse as "an embodied internet: instead of looking at a screen, you're going to be in this experience" (Zuckerberg, 2021). He continues describing a new version of the internet that can convey a full range of human expressions and deliver a deep feeling of presence. The Metaverse is, in his sight, all about creating new technology built around how people experience the world and interact with each other. He states, "It [the Metaverse] doesn't exist yet. Some basic building blocks are here, though, and others are emerging as we speak"; we are starting to understand how it could come together and how it will feel (2021).

Zuckerberg envisioned an entirely virtual environment reachable by putting on a virtual reality headset encompassing many aspects of daily life. Education will also benefit from this evolution of technology, making it possible for students to experience immersive learning content.

In Mark Zuckerberg's opinion, the Metaverse will embrace many aspects of life as we know it now, enhancing them. Although Zuckerberg's vision of the Metaverse received many critics, it undoubtedly set a milestone for the disclosure of the Metaverse's concept, that until just before the publication of his video, was limited to a small circle of people and now reached a broad audience, and he undoubtedly opened a discussion. Zuckerberg's views on the development of the Metaverse do not have to be taken for granted; it is impossible at this time to have a concrete idea about how the new internet will look because many aspects that will influence it are still developing.

NVIDIA focuses on helping and optimizing the creation of the Metaverse's 3D worlds on a more industrial-

Fig. 15. Education in the Metaverse according to Meta

oriented level. Richard Kerris, the General Manager of Omniverse, defines the Metaverse as "the network of the next generation of web, which will 3-D" (2022), where the users will be able to go from one virtual world to another virtual world seamlessly. "Here at NVIDIA, we believe virtual worlds are essential for the next era of AI," states Kerris (2022).

Its collaboration platform Omniverse enables "artists building content across multiple 3D tools, developers building AIs trained in virtual worlds, or enterprises building digital twins simulations of their industrial processes" (2022) to optimize 3D workflows.

Omniverse allows a direct connection and interaction among different 3D software, updating the modifications in real-time. Omniverse's core apps are Omniverse Create, enabling designers and engineers to create 3D objects, and Omniverse View, which allows the real-time visualization of the created 3D scenes. Additional application focus on specific markets like Machinima, Audio2face, IsaacSim, and Kaolin. Third-party firms, like the infrastructure-software provider Bentley, builds their digital twins (more on the digital-twin concept in chapter 4.4) on the Omniverse platform. Kerris states: "We believe that anything that will be built will be visualized. Anything that moves will be autonomous. And anything that's autonomous will be simulated" (2021), envisioning a virtual research playground where investigations are firstly visualized and simulated rather than in reality. Autonomous robots in factories or autonomous vehicles can be virtually trained on the Omniverse platform. NVIDIA is currently collaborating with BMW to create the "Factory of the Future" (Kerris, 2021), starting from the design and planning, to the training of the robots, to the end-to-end simulation and optimization of the factory operations as a digital twin.

Omniverse is a platform helping create and simulate virtual words, optimizing the pipelines and connecting different working areas, giving insight into one possible future view of the Metaverse.In an article for the American publishing platform Medium, Tony Parisi (2021) states, "As of now, we do not know exactly what shape the Metaverse will take. That does not matter, either. What matters is that someday, a global network of spatially organized, predominantly 3D content will be available to all without restriction, for use in all human endeavors - a new and profoundly transformational medium, enabled by major innovations in hardware, human-computer interface, network infrastructure, creators tools, and digital economies". Still, we must acknowledge the Metaverse as something beginning, even if it is not fully realized.

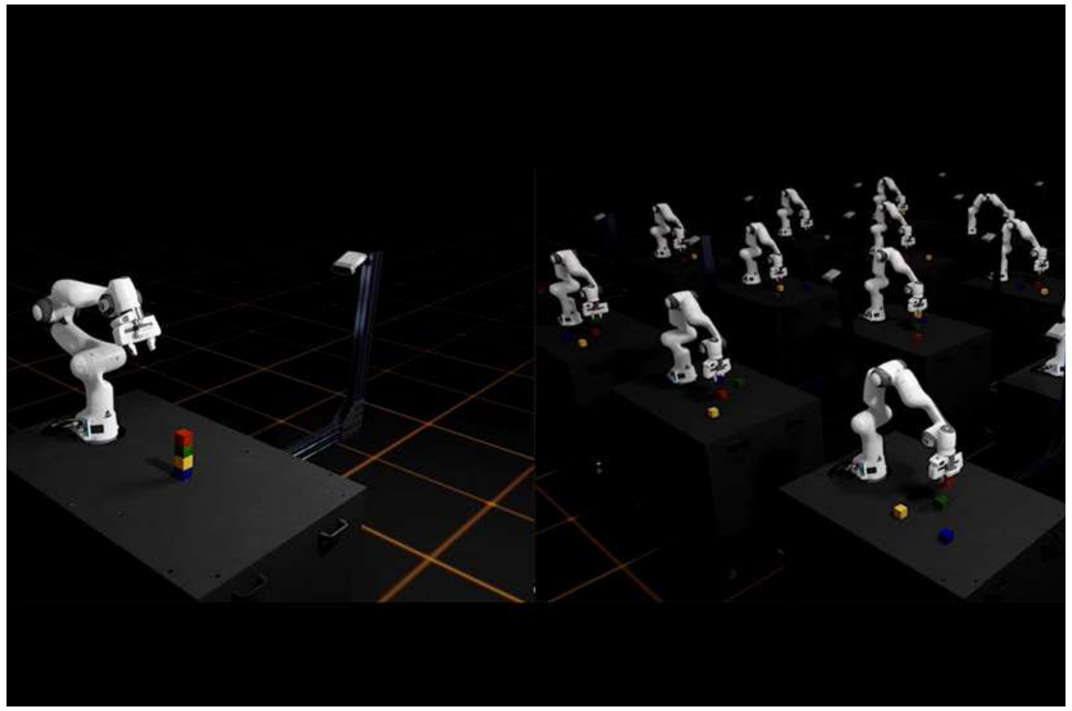

Fig. 16. NVIDIA, Omniverse, virtual robots training

Fig. 17. NVIDIA, Omniverse, digital twin by Bentley

4.3 conceptual foundation

The non-profit research group Acceleration Studies Foundation (ASF) published 2007 the "Metaverse Roadmap" by John Smart, Jamais Cascio, and Jerry Paffendorf, giving its 10-year scenario of the evolution of the internet.

The ASF defines the Metaverse as "the convergence of virtually-enhanced physical reality and physically persistent virtual space. It is a fusion of both while allowing users to experience it as either". The ASF considers the Metaverse "not as a virtual space but as the junction or nexus of our physical and virtual worlds" (Smart et al., 2007). The above description fits perfectly with the definitions given by contemporary theorists, showing a solid conceptual common point.

The ASF expects many 2D-based internet activities to "migrate to the 3D space of the Metaverse", envisioning "new tools, able to intelligently mesh 2D and 3D to gain the unique advantages of each, in the appropriate context" (Smart et al., 2007). This statement unquestionably reminds us of our modern-day Oculus, allowing users to access 2D and 3D-immersive content.

The 10-year scenario described by the ASF selected two continua that would probably impact the development of the Metaverse: the spectrum of technologies and applications ranging from augmentation to simulation; and from intimate (identity-focused) to external (world-focused).

- Augmentation: technologies that augment the real world by adding information to our perception of the physical environment.
- Simulation: technologies that provide new environments as new places for interaction.
- Intimate: technologies that provide the user the sense of control felt in real life through an avatar.
- External: technologies that focus on delivering information about the world in which the user is immersed.

Combining the two continua, the ASF identifies four key components of the Metaverse future: Virtual Worlds, Mirror Worlds, Augmented Reality, and Lifelogging.

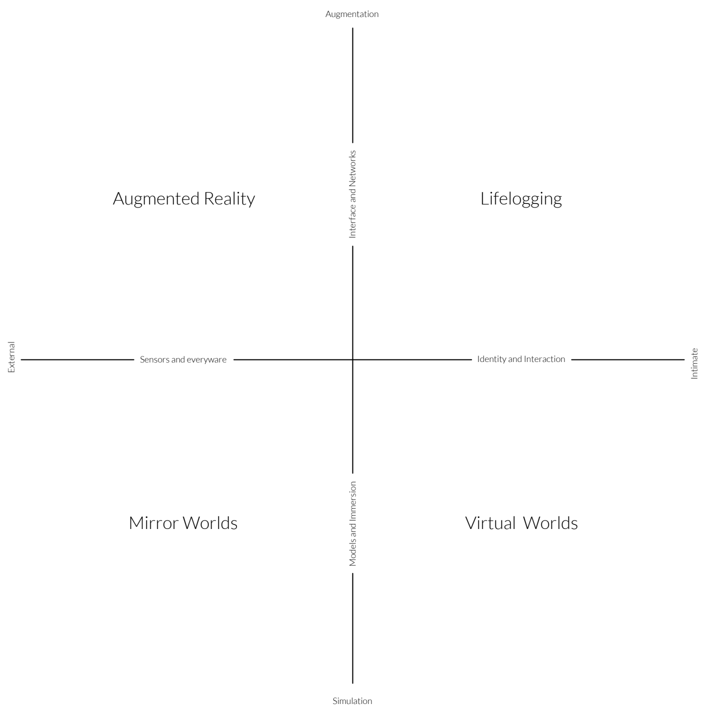

Fig. 18. The four types of Metaverse according to the ASF

Fig. 19. Reality-Virtuality Continuum, P. Milgram

Augmented Reality (External/ Augmentation)

"In augmented reality, Metaverse technologies enhance the external physical world for the individual, through the use of location-aware systems and interfaces that process and layer networked information on top of our everyday perception of the world" (Smart et al., 2007).

Augmented Reality is "a real-time direct or indirect view of a physical, real-world environment that has been enhanced/ augmented by adding virtual computer-generated information to it" (Wikipedia in Carmigniani and Furht, 2011).

Augmented Reality, unlike Virtual Reality, overlays a virtual information layer on top of the real environment instead of creating a whole new virtual world "AR supplements reality, rather than completely replacing it" (Azuma in Papagiannis, 2017). Carmigniani and Furht (2011) states: "While Virtual Reality technology [...] completely immerses users in a synthetic world without seeing the real world, AR technology augments the sense of reality by superimposing virtual objects and cues upon the real world in real-time".

To better visualize the concept of real and virtual, Paul Milgram introduced 1994 his Reality-Virtuality continuum as a continuous sequence that spans between a completely real and a completely virtual environment, in which Augmented Reality stands closer to the real environment and Augmented Virtuality (Virtual Reality) is closer to the virtual environment.

According to Azuma, AR systems need to:

- combine real and virtual
- interact in real time
- register in three dimensions (Papagiannis, 2017).

Azuma defines the augmentation implied by AR as either not limited only to the sense of sight or being limited to specific display technologies (Azuma in Carmigniani and Furht, 2011). It is possible nowadays to reach augmented content by scanning physical hyperlinks like QR codes or RFID tags with a mobile phone or tablet camera.

It is easy to imagine a near future in which such devices become of daily use, helping the user carry out everyday tasks. In fact, "Augmented Reality (AR) aims at simplifying the user's life by bringing virtual information not only to his immediate surroundings but also to any indirect view of the real-world environment, such as live-video stream" (Carmigniani and Furht, 2011). The user may be able to fix his car while wearing AR glasses, visualizing real-time instructions and highlighting components to move or replace.

It is, in fact, already possible to visualize through the smartphone camera AR route instructions from Google Maps. Thanks to Augmented Reality, the environment can become a mirror to the users, adapting to their needs (Papagiannis, 2017).

Cultural projects utilize AR to let objects tell stories, like Archeoguide at Greece's Olympia archaeological site, where historical monuments are visualized to show how the place once looked (Papagiannis, 2017).

The London designer Keiichi Matsuda released 2016 a short movie showing a "futuristic scenario where digital media and the physical world have merged," (Winston, 2016) creating a kaleidoscopic hyper-reality.

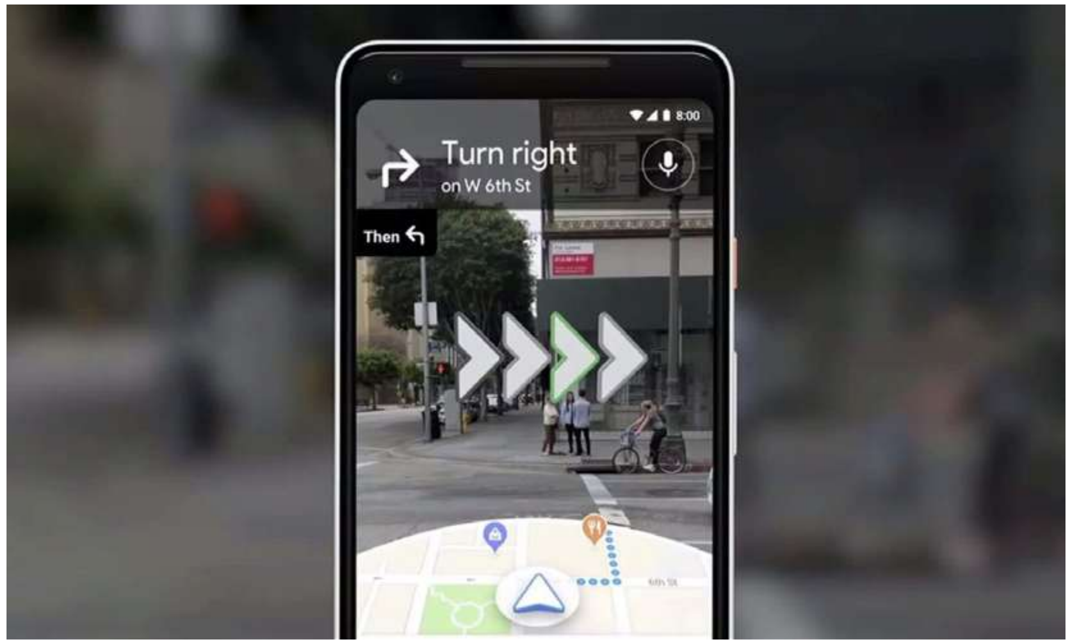

Fig. 20. Google Maps AR

Fig. 21. Archeoguide at Greece's Olympia archaeological site

Lifelogging (Intimate/ Augmentation)

"In lifelogging, augmentation technologies record and report the intimate states and life histories of objects and users, in support of object- and self-memory, observation, communication, and behavior modeling" (Smart et al., 2007)

The ASF defines Lifelogging as "the capture, storage and distribution of everyday experiences and information for objects and people" (Smart et al., 2007).

The captured data will create a sort of "backup memory" (Smart et al., 2007) that will be available for later inspection creating a record of human life. Nowadays, it is standard among the young generation to collect and share personal life experiences on social media. Social media are a form of Lifelogging without structure or consistency (Messieh, 2013).

Rather than social media, there are nowadays specifically made apps and devices to record and store personal information privately, like, among others, Instant, developed by Emberify and released in 2015, or Lifelog from Xperia.

The collected personal life data will stay available, creating an unbreakable memory. On the other side, such lifelog technology will allow users to look through another person's eyes (Smart et al., 2007). Lifelogging allows users to record the sights and sounds encountered during the day and enables connection and collaborative sharing of life experiences (Smart et al., 2007). The ASF considers both of these aspects to be potential "socially-disruptive", even if the users can instantly benefit from them (Smart et al., 2007).

4.4 Virtual Worlds and Mirror Worlds

Virtual Worlds (Intimate/ Simulation)

"Virtual worlds increasingly augment the economic and social life of physical world communities. The sharpness of many virtual and physical world distinctions will be eroded going forward. In both spaces, issues of identity, trust and reputation, social roles, rules, and interaction remain at the forefront" (Smart et al., 2007).

Fig. 22. Roblox, developed by Roblox Corporation

Fig. 23. View of Second Life, developed by Linden Lab

Virtual Worlds are fully digital simulated environments in which the users, emulated by their avatar, can participate in social activities such as playing a game, attending a concert, or having a virtual chat with friends. All the needed assets, clothes, concert tickets, and so on, will be available on the market for them to buy. Virtual Worlds are usually defined as massively multiplayer online games based on the interaction activities between avatars and reflect the user's ego (Bokyung et al., 2021). Many lack predetermined goals and provide the user significant freedom; players can usually create objects or spaces, interact with the existing environment, and communicate with other users. The most popular these days are Fortnite developed and published by Epic Games, Roblox, developed by Roblox Corporation, and Minecraft, developed by Mojang Studios. The online multimedia platform Second Life developed by Linden Lab and released in 2003, demonstrates the possibility of parallel existence in virtual space. Just in the first year, Second Life had over a million regular users and, shortly after, numerous businesses such as Adidas, BBC, and Wells Fargo, but also non-profit organizations such as Save the Children and even universities, including Harvard, joined the platform (Ball, 2022). Second life reflects real life in all aspects, creating a virtual copy of reality, with its economy based on its internal currency, the Linden Dollar, which users can use to buy land and objects. Virtual Worlds do not necessarily have to mirror reality, neither in style nor in the contents; they do not even have to follow our physics rules such as gravity. Developers have an infinite number of possibilities to create worlds that we cannot even imagine now.

The ASF imagines Mirror Worlds to become "primary tools (with video and text secondary) for learning many aspects of history, acquiring new skills, job assessment, and many of our most cost-effective and productive forms of collaboration" (2007). In an even stronger version of this scenario, Virtual Worlds will be so integrated and play such an important role that people might live "Spartan lives in the physical world, and rich, exotic lives in virtual space—lives they perceive as more empowering, creative and "real" than their physical existence, in the ways that count most" (Smart et al., 2007).

Considering just the Mirror Worlds, the Metaverse takes the shape of a virtual bubble containing an infinity of user-created other worlds available for everyone and every time, in which people communicate and act through their avatar. However, the whole concept of the Metaverse does not limit itself to just this.

Mirror Worlds (External/ Simulation)

"Mirror worlds are informationally-enhanced virtual models or "reflections" of the physical world. Their construction involves sophisticated virtual mapping, modeling, and annotation tools, geospatial and other sensors, and location-aware and other lifelogging (history recording) technologies" (Smart et al., 2007)

Unlike a Virtual World, Mirror Worlds can be directly connected to real models, like buildings and streets. Thanks to open geo-coding standards, users can add their geographical data as a new layer to the copy of the Mirror World present on their computer (Wikipedia, as cited by Google Arts & Culture, n.d.).

Google Earth and Google Maps are well-known examples of Mirror Worlds. Google Earth shows 3D models of the world based primarily on satellite images. At the same time, Google Maps, as an online mapping platform, "offers satellite imagery, aerial photography, street maps, 360° interactive panoramic street view, real-time traffic conditions, and route planning for traveling by foot, car, bike, and public transportation" (Google Maps, 2022). Google Maps is, furthermore, probably the most diffuse Geographic Information System (GIS) platform. Geographic Information Systems are computer-based tools that examine spatial relationships, patterns, and geographic trends. "GIS store, analyze, and visualize data for geographic positions on Earth's surface" (GISGeography, 2022). GIS follows four main goals: creating geographical data, managing it in a database, analyzing it, finding patterns, and displaying it on a map (GISGeography, 2022). The use cases of GIS are various, from routing for traveling by car to soil mapping for agriculture. The analysis and pattern emerging from such systems are instrumental in urban planning. By mapping a city, it is possible to analyze, among others, connections to points of interest, moving patterns of the population, and rescue routes. This is where the concept of the Digital Twin comes in. "A digital twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help

decision-making" (IBM, n.d.). A Digital Twin is, therefore, not only the exact digital representation of reality but also the connection between the virtual copy and the real object: "A digital twin is a virtual model designed to accurately reflect a physical object" (IBM, n.d.). Real-time data like, among others, temperature, weather conditions, crowd analysis, and object performance are collected through sensors, stored, and then applied to the digital copy. "Once informed with such data, the virtual model can be used to run simulations, study performance issues, and generate possible improvements, all with the goal of generating valuable insights — which can then be applied back to the original physical object" (IBM, n.d.). A digital twin of the Hong Kong International Airport to simulate the flow of passengers, the implication of maintenance issues or runaway backups, and other events that would impact airport design choices and operational decision-making has been created as a helpful tool for planners (Ball, 2022). Even without the full development of the Metaverse, the real world is already strictly connected to the digital world, and we are already benefitting from it.

Mirror Worlds are particularly suitable for preserving and cataloging cultural heritage; during the past decades, many museums and cultural institutions started creating digital data libraries and virtual

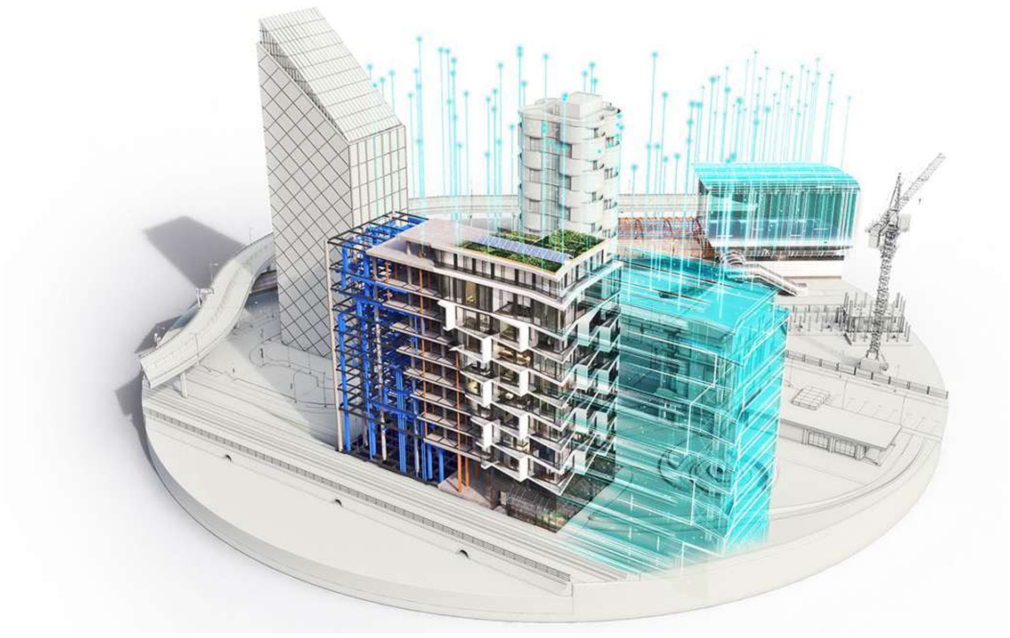

Fig. 24. Digital twin concept by Autodesk

exhibitions. The online platform Google Arts & Culture is a perfect example of the meaning of Mirror Worlds. It includes, in fact, high-resolution images, videos, and 3D models of artworks, archaeological artifacts, and architecture offered by museums and cultural institutions from all over the world.
Google Arts & Culture allows the digital exploration of artworks through augmented reality and features interactive experiences like sculpting an ancient greek pottery vase or 'playing' a Kandinsky painting. The user can also search for museums, exhibitions, landmarks, and cultural institutions based on their position.
The Europeana web portal, founded by the European Union, provides users digital access to European cultural heritage containing artworks, books, music, and videos on art, newspapers, archaeology, fashion, science, sport, and more. It relies on over 4000 European institutions like galleries, libraries, archives, and museums sharing the belief that access to cultural heritage empowers people and benefits society as a whole (Europeana, n.d.).
In this regard, Mirror Worlds represent an excellent means of information and education accessibility; as the ASF noted in 2007, "Mirror Worlds are democratizing and pluralizing only to the extent that everyone can access and can annotate them. If that access is restricted, they can easily become instruments of state corporate control" (Smart et al., 2007).

Fig. 25. Notre Dame de Paris reconstructed in Minecraft

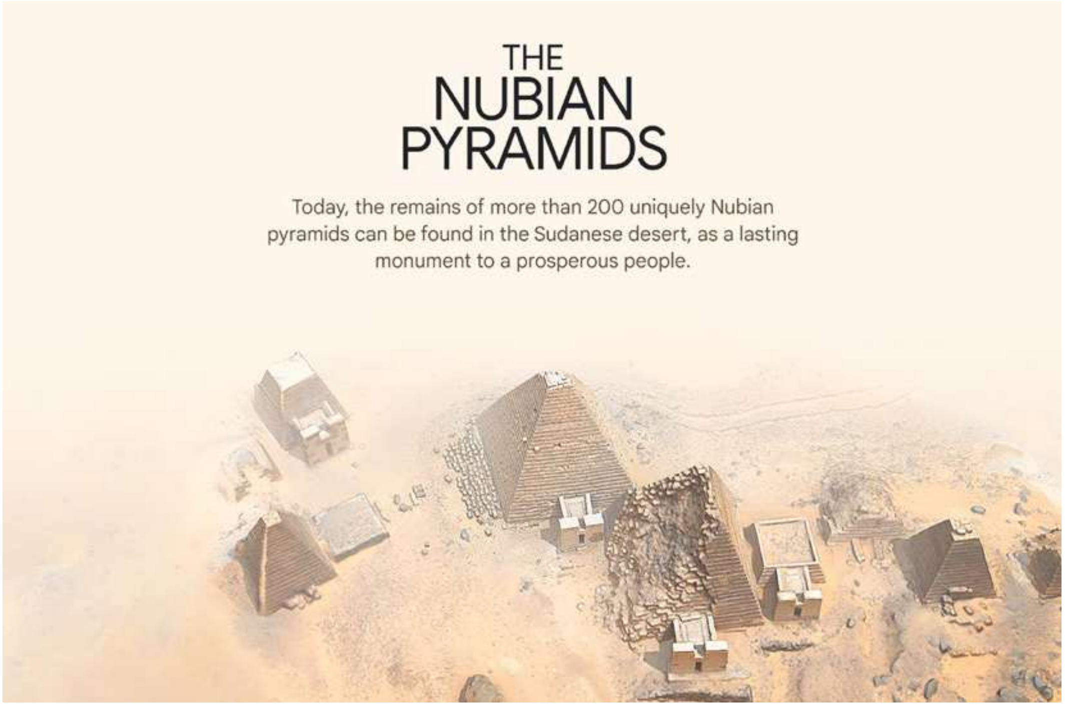

Fig. 26. Google Arts and Culture, The Nubian Pyramids (n.d.)

The ASF expects the four scenarios to combine within the Metaverse.
Virtual Worlds connected to Mirror Worlds will give a sense of immersion to the users and will be utilized in games and for educational purposes, which is the theme of this thesis.
Mirror Worlds and Augmented Reality will lead to the creation of sensors and wearable devices, the first collecting data and the latter operating as a medium to visualize and interact with them.
To link Augmented Reality and Lifelogging interfaces and networks to enhance the environment will be developed.
Moreover, the connection between Lifelogging and Virtual Worlds will eventually develop a consistent digital identity.

4.5 cultural heritage in the Metaverse

During the Digital Exhibitions Summit organized by MuseumNext in December 2021, Jon Astorquiza del Val, founder and CEO of ElektrART, stated: "Museums cannot remain oblivious to the virtual revolution that the art world is experiencing in the post-pandemic era. Finding the balance between the real and the virtual world is the key to adapting to the near future." This concept can be applied not only to museums but more generally to cultural heritage institutions. The "virtual channel" does not need to replicate the activity in the real world; it must be considered as a new medium and different mediums require different strategies (Astorquiza del Val, 2021). Metaverse exhibitions will be designed differently than those of the real world, "complementing physical exhibitions with all the experiences that generate and add value in the virtual world" (Astorquiza del Val, 2021).

According to Bokyung (et al., 2021), who investigated the Metaverse's educational applications, "By actively utilizing the characteristics of the Metaverse, it will be possible to design learning activities that can expand students' freedom and experience to an infinite extent. Students will conduct self-directed learning that allows them to explore their questions based on their endless autonomy".

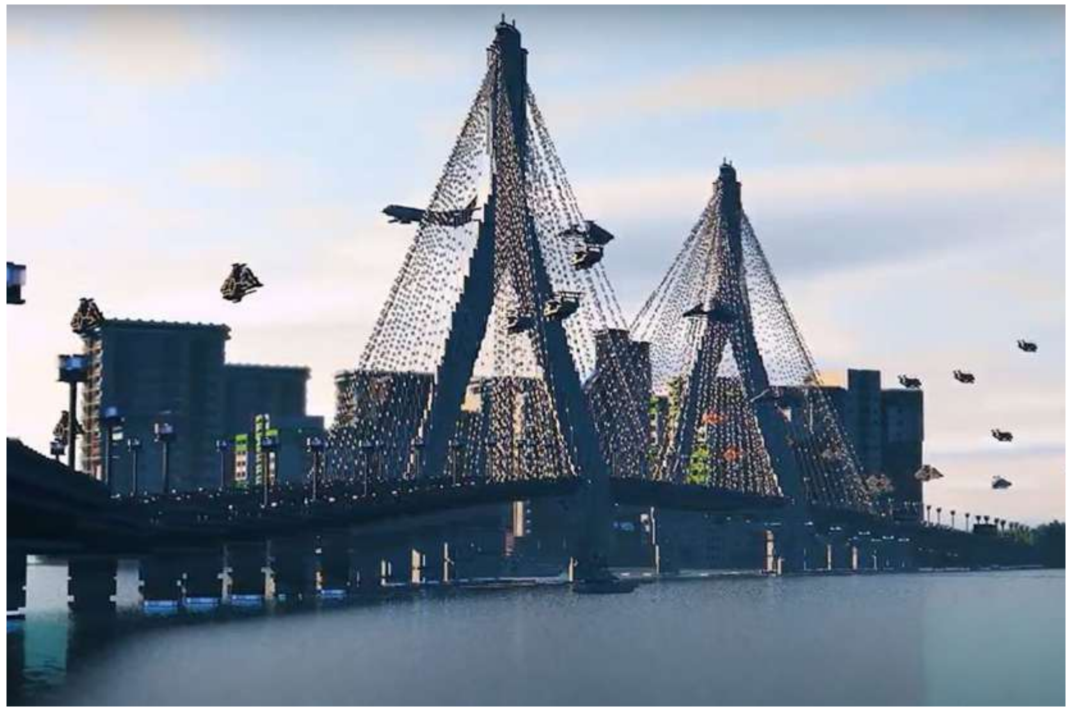

Fig. 27. Incheoncraft: reproduction of Incheon in Minecraft

Remote access to cultural heritage, available on demand, accessible from anywhere anytime, enables a broader distribution of information. Distant learning is, in this case, facilitated and enhanced, thanks to the immersive characteristics of Augmented and even more Virtual Reality, stimulating a strong sense of presence on the user's side. "MR [Mixed Reality, meant as a combination of Augmented and Virtual Reality] encourages users to experience and interact with historic items whilst in the real world by integrating engaging ways of narrative to involve visitors. It supports the integration of physical and digital displays by projecting digital information in real environments and also by displaying items with no material availability" (Buhalis and Karatay, 2022). Significant historical events can be narrated through storytelling, transforming the visitor into the protagonist. New adventures are available to live firsthand: "One of the biggest advantages of MR is that it places the spectator in the main role [...] while creating MR experiences it's crucial to conceive the user as a player, instead of an observer and to design adventures that emphasise traveler engagement" (Buhalis and Karatay, 2022). Reality is expanded into the virtual world. Examples of Cultural Heritage in the Metaverse are still a few and are now in development.

According to Um et al. (2022), "Incheon is the first selected area in South Korea to create a smart tourism city, providing services, content, and information for smart tourism to tourists. In addition, Incheon is making efforts to overcome the spatial limitation that a smart tourist city requires a physical space." Incheoncraft is an impressive reproduction of Incheon on the platform Minecraft, in which "users can experience historical events with historical figures, and learn educational facts" (Um et al., 2022). Um (et al., 2022) described this digital reproduction as a "Virtual-Based Metaverse". The "Real-Based Metaverse" can also be utilized to overcome physical accessibility and enhance tourists' experience "providing extended reality experience, such as environment-related historic figures guiding the tourists, panoramic virtual mirror world through AR where tourists can share experiences in a social network, seamlessly connecting real-world based and virtual world based metaverse" (Um et al., 2022).

This project represents the starting point for the development possibilities the Metaverse offers.

Fig. 28. In the next page: Umm el Qa'ab, desert and mountain

Fig. 29. View of Abydos

5 Visualizing the tomb of Queen Meret-Neith

The reconstruction of the tomb of Meret-Neith is part of the project "Visualizing an Ancient Egyptian Queen - VR/ AR Visualization of the Tomb of Meret-Neith Abydos", a collaboration between Vienna University of Technology, Vienna University, the German Archaeological Insitute and the Egyptian Ministry; founded by der Wissenschaftsfonds FWF and DFG Deutsche Forschungsgemeinschaft.

The fragile nature of the structure of the tomb imposes the archaeologists a backfill after the excavation, making the tomb impossible to reach.

Part of the project foresees a detailed photogrammetric reconstruction of the tomb's architecture, producing a model available for documentation and further development of touristic attractions. The digital material will eventually be accessible to visitors protecting the heritage and providing educational materials, thereby enhancing visitors' experience.

The Vienna University of Technology team consisted of Peter Ferschin, Project Leader; Balint Istvan Kovacs, Ph.D. student, computer science; Karl-Johann Mayr, photographer; Florian Sövegjarto, master's student, architecture and Sara Treccarichi Scavuzzo, master's student, architecture. The team joined the archaeologists' team in Abydos from the 16th of October to the 6th of November 2021 and from the 3rd of April to the 17th of April 2022. The team collected during both campaigns numerous data. Such data has been then computed in Vienna, creating a final 3D model of the whole tomb by joining the material from the first and second campaigns together.

Fig. 30. The TU team: Sara Treccarichi Scavuzzo (the author), Peter Ferschin, Balint Istvan Kovacs, Florian Sövegjarto, and Karl-Johann Mayer

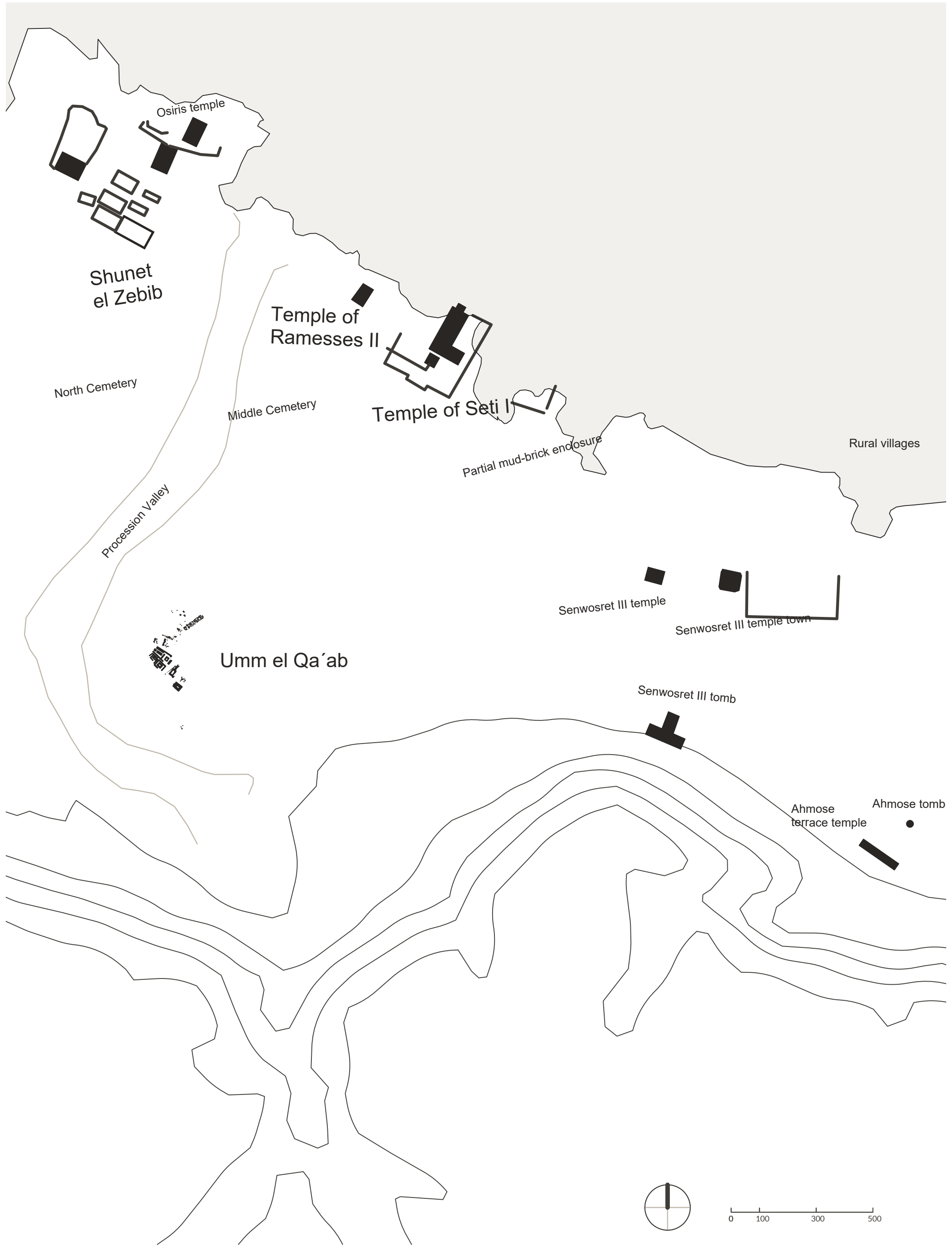

Fig. 31. Map of Abydos, based on Map of Monuments of Abydos of D. O'Connor, in Abidos, Egypt's Firts Pharaohs and the Cult of Osiris, 2009

Fig. 32. Temple of Seti I

5.1 Abydos

The city of Abydos is located in southern Egypt, under the Sohag Gouvernurat and approximately 11 km west of the Nile. The exposed red brickworks characterizing the rural buildings overlook rammed earth roads where children run around, men rest in the evening smoking their sheesha, cats move furtively looking for food, and birds sing loudly, storming the trees among the streets. Minarets stand out from the residential buildings defining the skyline with their sharp structure and filling daily life with prayers and singing. Among rustic facilities and green agricultural fields hide some incredibly well-preserved ancient Egyptian temples that amaze visitors with their monumental structure and the unique colors of their hieroglyphs. The Temple of Seti I (19th Dynasty), completed after his death by Ramesses II, his son, represents the main touristic attraction in Abydos. The regular rhythm of the massive limestone columns marks an extraordinary succession of different spaces like courtyards, terraces, chapels, and halls, all beautifully decorated with scenes of battles and gods. Carved on the Gallery of Ancestors' walls, one of the chapels in the southern part of the temple hides the famous Abydos King List. The Osiris Chapel leads

to different chapels and secret chambers devoted to the cult of Osiris, his sister and wife Isis, and their son Horus. (The Temple of Seti I in Abydos | American Research Center In Egypt, n.d.).
Nearby the temple of Seti I stand the ruins of the splendid temple of Ramesses II dedicated to Osiris. Despite the bad condition of the main structure, the hieroglyphs and the colorful scenes of war, captives, and religious figures engraved on what remains of the walls and columns still manage to astonish (Hench, n.d.). A huge mudbrick enclosure, known as Shunet el Zebib, rises northwest from the temples; built ca. 2750 B.C., the Storehouse of Grapes is one of the oldest preserved mudbrick buildings in the world and served as a funerary cult of the second dynasty King Khasekhemwy (Shunet El-Zebib | World Monuments Found, 2018). These are just some well-preserved examples of a wide variety of temples and cult places showing the importance of Abydos to ancient Egypt. With its distinctive atmosphere, colors, and sounds, the city extends into the desert, where everything seems to stand still. Massive mountains rise against the bright blue sky; the wind drags the sand around softly; electricity pylons are reminders of daily life happening on the other side. Everything remains silent, unmoving; the landscape suggests eternity. It is easy to understand why this site significantly impacted

Fig. 33. Temple of Ramesses II

Fig. 34. Shunet el Zebib

ancient Egyptians as the home of the god Osiris, who offered the route to immortality after death. Right here, in the middle of the low-lying desert, lies the today-called Umm el Qa'ab, the cemetery of the First Dynasty of Egyptian kings and what was thought to be the tomb of the god Osiris.

5.2 Umm el Qa'ab

The royal cemetery of Abydos - Umm el Qa'ab - represents a significant archaeological source. By studying the architecture and equipment of the tombs, egyptologists can develop theories not only about Early-Dynastic ideas of the afterlife but also about social structures, administrative organization, and even the evolution of writing and arts and crafts (Dreyer and Polz, 2007).
The tombs were firstly excavated by Émile Amélineau in 1895 and then by Flinders Petrie in 1900. Since the 1970s, the German Archaeological Institute has been conducting on-site research.
The necropolis comprehends three cemeteries:

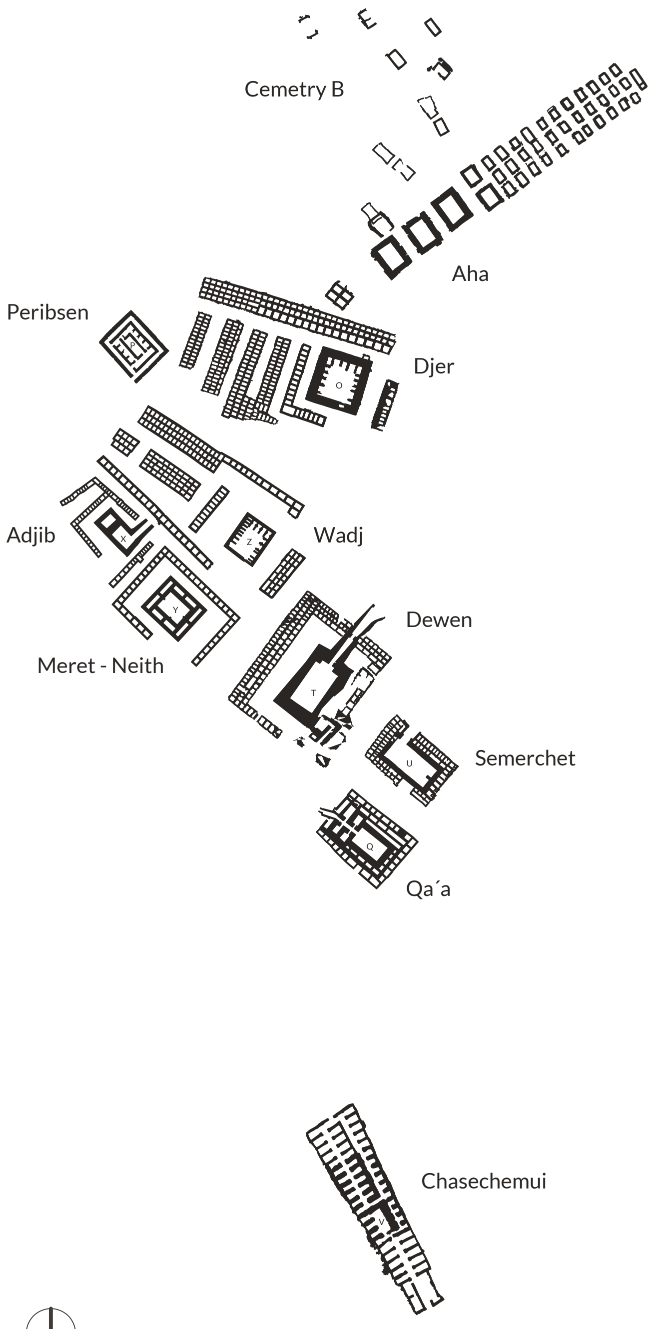

Fig. 35. Umm el Qa'ab, black plan

Fig. 36. Low desert and mountains of Um el Qa'ab

- The Predynastic Cemetery U: circa 650 graves from 3700 - 3050 BC.
- The cemetery B, with the tombs of the last Predynastic rulers from 3050 - 2950 BC.
- The tombs of the seven First-Dynasty kings: Djer, Wady, Dewen, Adjib, Semerchet, Qa'a, and queen Meret Neith, from 2950 - 2700 BC. (Dreyer and Polz, 2007).

Umm el Qa'ab played a significant role later on; during the XVIIIth Dynasty (1550-1292 BC), the site was recognized as the burial place of Osiris. All graves were excavated during the Middle Kingdom (2040 - 1782 BC) in search of the sacred tomb, and some were refurbished in the New Kingdom (1550 - 1352 BC) and later. The tomb of Djer, identified as the one of Osiris, was converted into a cenotaph. The quantity of the offering increased enormously, and the massive amounts of jars, which until today characterize the site, were brought to the desert. The site name Umm el Qa'ab is Arab for Mother of the Pots. Pilgrims would bring offerings in pottery jars, ensuring a better chance of safe passage to the afterlife. Abydos became one of the most important Osiris cult sites and, together with the temples of Seti I and Ramesses II, a "Mekka" of ancient Egypt (Dreyer and Polz, 2007). The ritual pilgrimage to Abydos and the participation in the yearly cult event were considered indispensable requirements for life after death (Dreyer and Polz,

Fig. 37. Ceramic debris mound

2007). The royal tombs lie closely together and are oriented 44° West of the magnetic Nord (Petrie, 1900). The essential structure, built of mudbricks, presents the burial chamber as a large square pit surrounded by additional magazines for supplies of food, drink, and equipment. The subsidiary graves for servants, courtiers, and others are placed around the main chamber and sometimes separate (O'Connor, 2009). A large wooden shrine filled almost entirely the burial chamber (O'Connor, 2009); timber was, in fact, the preferred material for the decoration of the royal tombs, employed for lining the walls and flooring of the chamber (Spencer, 1993).

Since the earlier tombs of Djer, Djet, and Queen Meret-Neith, did not have any access via a stairway, the only possibility, according to Spencer (1993), to place the hedging would have been after the installation of the burial. O'Connor (2009), instead, states that each tomb could be almost entirely roofed before the royal burial, a part of a small space for the final interment. After the ceremony, the graves were sealed, becoming inaccessible, covered by sand, hiding undisturbed (O'Connor, 2009). The roofing system consisted of wooden beams supporting a flat wooden roof covered by sand and bricks. The exact appearance of such superstructures remains unknown; there are, however, some theories about their design: Spencer (1993)

suggests them to be in the form of low square tumuli or mastabas cased with mudbricks and surrounded by an enclosure wall. He states that superstructures in the form of mounds were linked in Egyptian religious beliefs with the primeval mound of creation and were desirable in helping to ensure the benefits of resurrection for the dead (Spencer 1993). Each tomb was marked on the east side by two great stone stelae set upright, indicating the owner's name and the offering place.

The royal cemetery of the First-Dynasty Kings let Abydos become the center for initiatives and developments in monumental architecture and burial traditions, influencing the elite (and other) tombs throughout Egypt (O'Connor, 2009).

The royal cemetery lost importance as time passed; some of the tombs burned in an intense fire, destroying most of the woodwork; they were repeatedly plundered and even probably served as a refuge for vagabonds. The precise time and the cause of the fire are so far unknown.

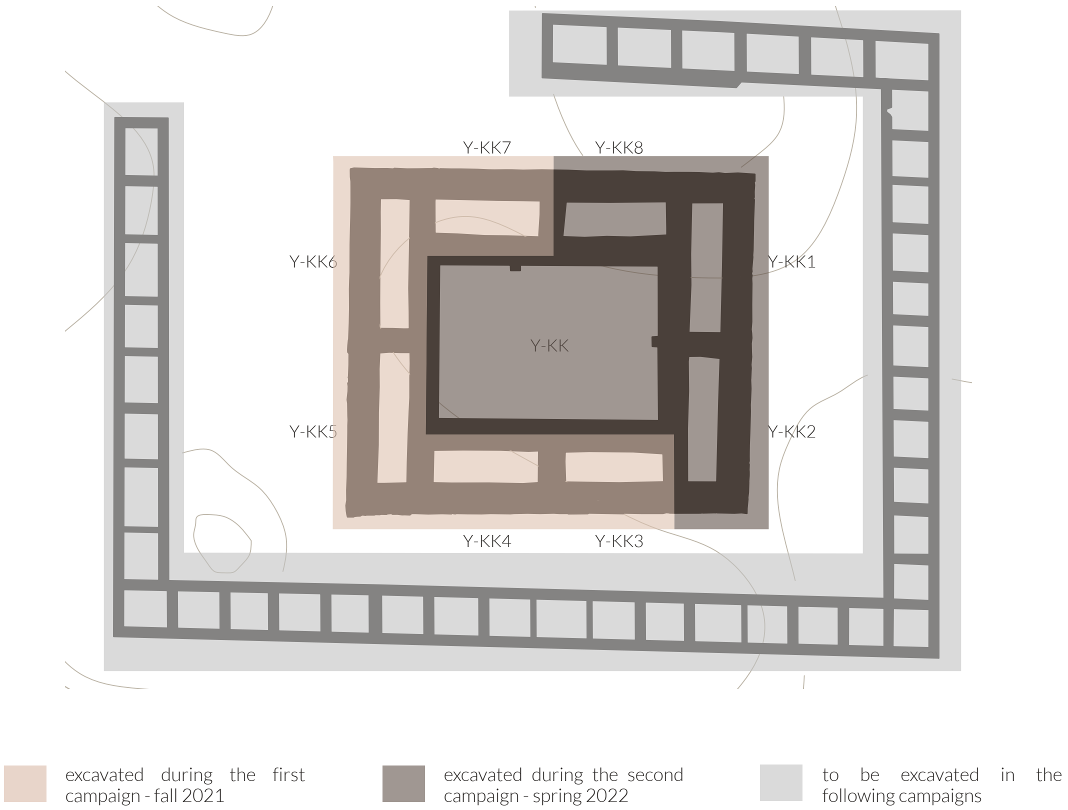

Fig. 38. Excavation process of the tomb of Meret Neith

5.3 the tomb of Meret-Neith

The tomb divides into two separate structures: a square central chamber with eight side chambers around it and 41 smaller subsidiary compartments built in a row separated from the main structure. The main structure measures 18 x 14 m, placed entirely underground. All the walls are bound by mortar and plastered with mud (Köhler at al., 2022). The side chambers surrounding the central chamber run parallel to it and probably served as magazines storing the funerary equipment (Köhler at al., 2022).
During the excavation emerged, that the tomb was probably built over a long period; "it appears as if the exterior and the interior wall, which are up to 1.30 m thick, were in part built roughly at the same time, that most of the partition walls between the side chambers were built thereafter and that the roof was initially planned to be at a lower level than how it was finally completed" (Köhler at al., 2022). The chambers were filled with funerary goods; they were covered with wooden beams, matting, and layers of mudbricks placed on the lower level of a ledge inside the walls (Köhler at al., 2022). A sand tumulus then probably covered the tomb's primary structure and the wooden roof (Köhler at al., 2022). An intense secondary fire burnt many of the royal cemetery's tombs, affecting Meret-Neith's, the walls, and the content of the chambers, and turning the sandy ground into a burnt, hard, hard, and partially molten mass (Köhler at al., 2022). One of the archaeologists' research questions is determining when the fire occurred.
Traces of fire are visible on the walls. A small piece of burnt wood on the floor suggests the presence of wooden pavement. Against the walls stand what remains of four brick pilasters; Petrie states in his report (1900) that the pillars were probably an addition to the first structure since they stand on loose sand and lean against the plastering. They might have been built as an additional load for the roof: the burning signs on the walls shows that they were still there as the fire spread all over the tomb. The depth of the side chambers varies between 2,00 m and 2,60 m. Some palm-leaf matting imprints on the corner of chamber two and the irregular heap of bricks on the wall crown show the sealing of the tomb. The side chambers measure ca. 1,20 x 4,00 m and 5,50 x 2,00 m; many still contained original ceramic jars, and chamber two revealed the magnificent view of sealed jugs.
The main structure of the tomb is very well preserved, although the walls and floor show signs of burning and numerous plunderings. A massive gap, probably the work of some grave robbers, connects magazine

Fig. 39. Excavation works, first campaign

Fig. 40. Excavation works, sifting process

Fig. 41. Excavation work in chamber two, second campaign

two to the burial chamber. Many other holes are scattered all over the walls and floor. The damaged, thick plaster layer reveals the mudbricks' clear structure.

During the two campaigns in autumn 2021 and spring 2022, the archeologists could empty the burial chamber and the eight magazines. The separated graves are going to be inspected in the following campaigns.

The side chambers are enumerated from one to eight, starting from the North-East corner and following a clockwise direction. The letter Y, which stands for the tomb of Mereth Neith, and KK for "Königskammer", german for kings-chamber, precedes the chamber's number.

Fig. 42. Excavation works, second campaign

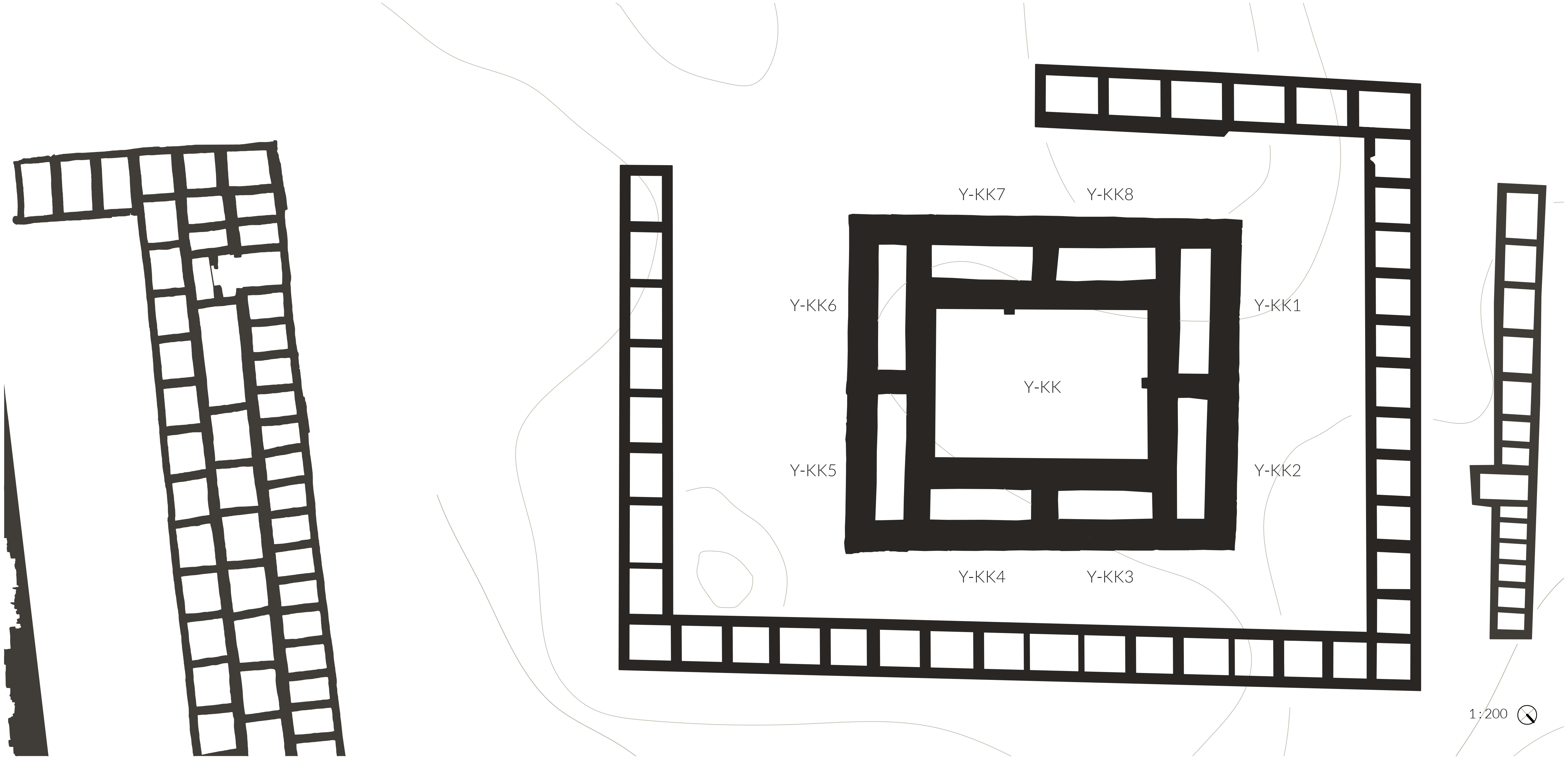

Fig. 43. Tomb of Meret-Neith, main structure and sidechambers, plan, 1:200

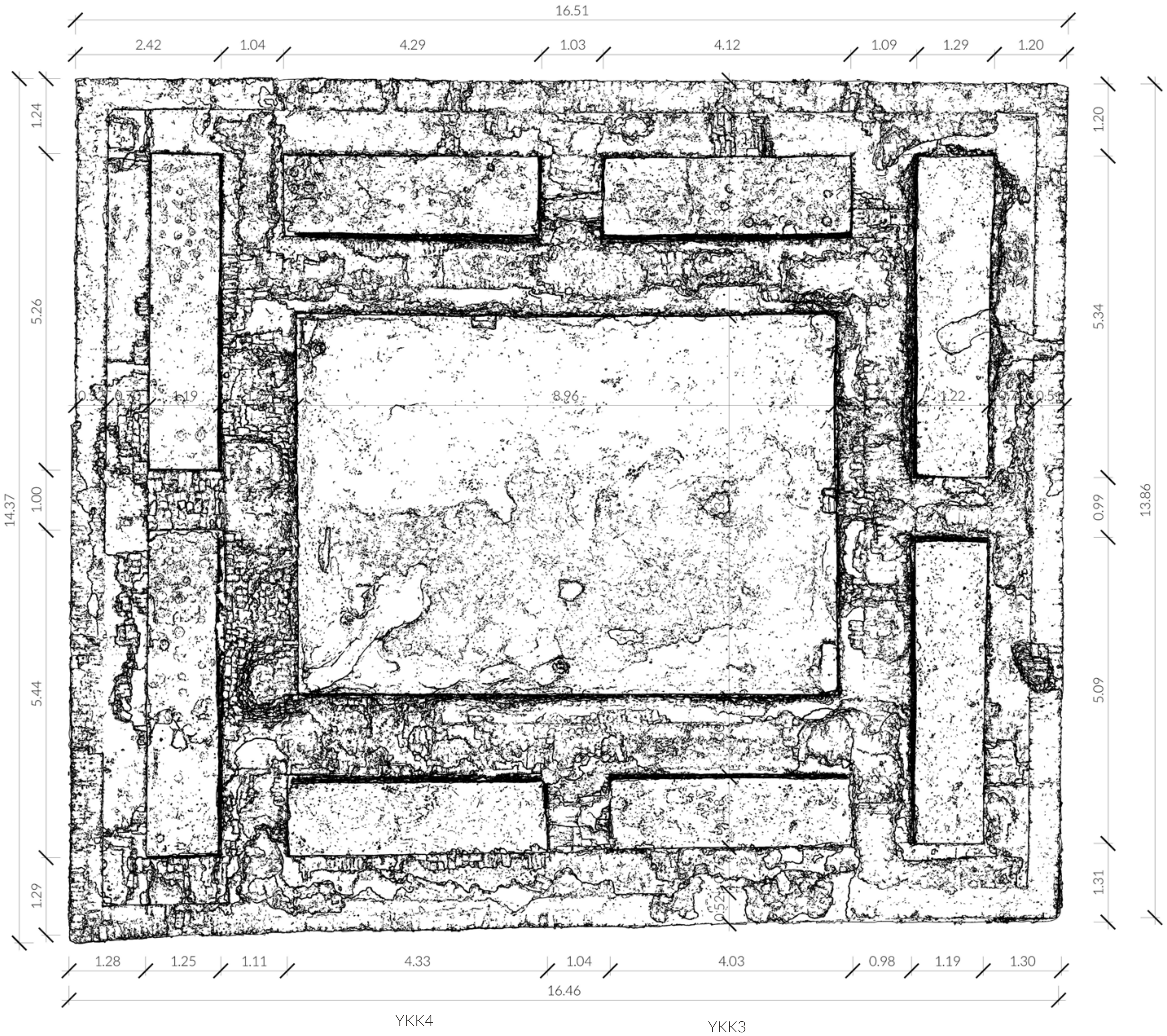

Fig. 44. Plan of the whole tomb

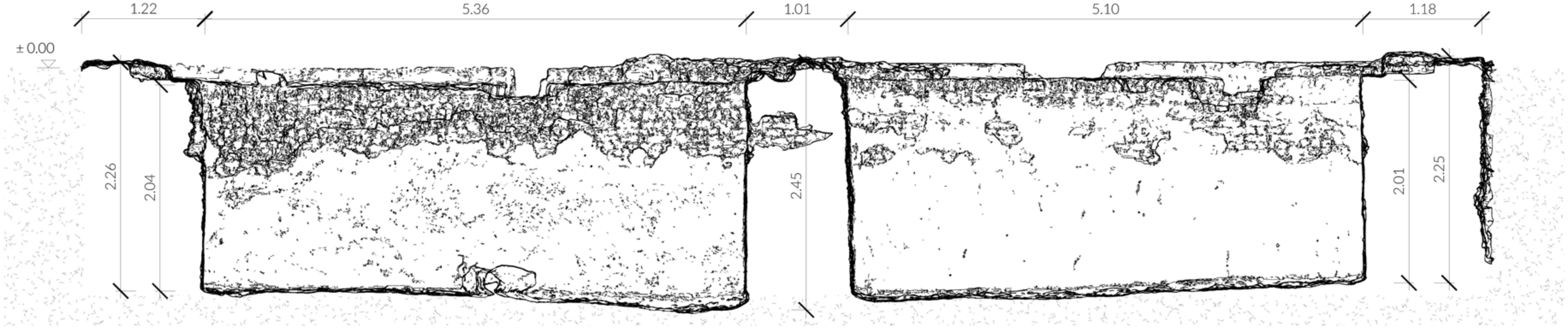

Fig. 45. Section through YKK1 - YKK2, east walls, 1: 50

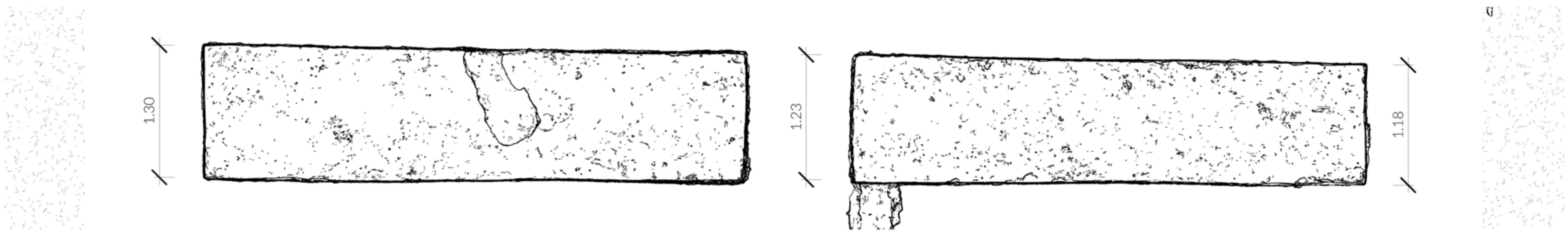

Fig. 46. Floor plan YKK1 - YKK2, 1: 50

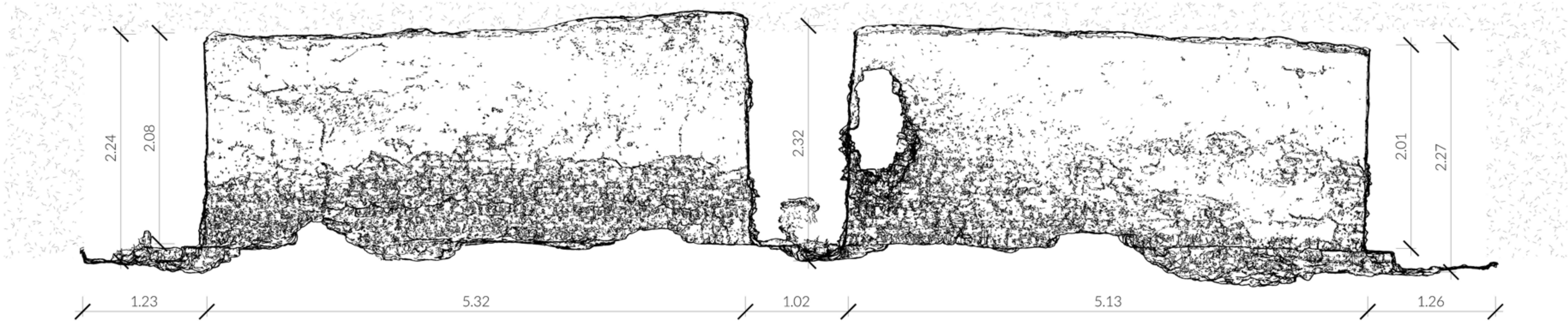

Fig. 47. Section throug YKK1 - YKK2, west walls, 1: 50

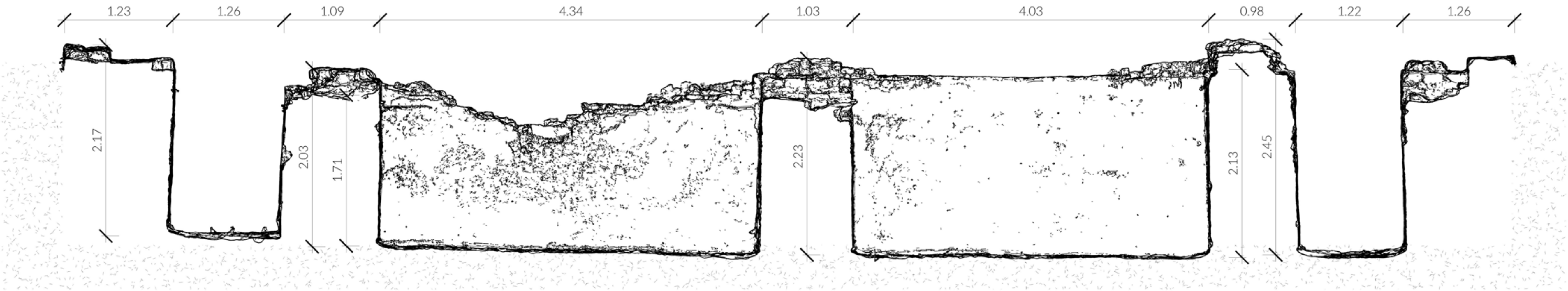

Fig. 48. Section through YKK5 - YKK4 - YKK3 - YKK2, south walls, 1 : 50

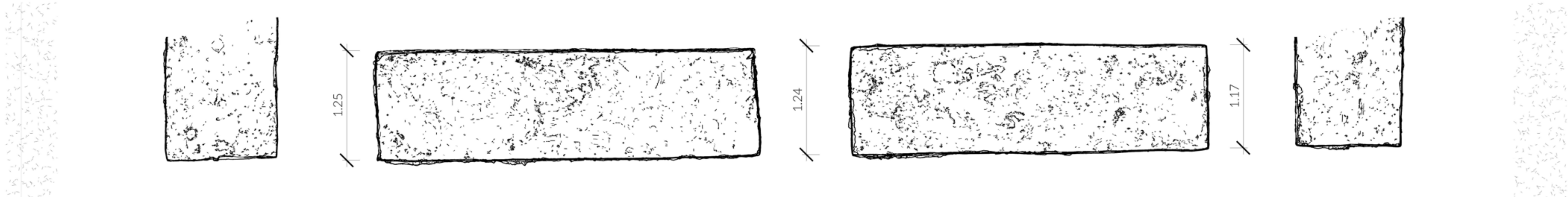

Fig. 49. Floor Plan of YKK5 - YKK4 - YKK3 - YKK2, 1: 50

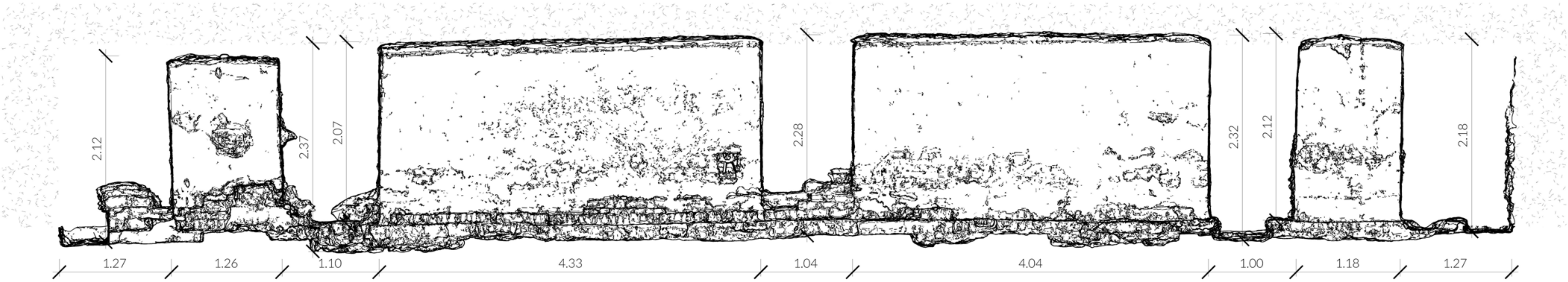

Fig. 50. Section through YKK5 - YKK4 - YKK3 - YKK2, north walls, 1 : 50

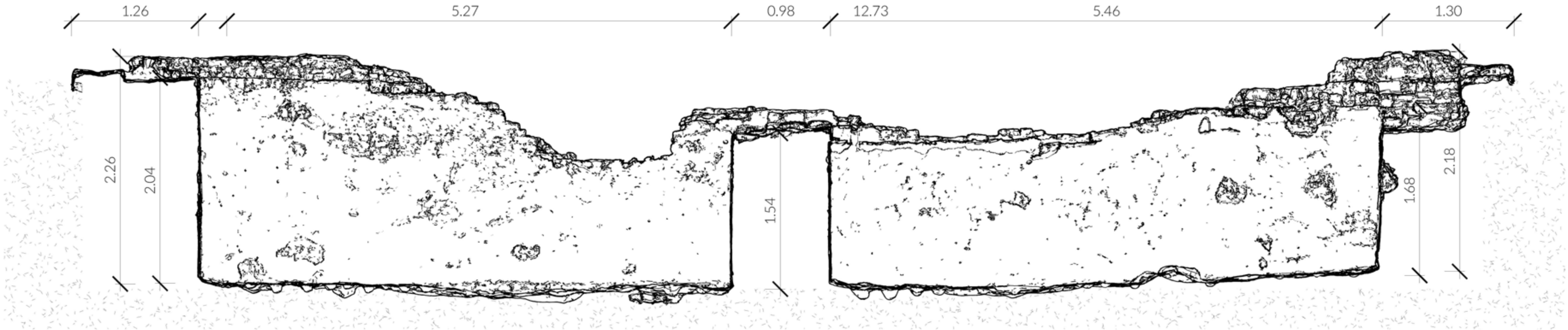

Fig. 51. Section through YKK6 - YKK5, east walls, 1:50

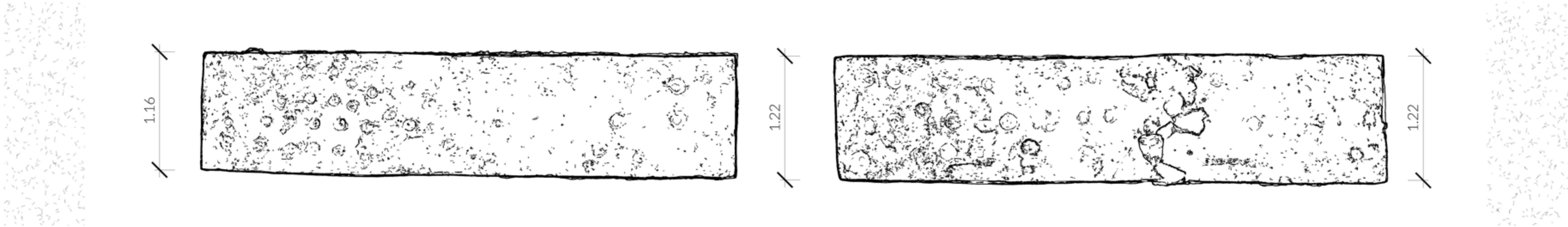

Fig. 52. Floor plan YKK6 - YKK5, 1:50

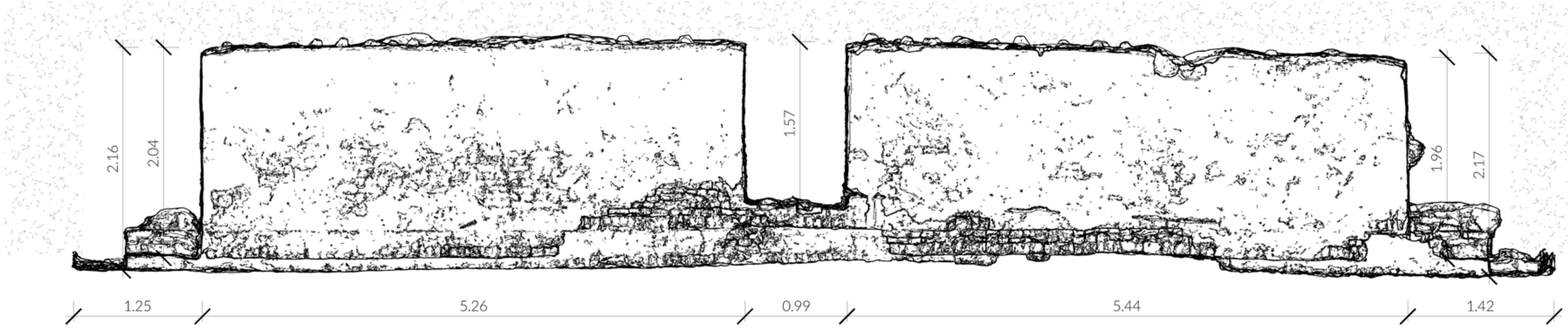

Fig. 53. Section through YKK6 - YKK5, 1:50

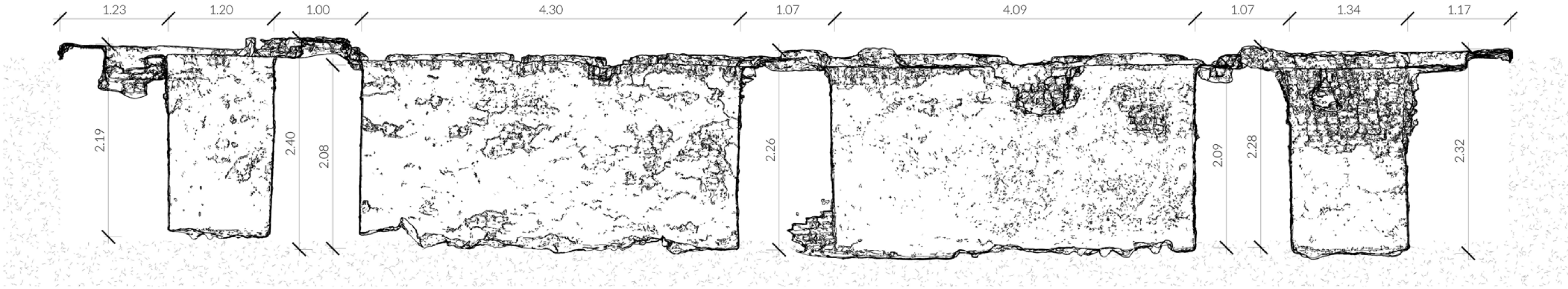

Fig. 54. Section through YKK6 - YKK7 - YKK8 - YKK1, south walls, 1:50

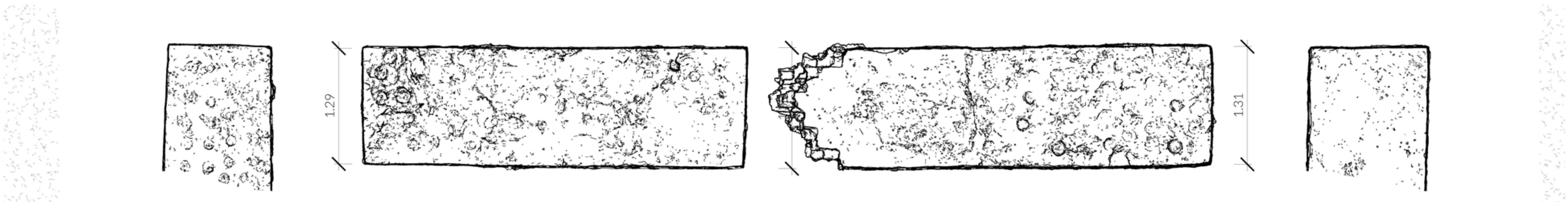

Fig. 55. Floor plan YKK6 - YKK7 - YKK8 - YKK1, 1:50

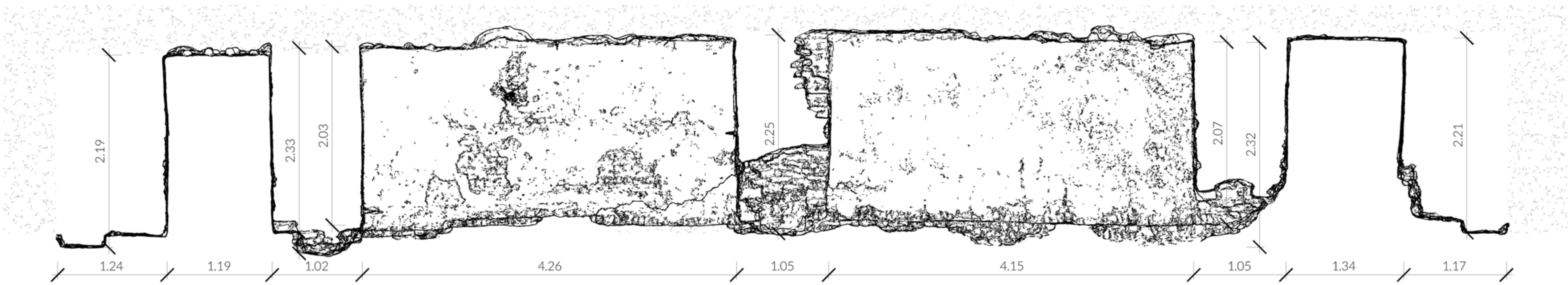

Fig. 56. Section through YKK6 - YKK7 - YKK8 - YKK1, north walls, 1:50

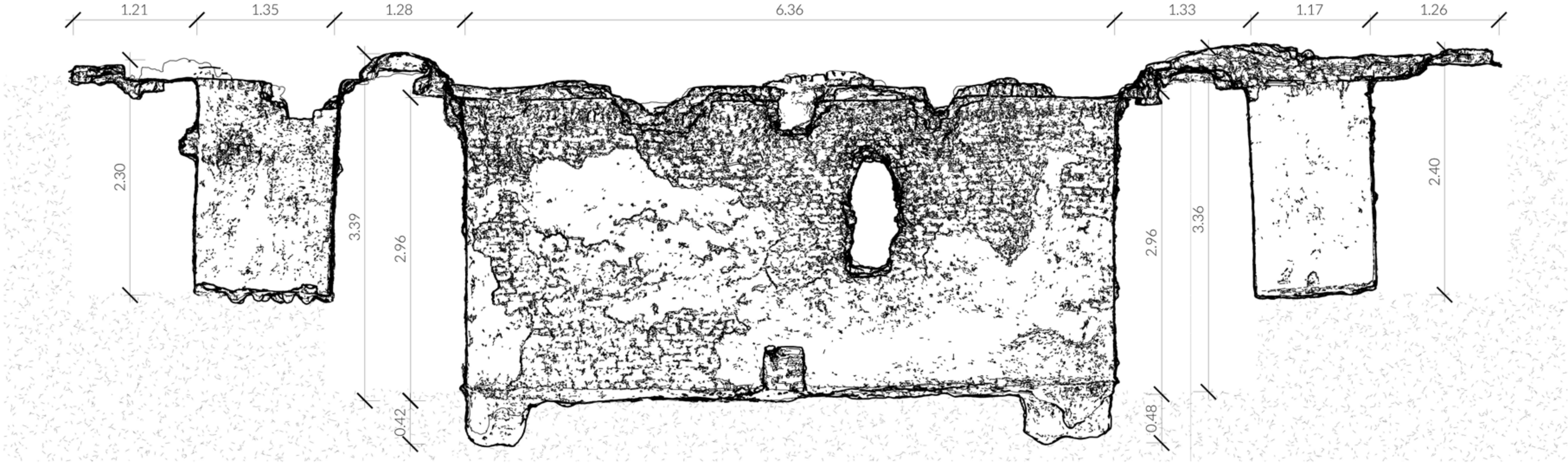

Fig. 57. Section through YKK8 - YKK - YKK3, east walls, 1:50

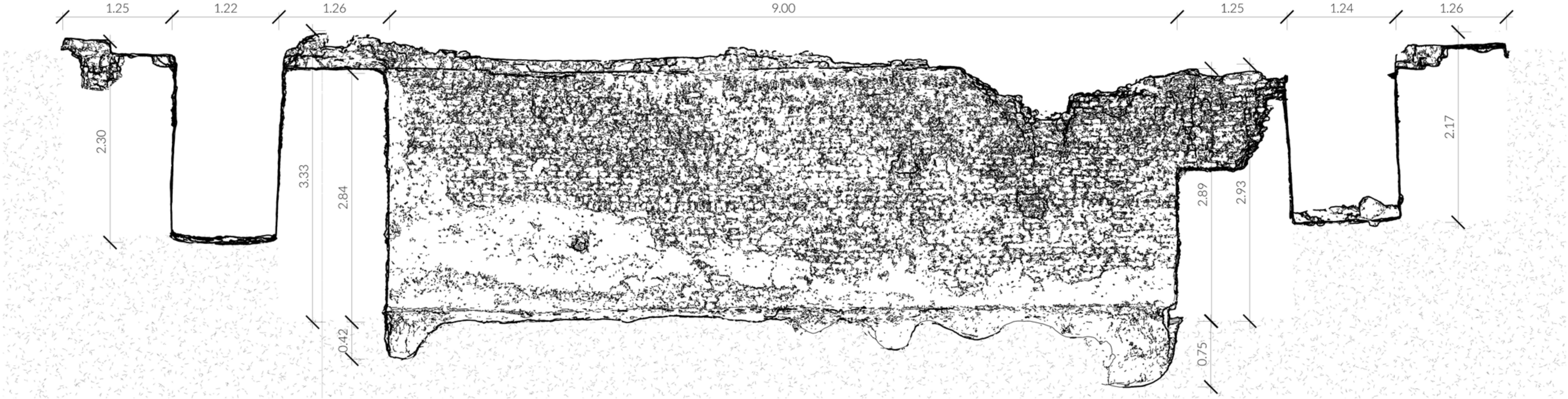

Fig. 58. Section through YKK2 - YKK - YKK5, north wall, 1:50

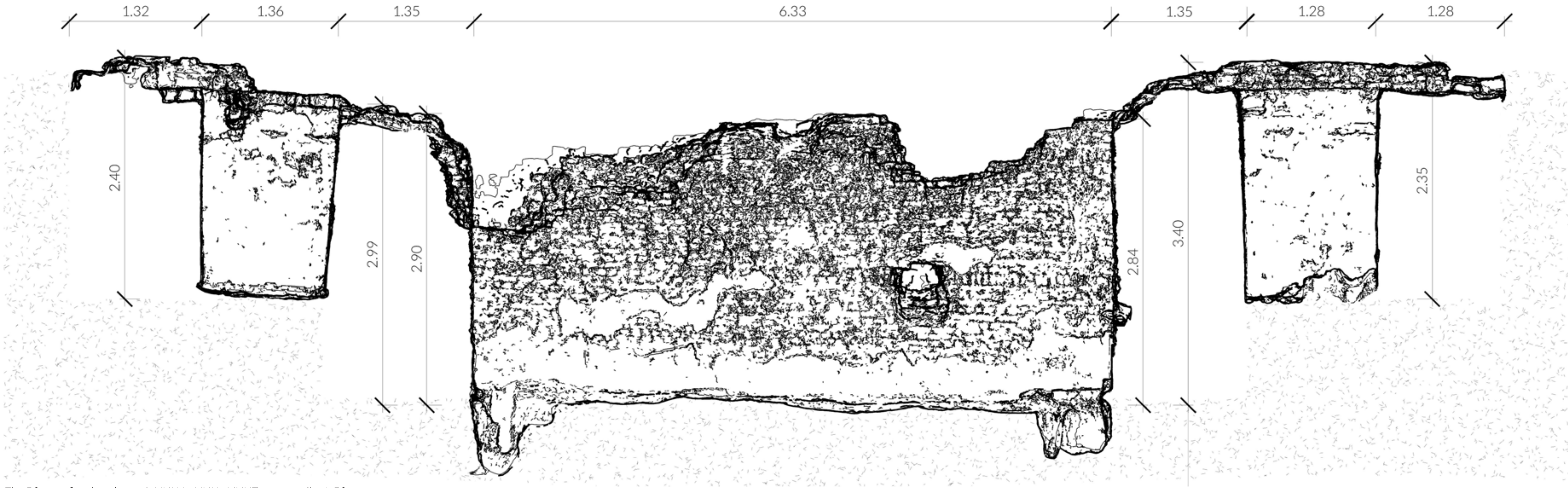

Fig. 59. Section through YKK4 - YKK - YKK7, west walls, 1:50

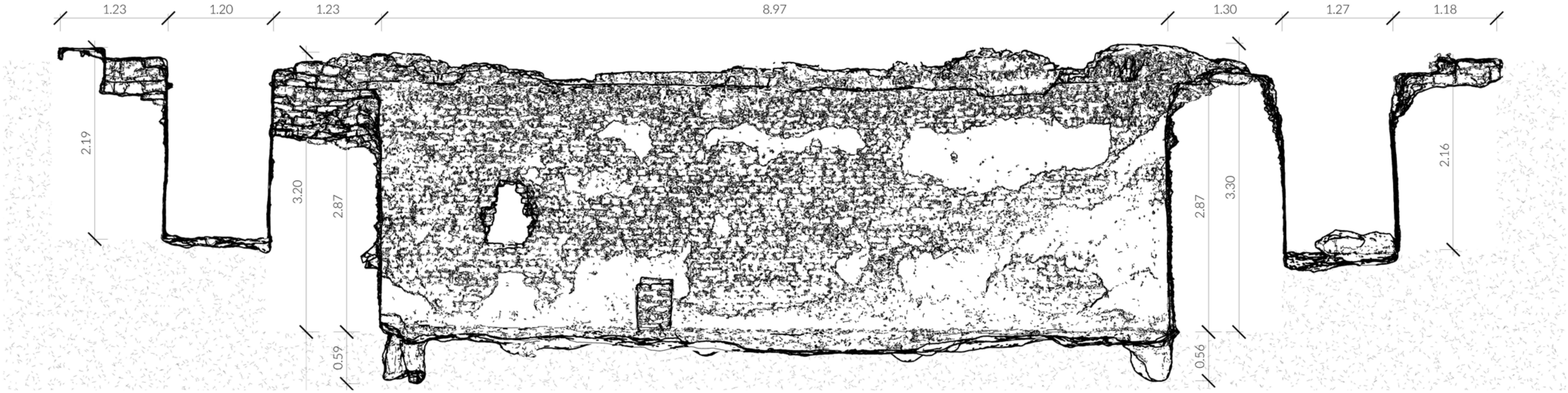

Fig. 60. Section through YKK6 - YKK - YKK1, south wall, 1:50

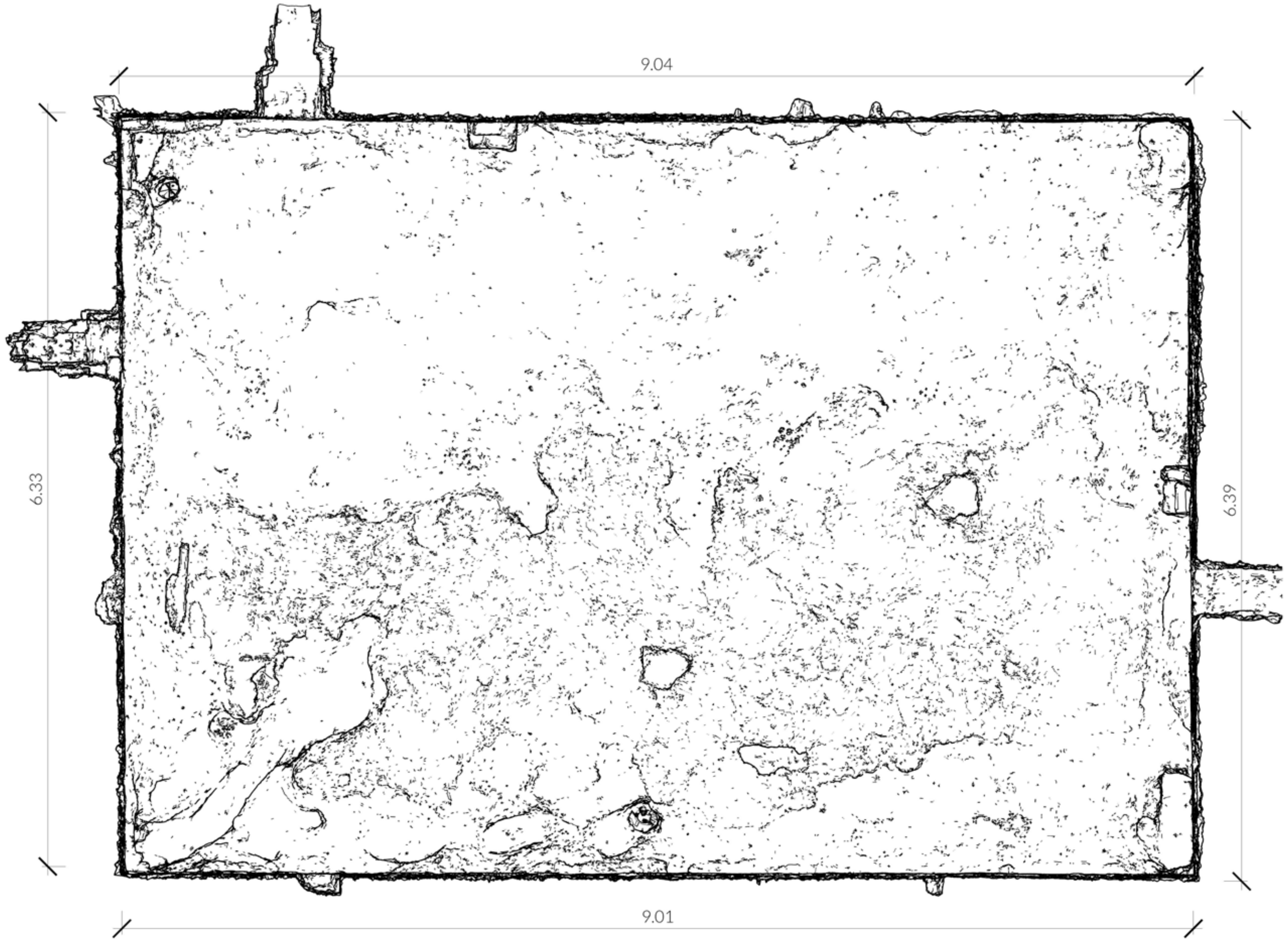

Fig. 61. Floor plan, main chamber

Fig. 62. In the previous page: the tomb of Meret-Neith, north-east corner

5.4.2 description of the architecture

5.4.2.1 chamber one

The first chamber measures 5,39 x 1,38 m and has a depth of 2,15 m. The plaster on the wall is well preserved in its lower part, while it completely came off in the upper part. Holes were dug in the north and south walls. The plaster is brown-grey, with a dark brown bottom displaying light white stains mainly on the east and south walls. The muddy floor was partially preserved. A massive white stone was found at the bottom; since it was too heavy to move, it was left there. The crown displays again a precise-built base topped by a chaotic layer of mudbricks, indicating maybe the sealing of a secondary structure. This chamber does not show any sign of burning; in any case, the fire did not seem to have reached the bottom. The partition wall between chamber one and camber two was probably built later than the main walls because it stands on a layer of fill slightly higher than the north and south walls (Köhler et al., 2022).

Fig. 63. Starting from top left: north wall, west wall, south wall, east wall, floor, orthoprojections, realized by F. Sövegjarto

5.4.2.2 chamber two

The second chamber measures 5,13 x 1,20 m, and its depth is 2,10 m. After removing the first layer of sand, a dozen beautiful, still sealed pottery jars were found standing in the sand, offering a magnificent picture. Once removed, the floor showed itself as a sandy surface. The brown-grey plaster on the wall is entirely damaged, displaying white stains all over the walls. The wall towards the main chamber, the west wall, presents a big hole, probably dug up by thieves trying to sneak into the burial chamber to steal precious objects and materials; in fact, a man can easily fit into it. This magazine likely served as the principal connection to the main room. The crown shows the messy layer above the primary structure again. Various holes were found, especially on the east wall. While the walls appear gray, the crown is red; the fire probably burnt the superstructure or the wooden roof, unable to reach the bottom.

Fig. 64. Starting from top left: south wall, east wall, north wall, west wall, midway floor, floor, orthoprojections realized by F. Sövegjarto

Fig. 65. Rendering of the reconstructed chamber two

5.4.2.3 chamber three

Chamber three measures 4.03 x 1,28 m, with a depth of 2,02 m. The plaster is well preserved, preserving its brown-grey color. As an indication of the burning, black stains are visible on the west wall's upper part. The mudbricks appear under the plasters' cracks. The upper part of the east wall is damaged. A small part of the muddy floor chamber's west side is preserved; otherwise, the bottom appears as a sandy surface. The messy layer of mudbricks lies on top of the primary structure. This chamber does not present particular signs of burning. A cursive hieroglyphic inscription was noted on the north wall picturing three signs: a stone, a cobra snake, and a horned viper snake (Köhler et al., 2022). Burnt timber was discovered under the mudbricks of the roof construction located on top of the roof ledge (Köhler et al., 2022).

Fig. 66. Staring from top left west wall, south wall, east wall, south wall, floor, orthoprojections, realized by F. Sövegjarto

5.4.2.4 chamber four

Chamber four measures 4,31 x 1,38 x 1,96 m. The plaster is particularly damaged on the wall towards the main chamber and well preserved on the other walls. Its color is brown-grey, like the other chambers. There are, however, red stains surrounded by a black outline on the western wall. The walls present, in this case, only limited evidence of burning at the top (Köhler et al., 2022). This wall is quite damaged, hollowing towards the main chamber. The mudbricks are exposed and particularly brittle in this area. The floor appears as a sandy surface. This chamber's messy layer of mudbricks, part of the roof construction, is well preserved on top of the crown. The crown is, as said above, very damaged on the south wall.

Fig. 67. Starting from top left: east wall, north wall, west wall, south wall, floor, orthoprojections realized by F. Sövegjarto

5.4.2.5 chamber five

Chamber five measures 5,35 x 1,24 m and has a depth of 1,89 m. The cracked plaster on the walls presents colors from red to dark orange and becomes black close to the base as a sign of the burning. Some white stains, or drawings, are visible on the two longitudinal walls. The mudbricks appear under damaged plaster. Holes were dug into the north and west walls. The floor occurs as a solid black layer, presenting small circular holes, indicating that many pottery jars were standing there as the tomb took fire. The north side of the crown is particularly damaged, showing two big holes. The messy layer of mudbricks topping the crown is mainly visible on the east side. The crown also presents a red-orange color with black stains on the east wall, evidence of the fire's burning. This chamber, together with chamber seven, shows significant signs of a tremendous burning.

Fig. 68. Starting from top left: north wall, west wall, south wall, east wall, midway floor, floor, orthoprojections realized by F. Sövegjarto

5.4.2.6 chamber six

Chamber six measures 5,30 x 1,21 x 2,00 m. The plaster in this room is particularly damaged, showing the structure of the mudbricks underneath. White stains are visible on the four walls. This chamber was clearly also part of the burning since the fire evidently altered the colors of the plaster from brown-grey to red-orange. The lower part of the walls and the floor are black. On its solid, hard surface, the floor shows imprints of the pottery jars standing there as the fire took place. The crown shows a red-orange color with some black stains and is significantly damaged; holes were dug into the south and north crown's parts, while the upper part of the wall towards the main chamber was almost completely destroyed. The messy layer of mudbricks lies on top of the wall towards chamber seven; it was otherwise either destroyed or removed.

Fig. 69. Starting from top left: south wall, west wall, north wall, east wall, floor, orthoprojections

5.4.2.7 chamber seven

Chamber seven measures 4.33 x 1,45 m, and its depth is 2,11 m. It is noticeable that this room burnt down, as the floor and the lower part of the walls are black. Imprints of the pottery vessels are dug into the hard floor, creating a messy, uneven structure. However, it is possible to picture the position of the jars while the fire spread by the marks left. The plaster presents colors ranging from red to light brown, revealing the mudbrick's structure underneath the numerous cracks. The wall crown shows a precise constructed base structure topped by an additional layer of chaotic mudbricks. A large hole on the east wall connects chamber seven to chamber eight; it was probably the work of grave robbers trying to get to the nearer chamber. Also the crown shows a red color compared, for example, to chamber eight, accentuating the happening of the fire.

Fig. 70. Starting from top left: west wall, south wall, east wall, north wall, midway floor, floor, orthoprojections realized by F. Sövegjarto

5.4.2.8 chamber eight

Chamber eight measures 4,15 x 1,39 m, with a depth of 2,13 m, which makes it the deepest among the magazines. Three of the four walls are well preserved. The wall towards chamber seven was almost destroyed. The removed bricks had been then piled up to a low fence in the middle of the room. The structure of this wall had to be improved with additional mudbricks to avoid collapse. Also in this room, the thick layer of the floor showed signs of standing pots. A dark yellow liquid emerged, melting from the heat, and was probably oil. Since the fire did not burn this chamber, the plaster is well conserved and presents a brown-grey color showing various white stains that resemble drawings. The crown displays again a precise-built base topped by a chaotic layer of mudbricks. Holes were dug in the south, west, and east parts of the crown. The southern wall was severely damaged, allowing for insights into the wall construction, indicating two construction phases (Köhler et al., 2022). "In the first phase, the main exterior and interior walls of the tomb were built with wall pilasters forming the south-east and south-west corners of the chamber. In the second phase, the gap between them was closed to form the partition wall between this chamber and the neighbouring Y-KK7" (Köhler et al., 2022)

Fig. 71. Starting from top left: east wall, north wall, west wall, south wall, midway floor, floor, orthoprojections realized by F. Sövegjarto

5.4.2.9 main chamber

The burial chamber measures 9,05 x 6,42 m and is almost 1 m deeper than its side chamber, having 2,76 m depth. The walls and floor are very damaged and burned from the fire. The plaster on the walls is very damaged and came off almost entirely. The walls are red with large black stains toward the lower part, indicating the occurrence of the fire.

A large piece of timber was found near the south wall, which may indicate the presence of a wooden floor. The colors of the wall suggest the presence of vertically rising timber forming a wooden compartment or shine, as observed in the other tombs (Köhler et al., 2022). The remains of some pilasters lean against the walls on top of the plaster. The burning marks suggest the presence of six smaller pilasters and four larger ones in the corners, probably encasing wooden posts standing in posts holes (Köhler et al., 2022). "As Petrie noted, these structures are later additions to the original design of the tomb" (Köhler et al., 2022).

Fig. 72. YKK8, main chamber, YKK3, east wall, orthprojection

Fig. 73. YKK6, main chamber, YKK1, south wall, orthoprojection

Fig. 74. YKK4, main chamber, YKK7, west wall, orthoprojection

Fig. 75. YKK2, main chamber, YKK5, north wall, orthoprojection

Fig. 76. Floor plan of the whole tomb

Fig. 77. YKK6 - YKK7 - YKK8 - YKK1, south walls

Fig. 78. YKK1 - YKK8 - YKK7 - YKK6, north walls

Fig. 79. YKK5 - YKK4 - YKK3 - YKK2, south walls

Fig. 80. YKK2 - YKK3 - YKK4 - YKK5, north walls

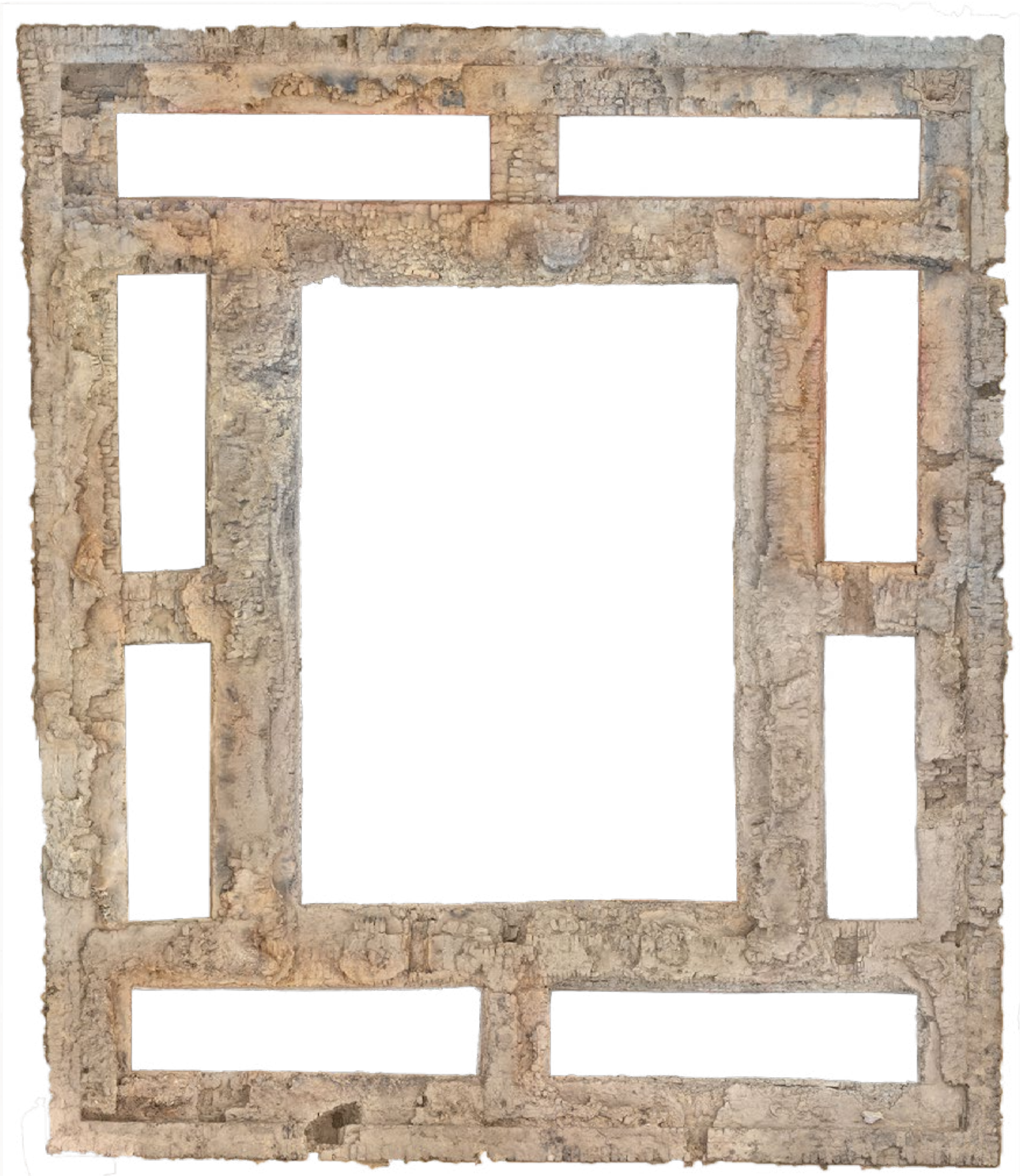

Fig. 81. walls crown, plan

Fig. 82. YKK6 - YKK5, west walls

Fig. 83. YKK5 - YKK6, east walls

Fig. 84. YKK2 - YKK1, west walls

Fig. 85. YKK1 - YKK2, east walls

5.5 fire hypotheses

The fire's origin, cause, and exact time the tomb took fire are still unknown. Three of the hypothesis providing a context to the tragic event are depicted below.

5.5.1 the tomb robbers hypothesis

The first one assumes that the fire was the work of some grave robbers; robbing was, in some cases, even adopted as a profession. The thieves would wait for the night to break into the tomb, looking for gold or other worthy materials to steal. The confession of Amenpanufer, living at Deir el-Medina around 1110 BC, illustrates his activity (Mark, 2017):

"We went to rob the tombs as is our usual habit and we found the pyramid tomb of King Sobekemsaf, this tomb being unlike the pyramids and tombs of the nobles which we usually rob. We took our copper tools and forced a way into the pyramid of this king through its innermost part. We located the underground chambers and, taking lighted candles in our hands, went down. We found the god lying at the back of his burial place. And we found the burial place of Queen Nubkhaas, his consort, beside him, it being protected and guarded by plaster and covered with rubble.We opened their sarcophagi and their coffins, and found the noble mummy of the king equipped with a sword. There were a large number of amulets and jewels of gold on his neck and he wore a headpiece of gold. The noble mummy of the king was completely covered in gold and his coffins were decorated with gold and with silver inside and out and inlaid with precious stones. We collected the gold that we found on the mummy of the god including the amulets and jewels which were on his neck. We set fire to their coffins. [...]" (Lewis, 2003, as cited in Mark, 2017).

By setting the coffin on fire, they probably hoped the separate the worthless materials, such as wood, from the valuable ones. Although the stolen items could not be directly sold because they were supposed to be reported immediately, they could be melted into other objects and traded (Mark, 2017). The threats of punishment and hauntings in the afterlife were not enough to stop a thief force his way into a rich tomb. In fact, according to Mark (2017), "Ancient Egyptians robbed the tombs of the wealthy for many of the same reasons people rob others in the present day: excitement, money, and a kind of empowerment in taking what one does not own." The royal cemetery of Umm el Qa'ab undoubtedly shows signs of numerous plunderings throughout the years.

5.5.2 the shelter hypothesis

The second hypothesis involves the tombs suiting as a shelter for vagabonds and homeless people. Petrie (1900) assumes "Runaway slaves and vagabonds taking refuge here would light fires and use the wood, and thus by accident the great beams would catch fire and be destroyed". Undoubtedly, the cemetery lost importance as time went by. It is plausible for it to become a gathering place for lost people. This hypothesis implicates the spreading of fire as an accident.

5.5.3 the Osiris festival hypothesis

The third hypothesis assumes an incident at one of the annual festivals celebrating the god Osiris. As explained in the previous chapter, the tomb of the First Dynasty king Djer was later identified as the one of Osiris.

During the Middle Kingdom, in his honor, was performed an impressive festival that attracted national engagement "it seems likely that Egyptians came from all over Egypt to witness and participate in it" (O'Connor 2009).

The course of the ceremony was carefully explained by M-Christine Lavier in Les fêtes d'Osiris à Abydos au Moyen Empire et au Nouvel Empire, in 1998 (Lavier, 2004).

The procession was meticulously prepared; it probably started from outside the temple, where the god statue was in a sacred boat, "Carried in the Neshmet-barque, the god was cheered and adored by the crowd of faithful". The figure appropriating the functions of Osiris' son, a figure called Wepwawet, proceeded the procession and was probably impersonated by the king in person. The rituals continued in the crossing of water, symbolizing the ride to another world and brought to his tomb.

The third and last part consisted of the funeral, as an intimate ceremony, where only the high-rank officiant could participate. It followed a resurrection ritual officiated at night, during which the spirit of Osiris, considered alive, went to dwelling a newly shaped statue and was brought back to the temple on board the Neshmet-barque.

The third hypothesis regarding the burning of the tomb assumes the accidental drop of a lighting source during this ceremony, setting fire to one of the tombs, which quickly spread all over the cemetery due to strong wind.

Visualizing the three hypotheses aims to examine the events spatially and visually, creating a base point for starting a discussion to understand this historical event better.

5.6 reconstruction of the tomb

5.6.1 data aquisition

After testing some professional photogrammetry software on the market, our team chose to work with Reality Capture, developed by Capturing Reality and recently acquired by Epic games.

The data acquisition proceeded following the official suggestions of the software developer. Since the resulting model's quality relies on the photo's quality, it is necessary to shoot sharp pictures while maintaining the highest resolution possible. To achieve a deep depth of field, or in other words, to keep most of the image in focus is necessary to maintain a small aperture while shooting. Holding a high f-number increases the focal length but leads to a lower shutter speed since the camera needs more time to let the light enter or a higher ISO value. Otherwise, the picture will appear dark. Lowering the shutter speed leads to motion blur. Keeping a high ISO value, ISO, meant as the International Standard for measuring the film sensitivity to light, will give a bright but noisy image. Finding a balance

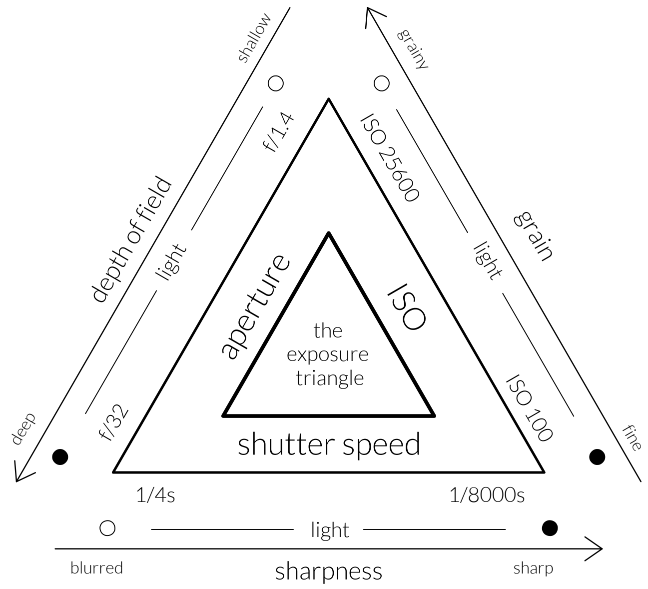

Fig. 86. Photo balancing triangle, based on How to make photos for Reality Capture, Capturing Reality

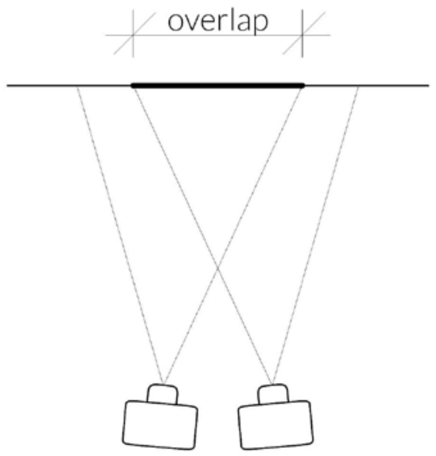

Fig. 87. Overlapping area of 60 - 80 % between images

between the ISO, the shutter speed, and the aperture is necessary to shoot the right pictures. The image's resolution should be kept at the highest possible by choosing file formats like RAW or DNG. Each point of the object should be visible in at least two images for Reality Capture to reconstruct it; more images will lead to a better result. Assuming that it is not always possible to reshoot missing parts but always the possibility to delete undesired pictures, Capturing Reality suggests shooting the highest possible amount of photos. The tomb of Meret-Neith was supposed to be emptied, analyzed, and refilled immediately after due to its fragility.

The shooting should proceed in full loops, following the object's shape and keeping the same distance to maintain the same level of detail. It is essential to maintain a high overlap, of 60 to 80%, between images and shoot from several elevations by not changing the viewport to more than 30°. Regarding architectural spaces, particularly square spaces, it is necessary to stand at one point at a given distance from the wall and shoot the opposite wall by moving slightly, following the room's shape, and avoiding panoramic pictures. A constant light situation is crucial since light and shadow changes will be baked into the texture. To control

the light was one of the most demanding challenges encountered during the shooting in Egypt; this topic will be covered in the next chapter.

Capturing Reality suggests avoiding featureless texture; this was not entirely the case in the tomb of Meret-Neith, but the warm colors of the mudbricks and the plaster blended with the color of the surrounding sand, and the messy form of the broken bricks created a rambling structure. It is possible to use markers to help the software recognize confusing features. For the tomb of Meret-Neith, numerous markers have been generated and exported from Reality Capture; this topic will be covered deeper in the following chapter. The strategy by which the tomb was taken is the following:

First markers were spread around it, full loops of overview shots of the entire structure were shot from different heights. Given that in Egypt, drones are not allowed, the tallest height reached was 5 m with the help of a tripod. Such loops are needed to help the alignment process and will not be used for meshing or texturing the model. It is essential to take pictures of most of the tomb at once and of the markers without paying attention to the light and shadow situation. For the tomb of Meret-Neith, four full loops have been shot, two at a distance of circa five and three meters with the tripod and two while standing and kneeling. The process continued by photographing the chambers one by one, applying the same principle of shooting some overview pictures whit markers first to help the software better understand the space and incrementally moving closer to the object to shoot more detailed pictures. Each chamber needed to be covered by a self-made sun shade while shooting to avoid sharp shadows from being baked into the

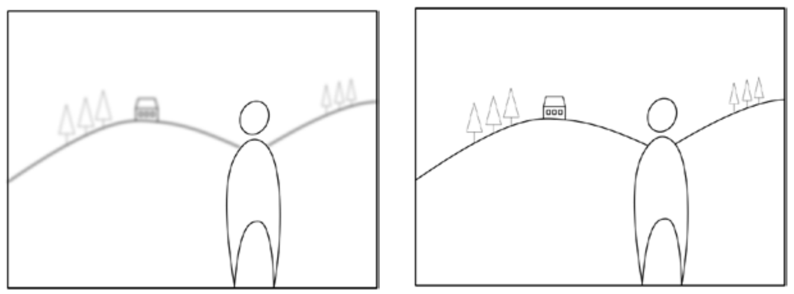

Fig. 88. Shallow and deep depth of field

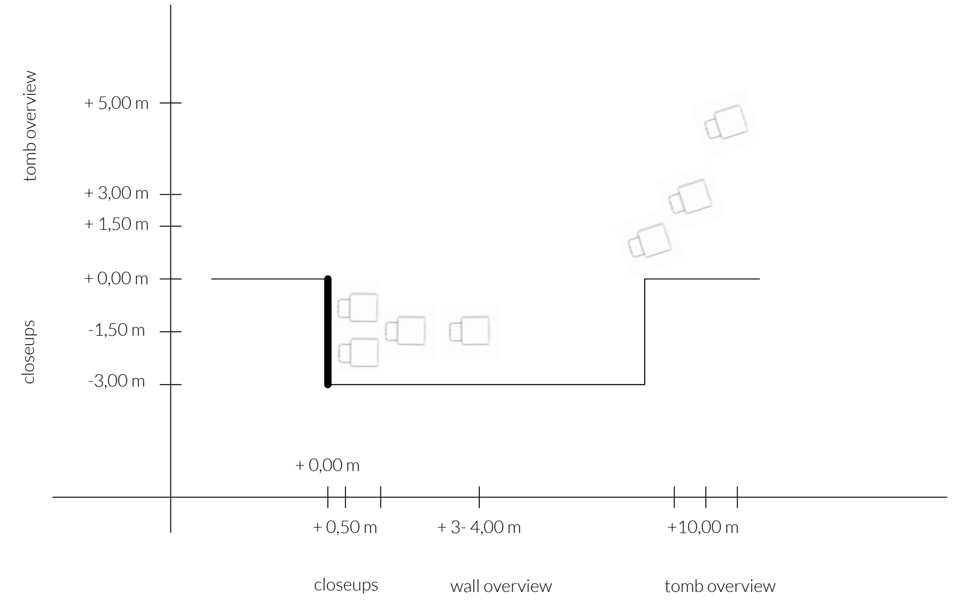

Fig. 89. Shooting strategy distances

texture. The picture loops were shot at a constant distance of ca. 50 centimeters while moving closer to capture complex parts. Every chamber was shot twice, once with markers, as said before, to help Reality Capture reconstruct the main structure and once without markers. The photos without makers and with the right light situation were used to mesh and texture the model.

A subsequent video shoot of the object proved to help the reconstruction greatly. It is, in fact, easier by filming to capture the modifications of the object's shape in a flow. The videos can be converted into frames directly into Reality Capture by setting the pictures to frame steps. To avoid blurred filming with a gimbal was demonstrated to be very effective.

Chamber three, four, five, six, and seven were shot during the first campaign and then filled with sand, while chambers one, two, eight, the main chamber, and the whole wall crown were shooted during the second campaign.

The photographing followed the excavation process; if relevant objects were found in situ, an additional mid-layer of the chamber had to be shot.

The shooting situation in Egypt proved to be very challenging. All photos were taken with an iPhone

13 Pro and an iPhone 12 Pro Max. Such devices were chosen over a camera because of their small size and the possibility of fast shooting. The autofocus feature proved to be both helpful and sometimes counterproductive. The light adaptivity proved to be the biggest problem in reproducing authentic colors; the topic of color reproduction will be covered in the following chapters. During the second campaign, the heat became a massive problem; the iPhones stopped working after one hour of intense photographing, automatically turning off. They had to be cooled down in order to resume the shooting.

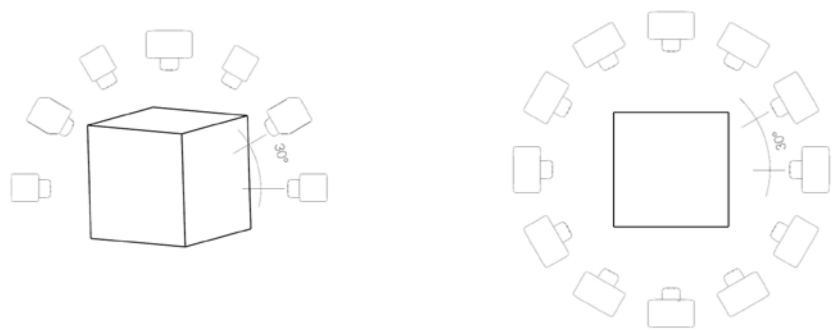

Fig. 90. Optimal shooting for photogrammetry, changing the viewport to max 30°, based on How to make photos for Reality Capture, Capturing Reality

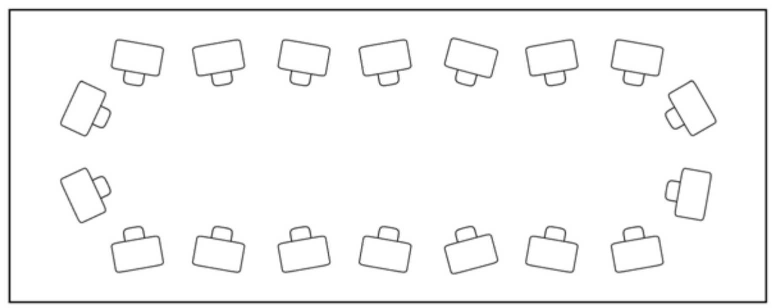

Fig. 91. Optimal shooting for a photogrammetric reconstruction of square architectural spaces, based on How to make photos for Reality Capture, Capturing Reality

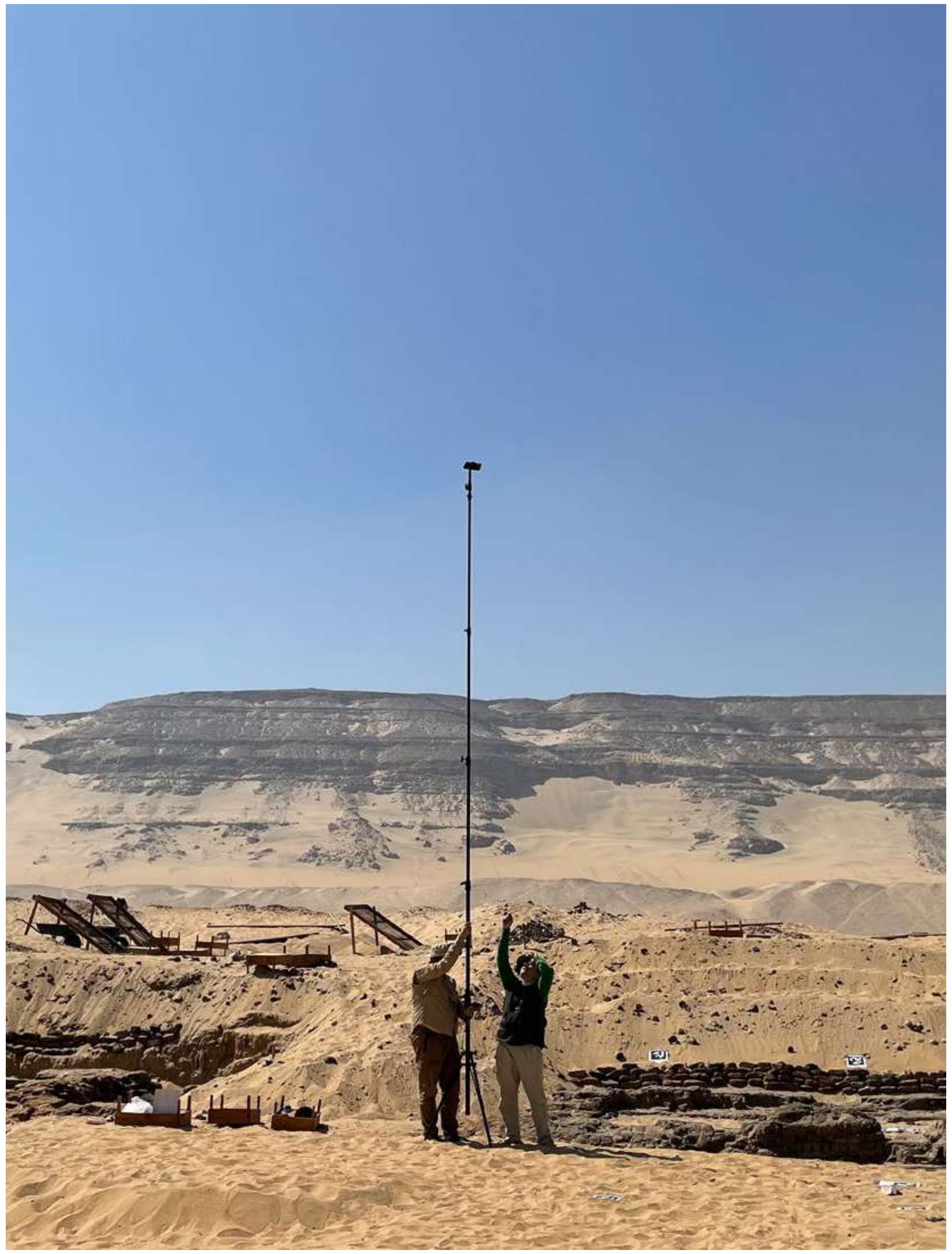

Fig. 92. Florian Sövegjarto and Balint Istvan Kovacs setting up the tripod

5.6.1.1 markers

The tomb's structure and texture were messy and confused due to the similar colors and brittleness of materials. Markers were used to help Reality Capture reconstruct the main structure and to scale the model to the actual dimensions. Different types of markers have been generated and exported directly from the software. During the alignment process, they will be automatically recognized by the software being recognized as features. For the first campaign, circular and square markers were printed on robust, opaque cardboard and glued to small wood panels in different dimensions. The chosen markers type were: Circular, single ring 12- bit, circular, dual ring 12- bit, Square, April Tag 25h7, and Square, April Tag 25h9. The square markers worked best under the bright sun and were easier to recognize by the software on photos shot from longer distances. Some dimension references for scaling the model were designed by putting markers on a steel pipe at a given distance; this was put as straight as possible on the sand surface with the help of a water wage. The markers should be positioned where they do not interfere with the reconstructing object, in places that can be easily cut off the mesh after reconstructing the model.
It is not necessary to have markers on every photo, but it is essential to shoot some context photos where more than one marker and, in the best case, at least three markers are visible. During the first campaign, the markers were spread around the area to shoot, removed, and used for the following zone. The result was different reconstructed chambers with the same markers, creating confusion while merging

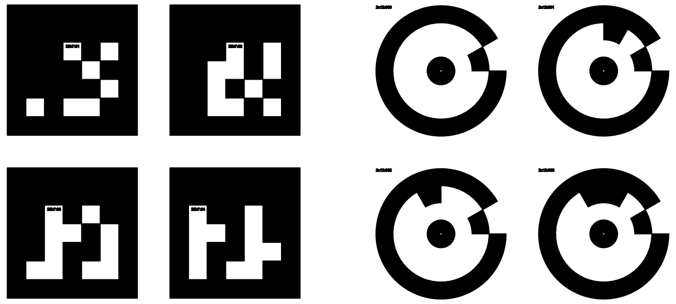

Fig. 93. Square markers: April Tag 25h7 and round markers: dual ring 12-bit

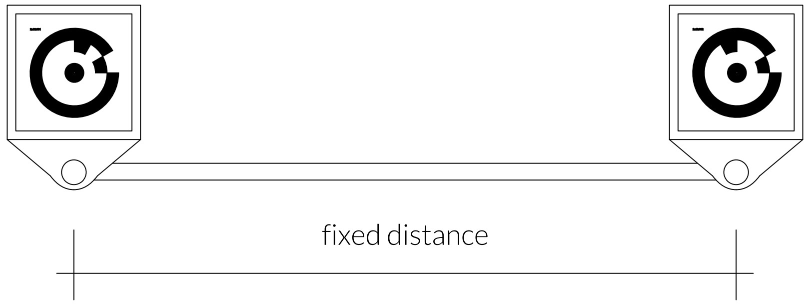

Fig. 94. Steel pipe with markers

different components. For this reason, during the second campaign was decided to keep a markers catalog, monitoring which markers were used where and eliminating them from later use. During the second campaign, stationary markers were put on the walls of the main chamber. These fixed points of reference and the process of eliminating the already used markers proved to be of excellent help during the reconstruction process.

Fig. 95. Steel pipe lying on the floor of chamber five

Fig. 96. In the next page: Florian Sövegjarto and Balint Istvan Kovacs measuring the distance between the fixed markers on the walls of the main chamber while the archaeologists and field worker excavated chamber eight

5.6.1.2 light and colors

The ideal weather for taking pictures for photogrammetry is a cloudy day, where the light is white and diffuse. Otherwise, the shadows would be printed into the texture, causing a falsification of the object's appearance. Waiting for a cloudy day in the Sahara desert is impossible.

The first solution taken into account was to use a delighting tool like Metashape from Agisoft and the Unity delighting tool. Both worked very well with the Austrian weather condition. However, none delivered satisfying results in Egypt, probably due to the extremely low contrasts of the surface and sand colors and to the stronger sunlight and sharper shadows.

A white textile was chosen to cover the area to shoot from the direct sunlight. During the first campaign, some synthetic textiles with different levels of translucency were brought from Austria to Egypt. None of them were found to work; they were either too thick or too thin, where the first caused a dark shooting scene, and the latter could not cover enough sunlight leaving visible shadows. What worked best was a white cotton textile with a light but not too thin fabric; a blanket. An ample sun shade was put together

Fig. 97. Color chercker X-Rite Passoport

Fig. 98. Four blankets put together to a sunshade in the first campaign

from four blankets reaching a span width and length of four meters. Such sun shade was stretched over the shooting area protecting the object from the intense sunlight and had to be moved synchronously with the shooter, anticipating him/her. The photographer had to pay attention not to take any bright areas in the picture.

For the second campaign, a sunshade made of white cotton textile, span width and length of six meters, was prepared in Austria and brought to the archaeological site.

The coordination and spanning of the sunshade presented its challenges: first, the wind blew strongly against it, making the stabilizing very difficult; second, the language barriers between our team and the Egyptian team made the coordination of the movements uneasy at first, but the cooperation turned out to work very well after a while.

The shade was stretched, closing the room for shooting the inside of the chambers. The main chamber was too big for the shade to cover it at once, so each wall was photographed during the daytime when it was entirely in self-shadow.

The Egyptian sunlight caused problems not only in the shadow situation but also in color reproduction. The

Fig. 99. Balint Istvan Kovacs setting the markers on the ground of chamber seven

light color changes extremely quickly. The color checker Passport Photo 2, from X-Rite, was photographed in defined periods and for every chamber or object shooted.

The photos used for the texturing were color-corrected through a white balance in Adobe Lightroom and then harmonized with the Color Correction tool direct in Reality Capture.

The iPhone was excellent for practical and fast shooting but bad for color correction. The live light adaptivity caused different color brightness during one single shooting, making the color correction via color checker valid just for a part of the pictures.

A solution regarding accurate color reproduction was not found yet.

Fig. 100. Florian Sövegjarto photographing the main chamber

Fig. 101. In the next page: Sara Treccarichi Scavuzzo (the author) shooting chamber five under the sunshade - firts campaign

Fig. 102. In two pages: Balint Istvan Kovacs shooting the crown between chamber five and the main chamber under the new sunshade - second campaign

5.6.2 data processing

At the end of the two campaigns, 35600 pictures were collected.

The pictures were sorted immediately after shooting and divided into four external Hard Disks (SSD). The considerable amount of data and the disheveled appearance of the texture of the tomb would have made subsequent organizing extremely difficult.

The pictures were sorted into context, with ca. 400 images, chambers, one by one, with ca. 1500 pictures each, and wall crowns, with ca. 2000 pictures.

The strategy followed to produce the model was incremental alignment. This strategy foresees the creation of a separate project for each dataset, starting with a rough point cloud of the entire tomb, aligning the context pictures, and following with each chamber one by one. After the images were loaded into Reality Capture, it followed the detection of the markers, which the software can automatically process.

The pictures were then aligned to form a dense point cloud and scaled by defining the distance between the markers. The result was eventually exported as an RC alignment component. The alignment time of

Fig. 103. Markers on the steel pipe automatically recognized from the software

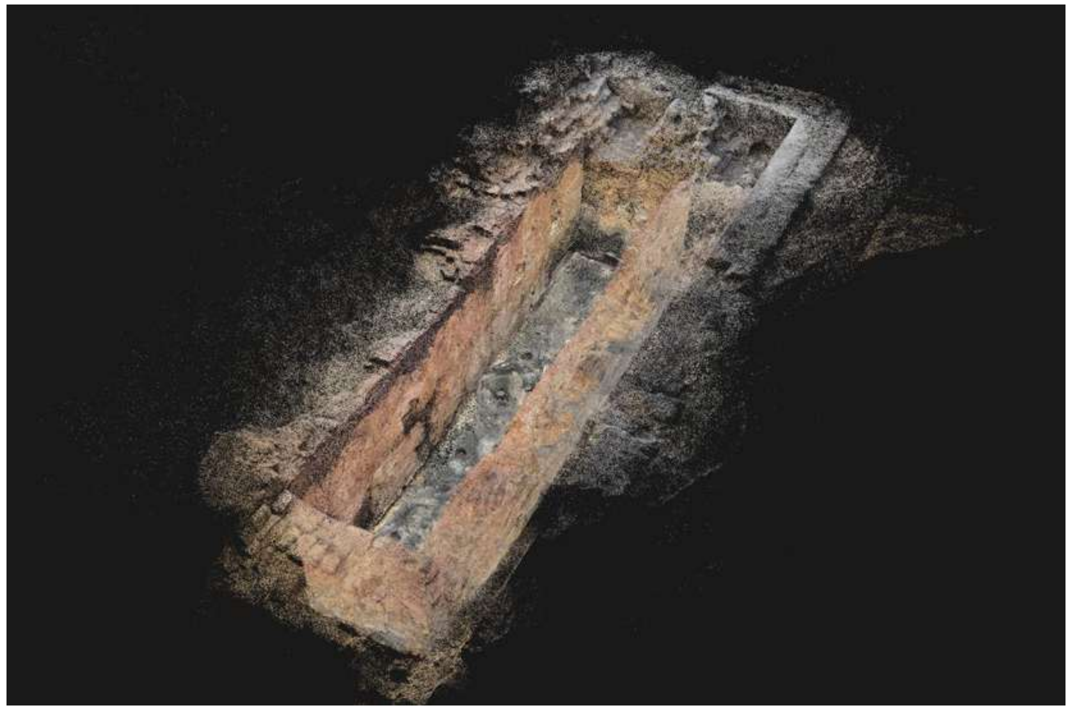

Fig. 104. Point cloud of chamber five

the different datasets varied from three to six hours. The point cloud was then inspected; manual control points were added in case of misalignment by setting numbered points on at least three pictures where the chosen feature was photographed from different angles. The alignment process needed to be repeated until a fine point cloud was reached.

All the components must then be imported into a new project and merged to create the whole model by adding manual control points to help the software recognize the spatial organization and the connections among the chambers.

As soon as the definitive point cloud is built, it is possible to start with creating the mesh. Depending on the number of pictures, this process took eight to fourteen hours, and the resulted 3D model presented a polycount of 285 Million triangle, which is extremely high for nowadays standards.

The meshed model was then unwrapped into UV maps. UV maps are the flat representation of the surface of a 3D model to project the textures onto it. Good examples of UV mapping are world maps, which are the flat representation of the globe; the whole surface of a sphere, which is a 3D object, is mapped on a 2D plane. The letters U and V indicate, in fact, the axes of the 2D space since X, Y, and Z are already used

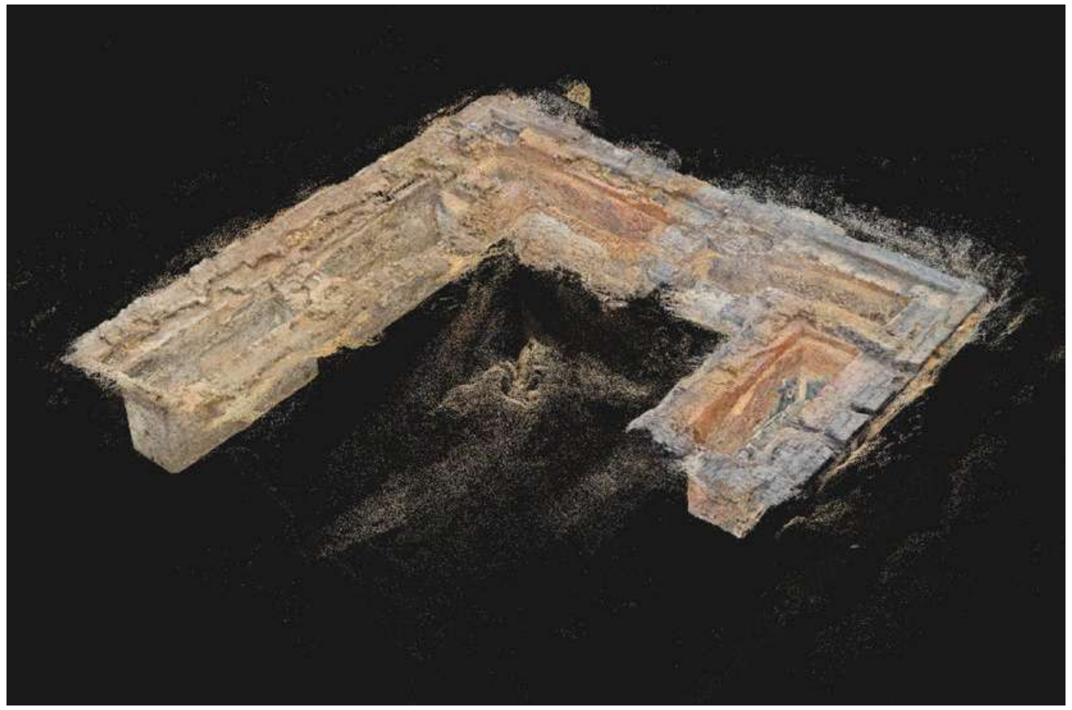

Fig. 105. All the chambers shooted during the first campaign aligned together

Fig. 106. All the chambers and crowns shooted during the second campaign aligned together

in the 3D space. Since the texture will then be mapped on the UV map, having one tile could impair the resolution, especially on large objects. UDIM (UDIMension) allows spreading the mapped surfaced across several textures; it is based on a tile system in which each has its own UV space (u1_v1, u2_v1, ...) and can have a different texture assigned. This workflow improves the quality of the final outcome, enhancing the resolution of the texture. In this case, it is essential to achieve the highest possible resolution by setting the proper texel density, which refers to the texture resolution of a 3D object compared to its actual size, measured, in this case, in pixel/meters. Reality Capture can automatically calculate the optimal texel size based on reproducing the 100% texture quality.

After unwrapping, the model is ready to be textured. The texturing process was revealed to be the most time-consuming. The highest possible resolution was impossible to reach on the available laptop. The resolution had to be reduced to 25% of its maximal value. After texturing the high poly mesh, the model needs to be simplified to reduce the poly count by subsequentially reducing the mesh by 50% of its initial poly count until reaching the desired poly count. The high poly mesh and its texture were projected onto the low poly one by baking texture and normal map.

The baking process enables the optimization of the mesh by rendering the high-resolution model details to a surface texture, which can then be applied to a model with a lower resolution. More specifically, by generating a normal map of a high poly model, the geometry details are stored in RGB values corresponding to the actual XYZ coordinates. This process enables the faking of the lighting of bumps and dents, enabling the enhancement of a low poly model without increasing the polycount.

The components of the first and second campaigns had to be joined together to complete the tomb's final model. Eventually, the exported point clouds were: the side chambers photographed during the spring campaign (chambers one, two, and eight), each one as a different component containing floor, walls, and wall crown; the main chamber, containing floor, walls, and crown; the chambers photographed during the first campaign (chambers three, four, five, six, and seven), containing floor and walls. The crown of the latter chambers was photographed during the second campaign to have a coherent version since the mudbricks' fragile structure inevitably got a little damaged during excavation. Since the tomb had to be refilled immediately after the excavation, each chamber was photographed empty and filled with sand.

The alignment strategy proceeded by merging all the components of the second campaign; therefore,

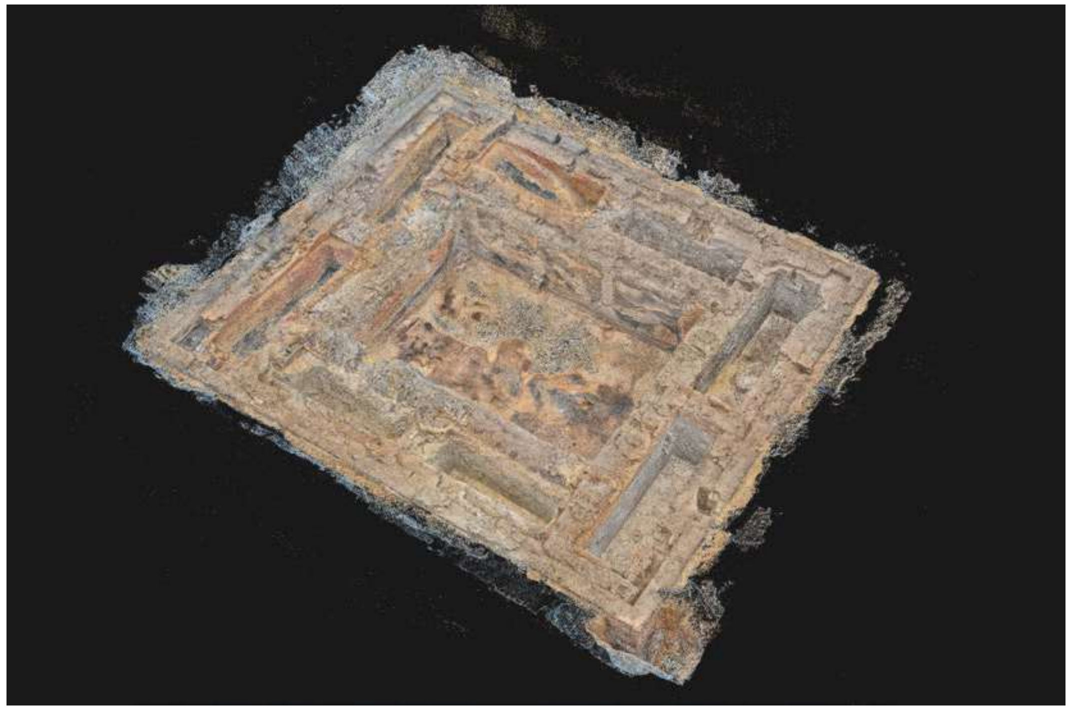

Fig. 107. Point cloud of the whole tomb

chambers one, two, eight, and the main chamber were exported as a single point cloud. This procedure worked flawlessly, demonstrating the effectiveness of the developed photographing strategy.

Chambers three, four, five, six, and seven were aligned with the new crown with the help of manually set control points, ca. three each, and exported.

The process of merging these two components was revealed to be highly time-consuming. Several control points had to be set to correct the misalignments, and since this process took ca. 14 hours, every failed attempt meant losing one day of work. For the final model, 35600 pictures were aligned together, creating the point cloud of the tomb. Additional components had to be created, imported, and merged into the tomb's point cloud to improve parts where the tie points were not dense enough. The final point cloud was scaled by defining the distance between several couples of detected markers. Once the point cloud was scaled, all the images picturing markers had to be disabled, and a clean, aligned component was again exported and imported into a new project. The meshing process took ca. twelve hours and thirteen minutes and had 285 Million triangular faces. The mesh was cleaned by selecting the component with the highest number of triangles and filtering the smaller, detached ones. The created mesh was inspected

Fig. 108. Point cloud of the whole tomb with markers recognized as control points

and turned out to be good, without holes or intersecting faces. The unwrapping process set at the optimal texel size, namely the highest possible texture resolution, provided 81 UV udims with a resolution of 16K. The attempts to texture such an enormous model failed several times.

The texel size was reduced to 25% of its maximal resolution, achieving 81 UV udims with 8K resolution. The texturing process took ca. 50 hours. The high-poly mesh was reduced, reaching 35.5 Million trangular faces by successively reducing the mesh by half of its polygons and then unwrapped again, defining a maximal udims output of ten. The simplifying process reduced the quality and detail-richness of the mesh. It followed the baking of the high-poly on the low-poly model, transferring the texture and the geometry details through normal maps.

Fig. 109. Point cloud of the whole tomb with the shooted photo displayed as white pyramids

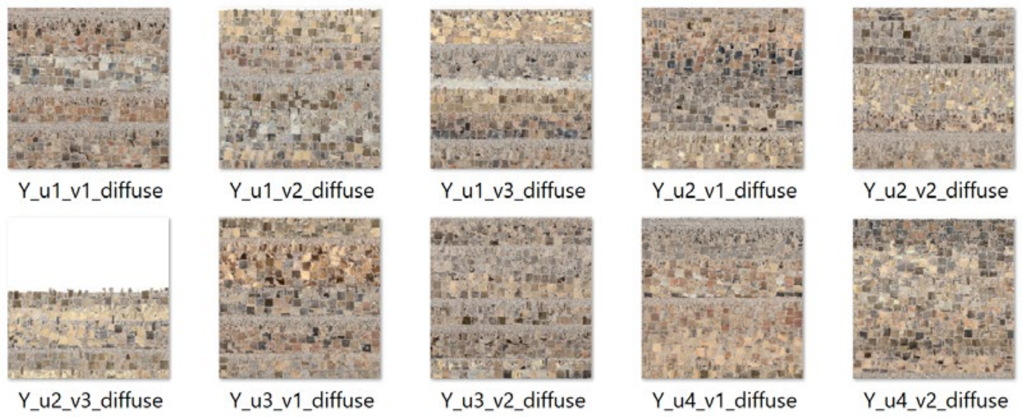

Fig. 110. UV Udims, diffuse layer

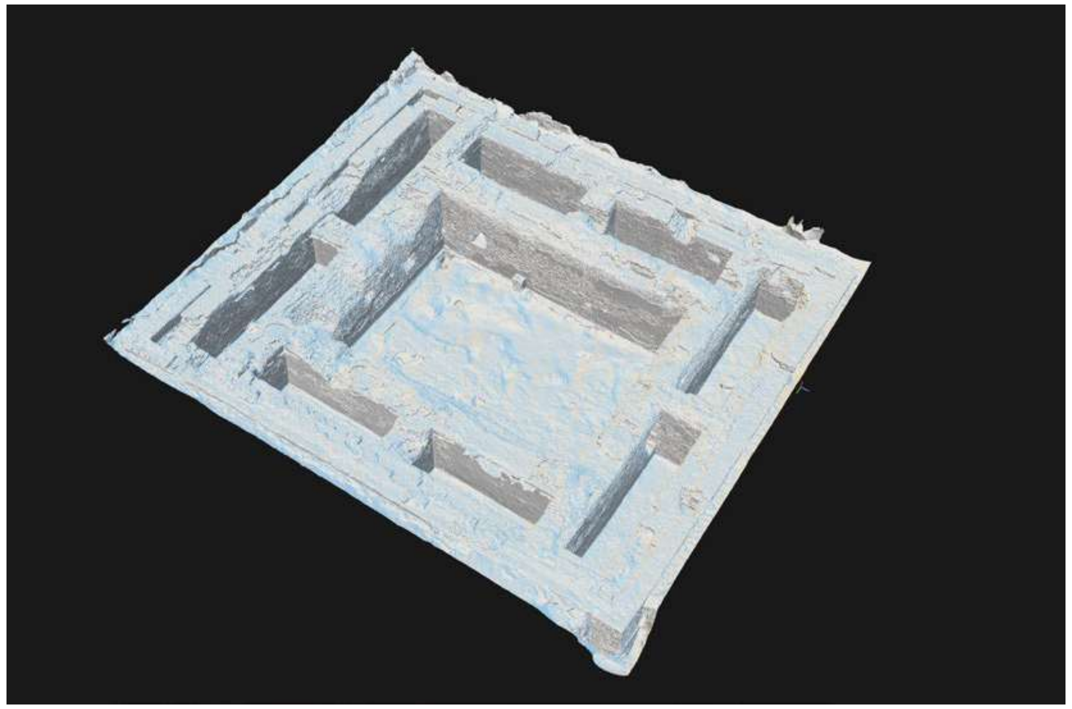

Fig. 111. Mesh model of the whole tomb

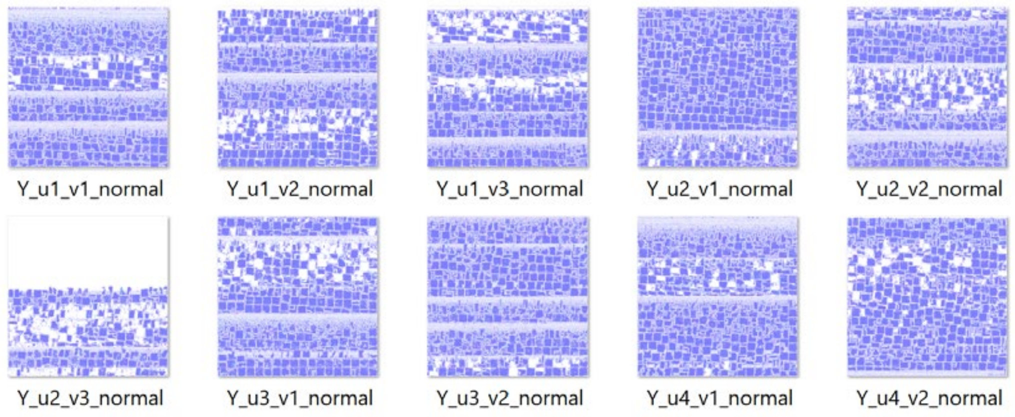

Fig. 112. UV Udims, normal map

Fig. 113. Textured 3D model of the tomb, south - west side

Fig. 114. Textured 3D model of the tomb, south - east side

Fig. 115. Detail rendering of the reconstructed main chamber, south wall

Fig. 116. Detail rendering of the reconstructed main chamber, east wall

5.7 the queen's tomb fire

5.7.1 project

The project's primary goal is to visualize the reconstructed tomb of Queen Meret-Neith, ensuring its availability for a broad audience instead of its remote location and fragility. It was important not only to show the tomb in its authentic appearance but also to convey the unique atmosphere of the Sahara desert where it lies, contextualizing it in its environment.

Virtual reality proved to be an excellent medium for this purpose, enabling the creation of an immersive experience, allowing the user to experience the tomb in first person. A virtual tour through an ancient historic building does not need to emulate reality; on the contrary, it enhances it, enabling the visualization of happenings, the process that led to such happenings, and even different hypotheses about what might have happened. Understanding events that have taken place so far in the past might be complex, so the visualization of them creates one common starting point to discuss and investigate, trying to understand them better.

This is the case of the visualization of the tomb of Meret-Neith. What is known so far is just the fact that the burial took fire; many are assumptions regarding the cause of the burning. This project visualizes three of them, enabling a direct comparison. It consists of one main scene, where the users are free to move around the tomb, exploring it. The starting scene depicts the tomb and its environment similarly to reality, conveying to the user the impression of actually being inside the tomb. Starting from the main set, the users can virtually live the three hypotheses about the causes of the tomb burning in the first person. These three scenes are shown more abstractly to avoid the users' risk of taking them as truth. It follows a final set in which the users can reflect on the visualized event while analyzing the tomb (see chapter 5.7.7 for the design concept of the visualization).

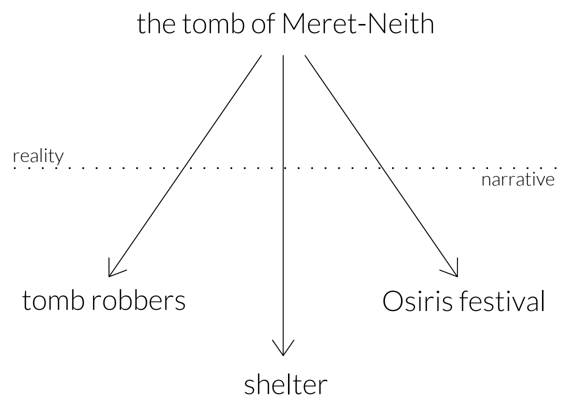

Fig. 117. Project's core structure

5.7.2 processing to VR

The polycount of the photogrammetric model was reduced from 285 Million to 8.9 Million triangles.
Such a massive reduction implies a significant loss of details since the mesh triangles get bigger and simplify the geometry. In order to maintain a level of detail directly comparable to the original model, the high poly model was baked on the low poly one, projecting both the texture in the form of a diffuse map and the geometry details in the form of a normal map. Normal maps are, in fact, "regular RGB images where the RGB components correspond to the X, Y, and Z coordinates, respectively, of the surface normal" (Wikipedia, 2022).
The optimization of the scene components is essential for the creation of a VR experience. Virtual reality requires, in this case, the use of real-time rendering, allowing a flawless interaction between the user and the virtual environment. The scene needs to be simple, allowing the computer to render, therefore, produce images from 3D data as quickly as possible.

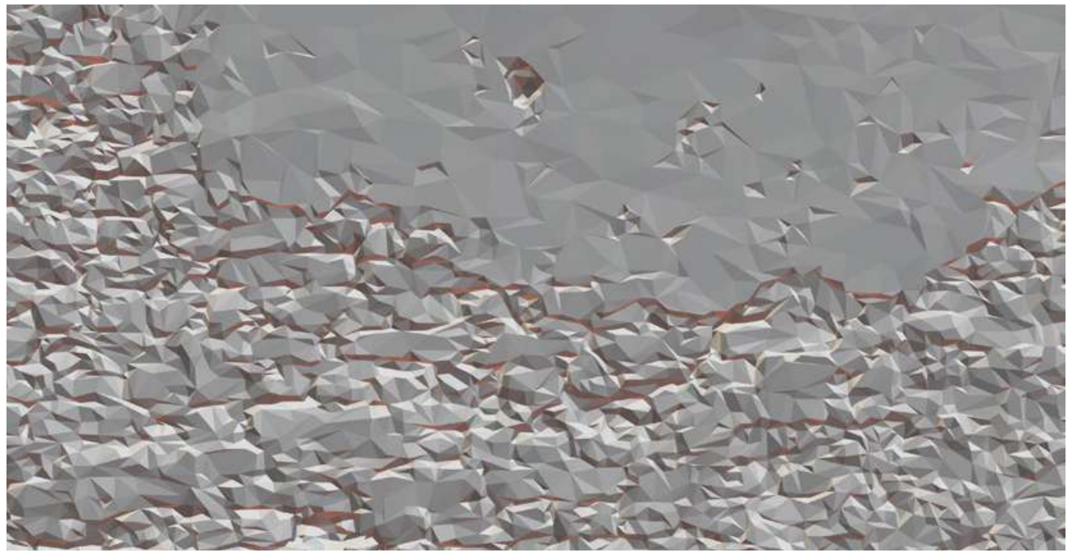

Fig. 118. Detail of the high poly above, and simplified low poly below, model of the tomb

Fig. 119. Detail of the high poly above with the diffuse map applied, and simplified low poly below, model of the tomb with baked diffuse and normal maps applied

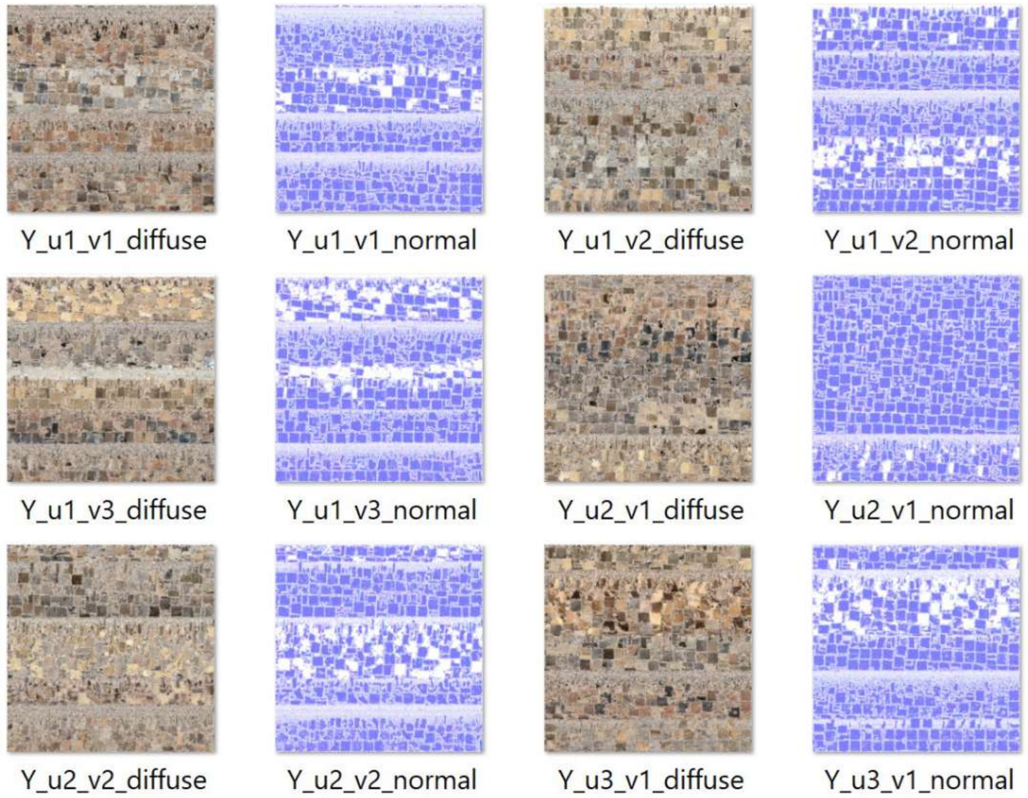

Fig. 120. UV Udims, diffuse and normal maps

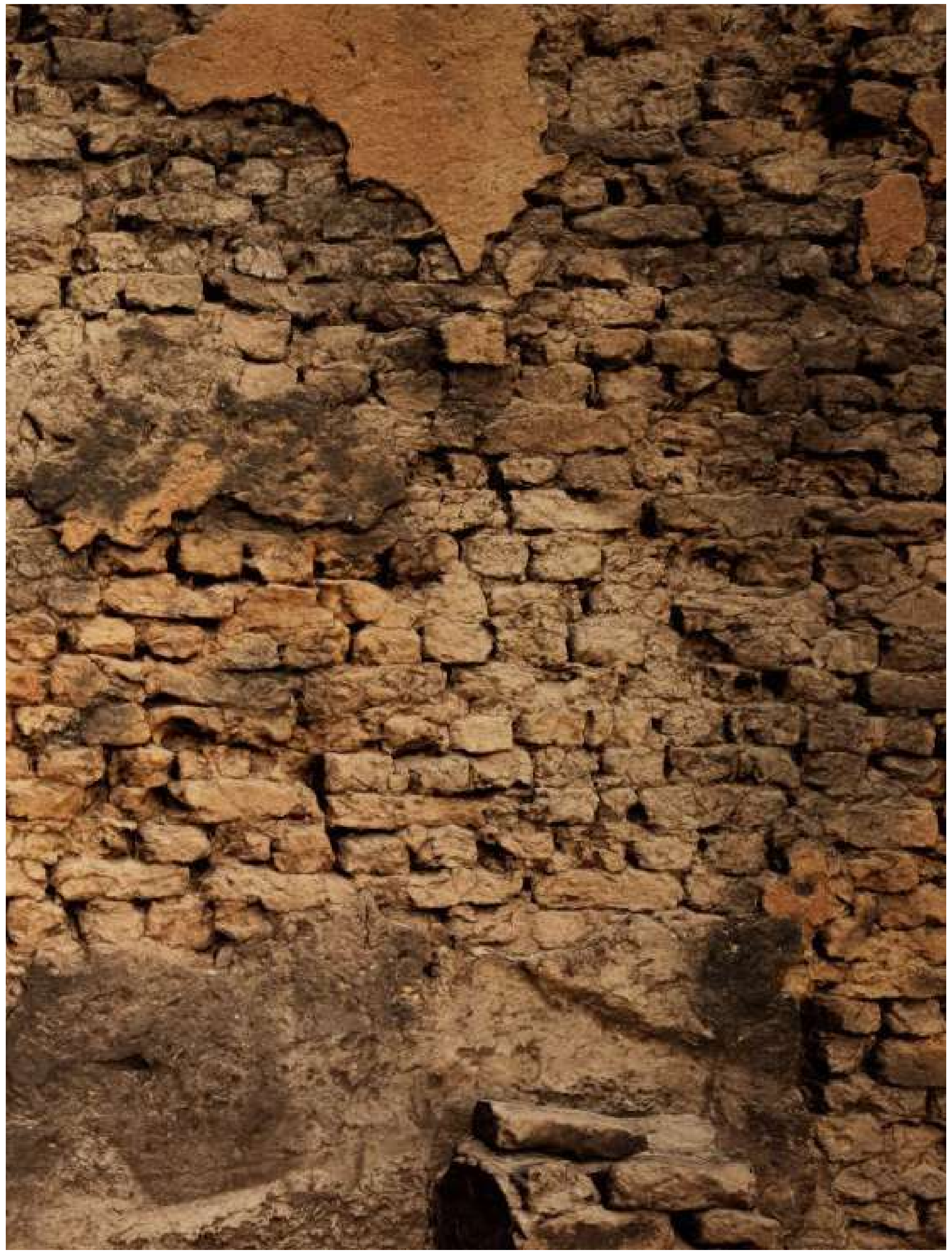

Fig. 121. Detail, quality of the model imported in Unreal Engine, south wall main chamber

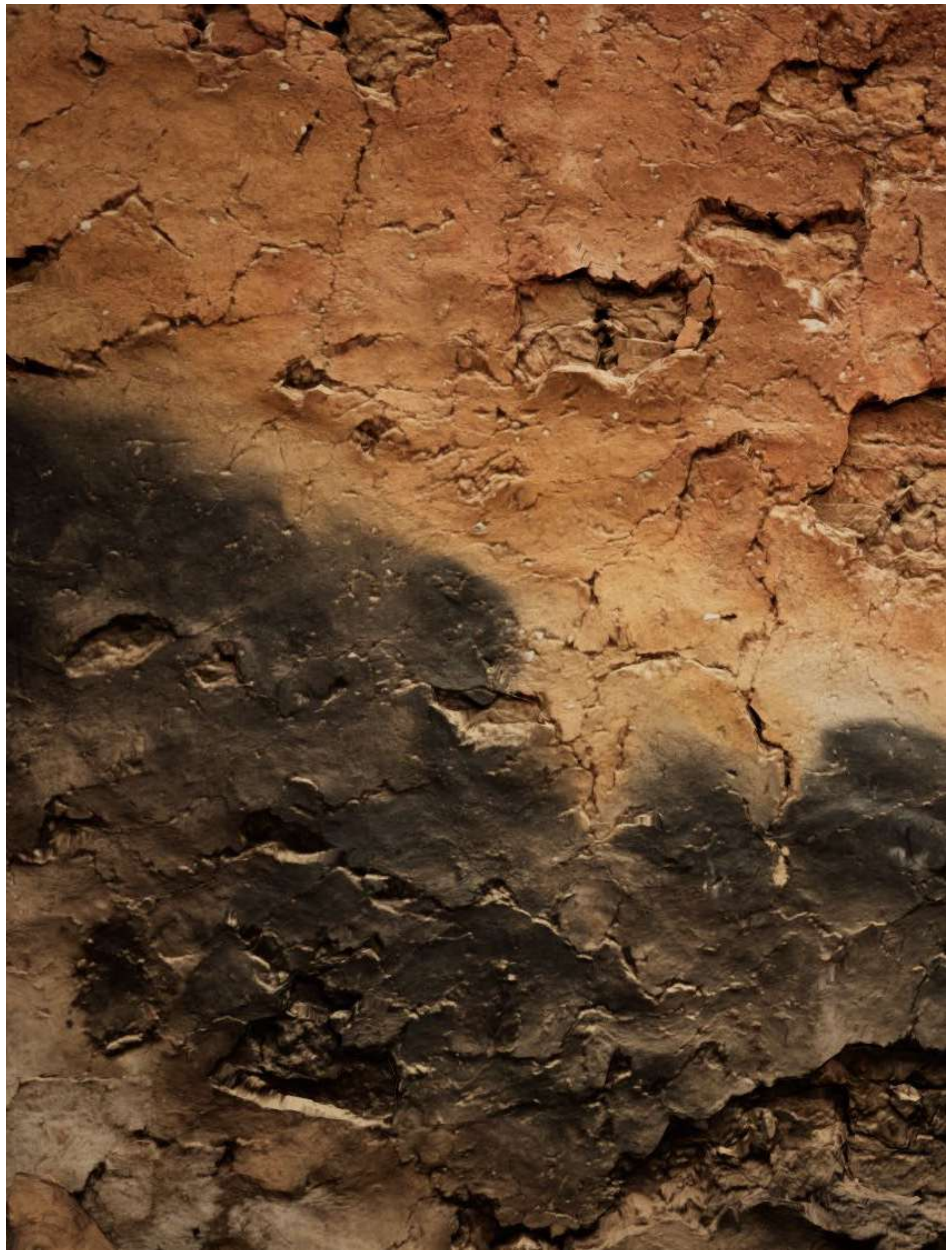

Fig. 122. Detail, quality of the model imported in Unreal Engine, east wall chamber five

5.7.3 mountains

To create the mountains that characterize the site, the contour lines from the terrain view of google maps were extracted. The topography model was created by adjusting the contour lines' height and using them as references for the creation of a mesh. In this case, the mesh was created using the command MeshPatch in Rhino 7. The created mesh presents an excellent form and volume, depicting a similar situation to the real one. However, the mesh's topology was messy; the size of the triangles varied a lot, and some unwanted connections and intersecting faces had to be deleted. After manually cleaning it, it was automatically retopologize with the QuadRemesh tool in Rhino 7. Eventually, the mesh was exported from Rhino and imported into Blender to adjust the form by sculpting it. In order to add some detail, the mesh had to be subdivided with a subdivision-surface modifier, which follows the Catmull-Clark subdivision algorithm. The final mesh presented 11783 triangles and was imported into Unreal Engine 5 to create the scene.

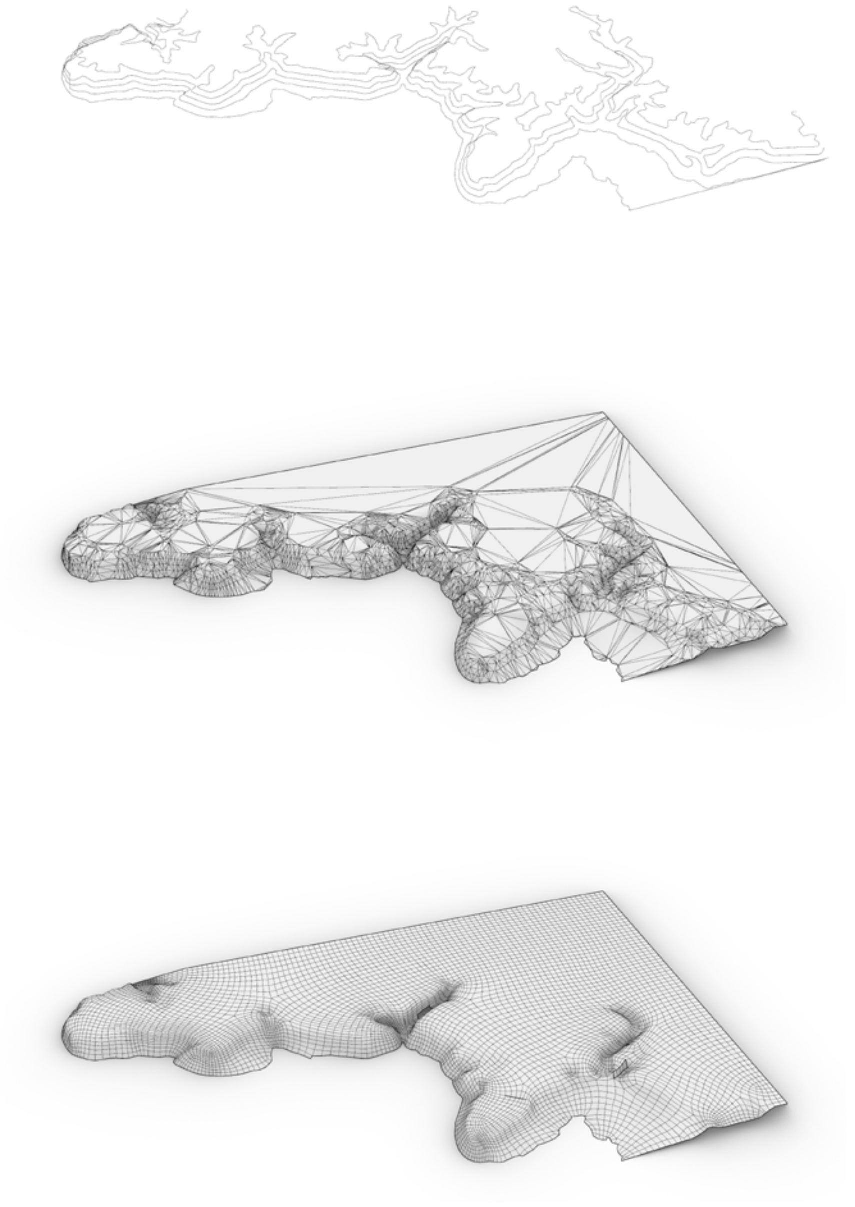

Fig. 123. Reconstruction of the mountains, contour lines, mesh paths and retopology

5.7.4 other tombs and superstructures

All the tombs of the site have been quickly modeled in Rhino 7 by extruding the lines of a dwg-file provided by the archeologists. The exported mesh was again too messy, so all of them have been retopologized in Blender 3.2 to create a clean topology and the less possible number of polygons. Retopology is the process aiming to simplify the mesh by making a clean topology easier to work with. The 3D object should ideally have the less possible number of polygons and a clear structure, allowing a faster calculation.Since the tombs will be shown in a simplified style because they are not the main subject of the experience, it is possible to maintain a low count of polygons.
The tomb of Meret Neith's superstructure was modeled in Blender after the guidance of Dr. Köhler. The superstructures covering the other tombs of the cemetery were modeled as stylized as possible since they only served to create the atmosphere.
The wooden shrine and the beams holding up the roof placed inside the tomb of Meret-Neith were also modeled abstractly since their authentic look is still unknown.

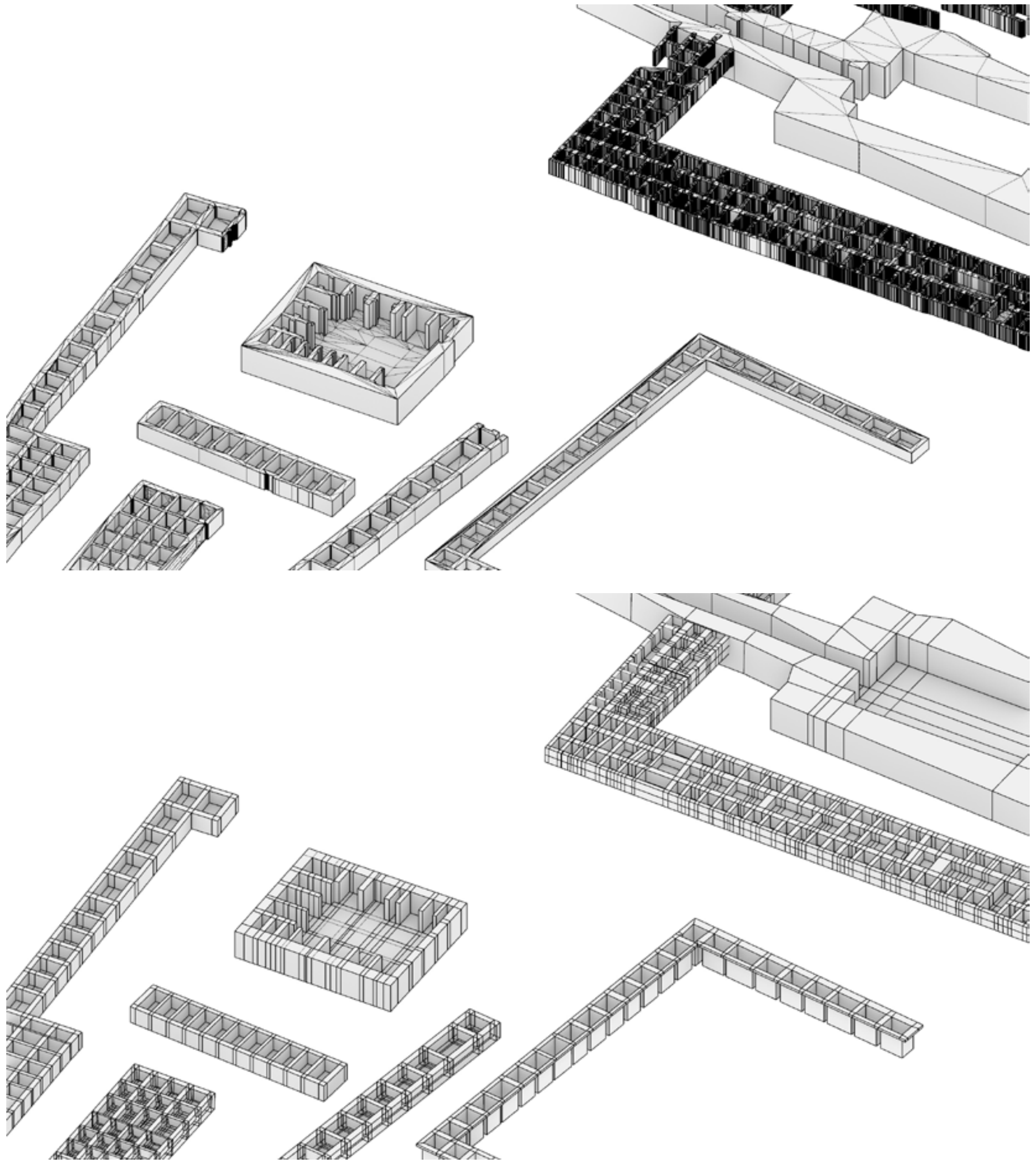

Fig. 124. Bad topology above, good topology below

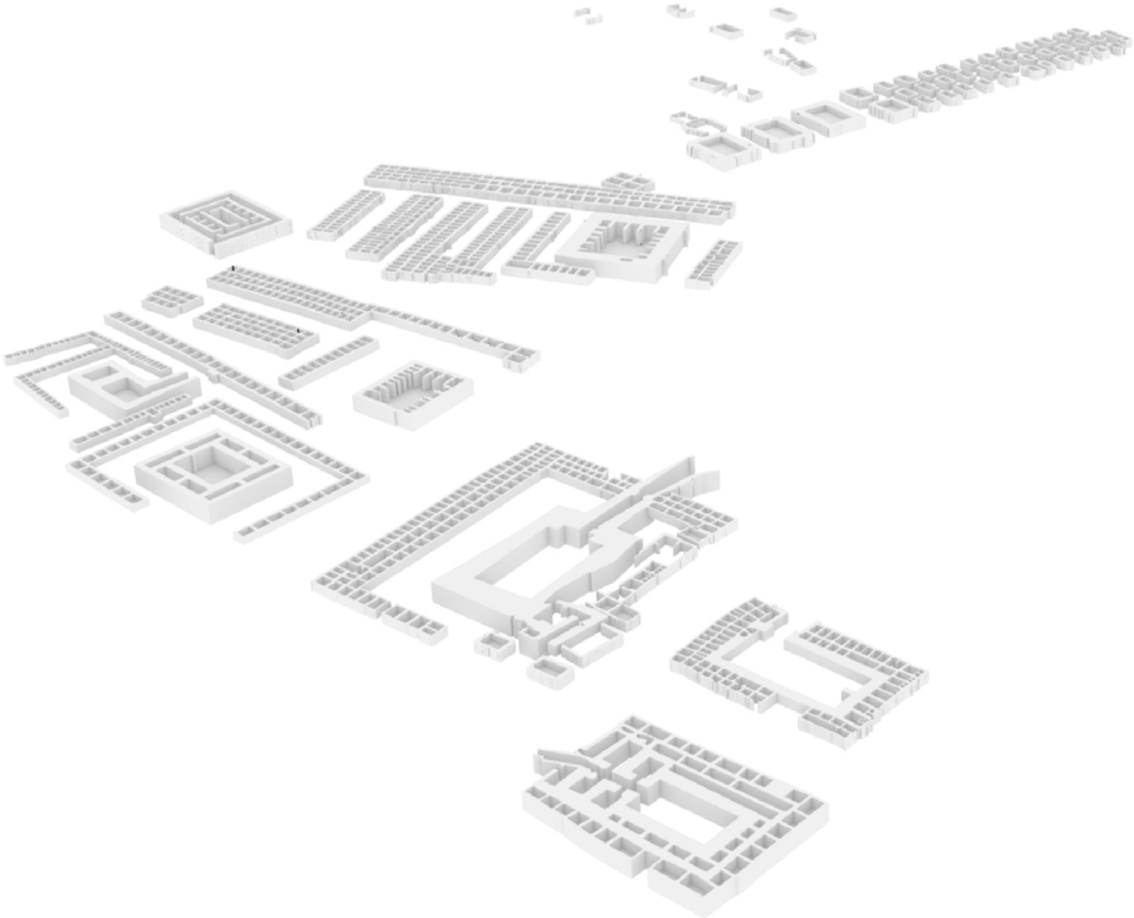

Fig. 125. Reconstruction of the other tombs of the Royal Cemetery, perspective

Fig. 126. Reconstruction of the sand mounds covering the tombs, perspective

5.7.5 desert

The desert was modeled directly in Unreal Engine 5 (UE5) as a Landscape. The light variations of the height were achieved with a noise texture affecting the z-axis. The brighter areas make the mesh move upwards on the z-axis creating hills, and the darker ones make the mesh move downwards, creating valleys.
The particular pot mounds characterizing Umm el Qa'ab were then sculpted with the sculpt tool of UE5.

Fig. 127. Noise texture

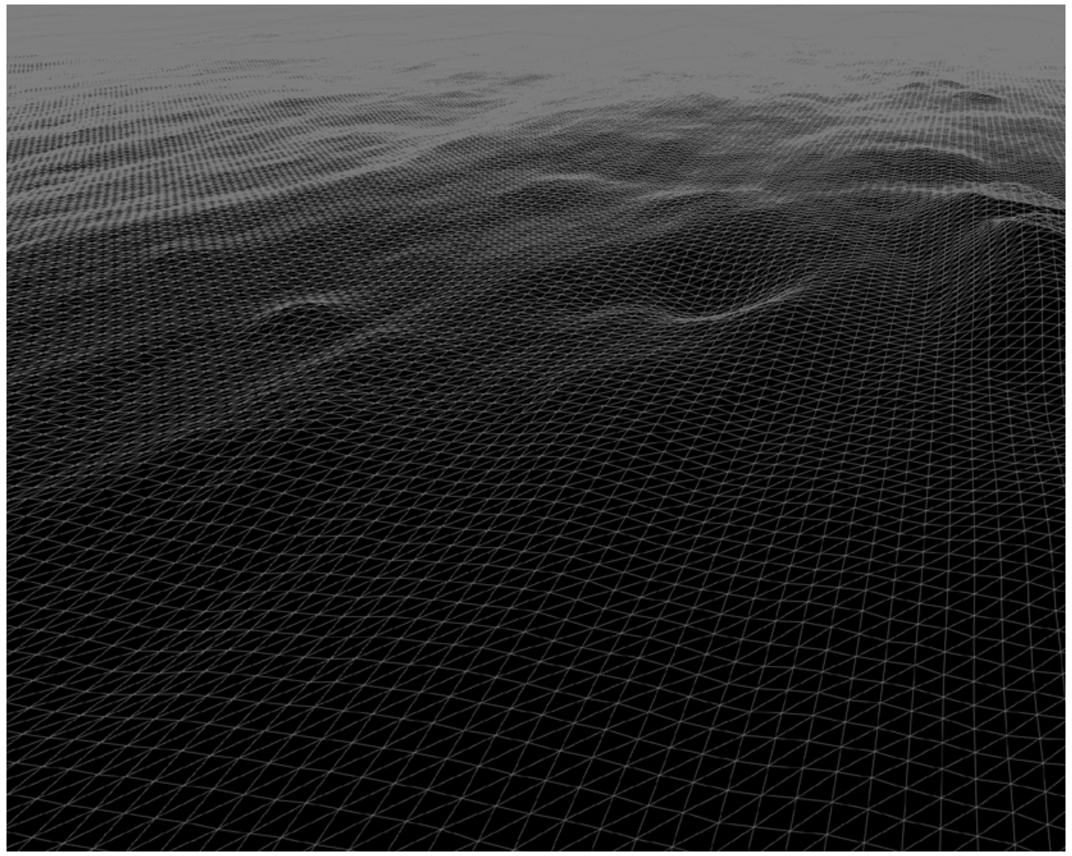

Fig. 128. Reconstruction of the desert as a landscape, wireframe

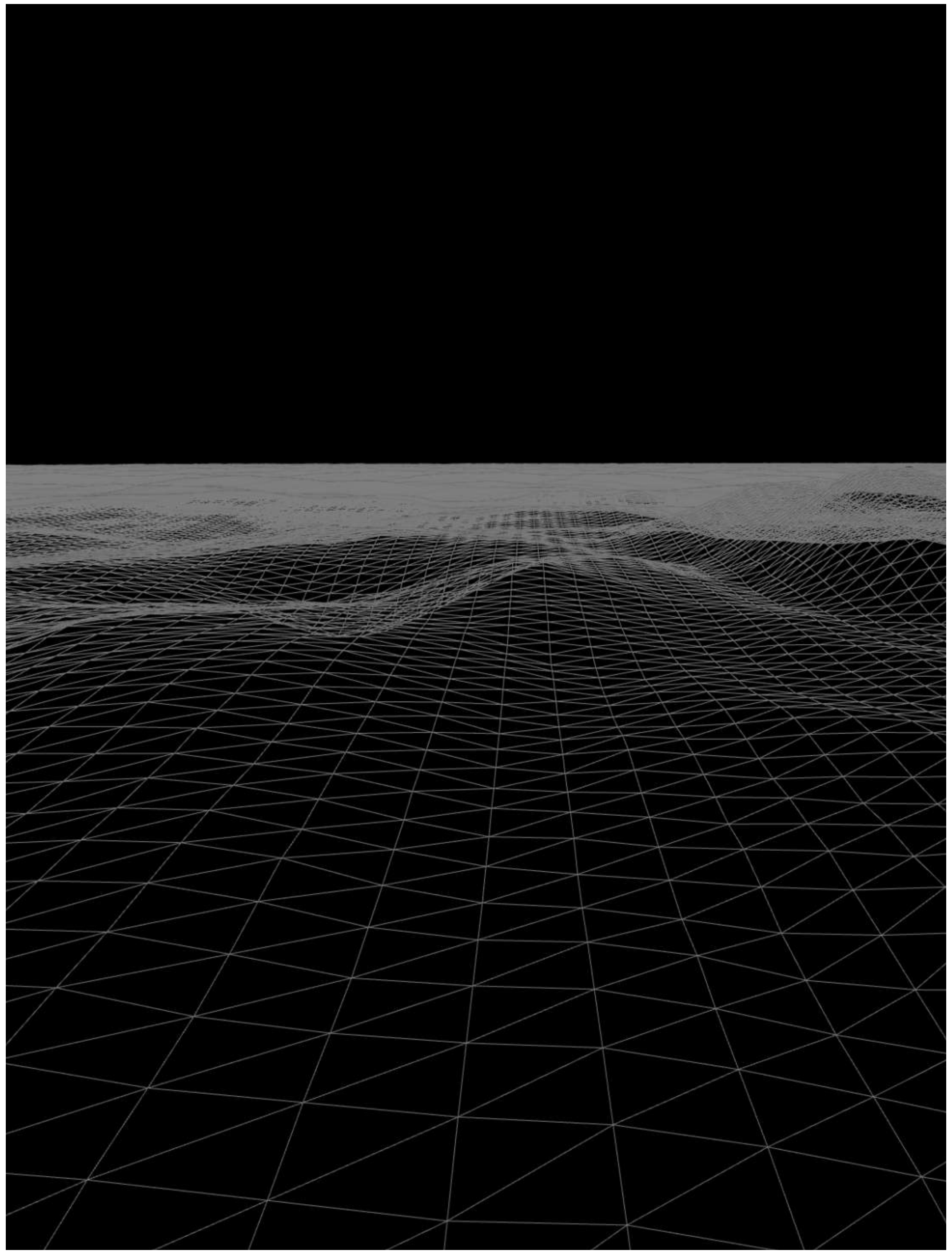

Fig. 129. Reconstruction of the desert as a landscape with sculpted mounds, wireframe

Fig. 130. Reconstruction of the desert as a landscape with sculpted mounds, textured

5.7.6 scene assembling

The scene has been assembled into Unreal Engine 5, using the VR game preset. The mountains and the tombs, together with the photogrammetric model of the tomb of Meret-Neith, were imported into UE5 as obj files, joining the modeled desert and creating the characteristic site of Umm el Qa'ab. The process worked flawlessly.
The sky atmosphere was achieved by adding a sky sphere and a directional light as the sun.

Fig. 131. Assembling of all elements into one scene in UE5

5.7.7 style

The representation style was designed to maintain a clear difference between what is real, what is reconstructed, and was is just a hypothesis. The visualization should, in fact, be an explicit statement itself, communicating to the user what is authentic, what is similar to the original, and what is just assumed. Therefore different levels of abstraction were needed, ranging from realistic to abstract and from 3D to 2D, leaving realism only for those assets that exist and can be represented exactly the way they look.
Starting from the tomb, visualized as a realistic 3D object, displayed as an exact copy of reality because of the photogrammetric reconstruction, assures the user that the way it is represented corresponds to its

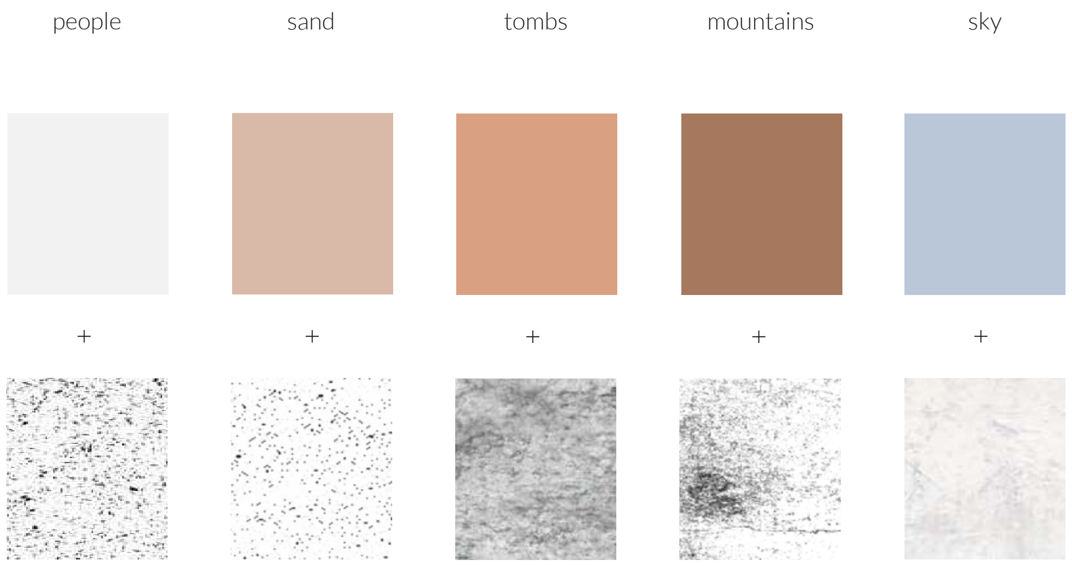

Fig. 132. Color palette and noise textures

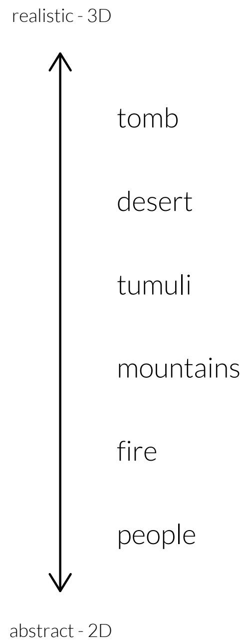

Fig. 133. Abstraction scale for the representation of all the elements

actual appearance.
Following the desert, modeled as a generic desert based on photos of the original one, contextualizes the tomb in its environment. Still, since it does not look exactly how it is represented, it cannot be portrayed realistically. The same applies to the sand tumuli, modeled after the reconstructed versions in the desert but slightly more stylized since there is no clear evidence that they looked precisely that way in the past.
The level of abstraction is brought even further by the representation of the mountains in the background, modeled following just the main shape of their original version, having as only purpose to transmit the characteristic appearance of that specific place. The representation of the fire takes a big step toward the abstract direction. It is, in fact, represented on 2D planes placed in 3D space. It is still unknown where and how it burnt, but it is known the fire generally looks. The representation of the fire aims, in the first place, to create a concrete common picture that provides evidence for starting a discussion and, in the second place, to raise a feeling enabling an emotional connection between the user and the historical object and its related events. The representation of human figures ranks in last place on the realistic-abstract scala. It is unknown who these people were, what they were wearing, and what they were precisely doing and

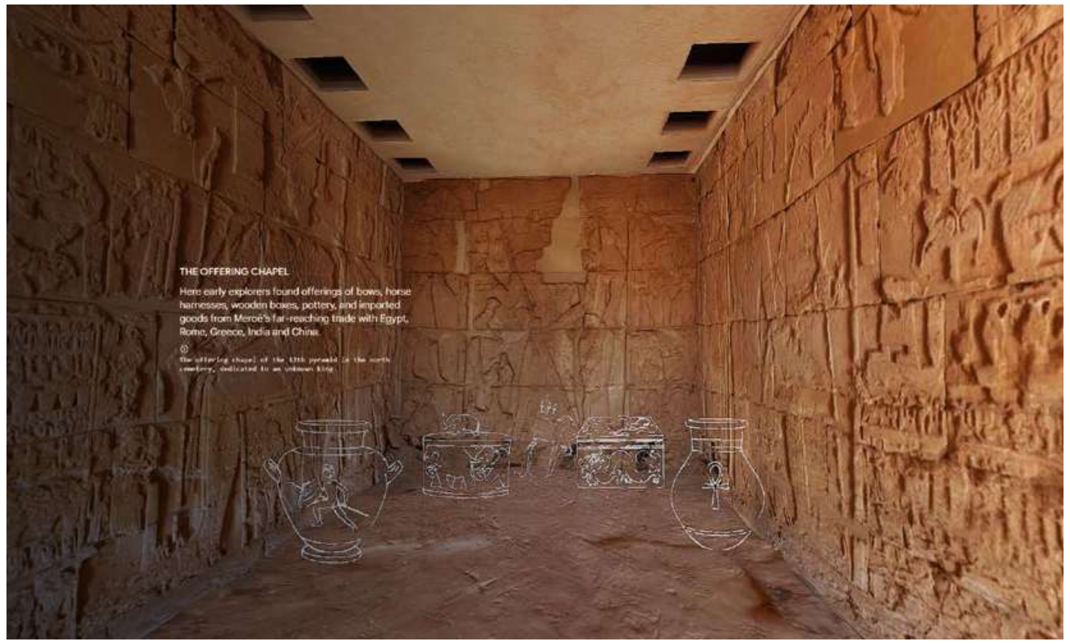

Fig. 134. Google, reconstruction of the Nubian Pyramids

where. It was chosen to represent them recalling the hieroglyphics, them already having a good level of abstraction and creating an immediate connection with the context of ancient Egypt.
The color palette reminisces the radiant atmosphere of a bright day in the desert, comprising different warm, bold tones of brown. Different noise textures were used to achieve the assets' abstract, almost flat appearance. The fog was added to the scene to enhance the monumental scale of the mountains and the desert, making the assets far away more whitish and blurred, improving the depth of field.
The primary reference for the project is the reconstruction of the Nubian Pyramids by Google.

Fig. 135. Figures

5.7.8 navigation

The scene navigation is allowed inside the tomb and in its immediate proximity; the desert and the other royal tombs only help to create an immersive atmosphere. The visitors can virtually walk around the tomb freely, exploring it, moving on the wall crown, and inside each chamber.
Navigation in the virtual space occurs with teleportation. The virtual space does not always correspond to the available space for the users. The teleport solution allows crossing long distances instantaneously.
The users need to point the controller in the chosen direction, moving the stick to reach the desired location. A blue circle visually clarifies the target, while a multicolor ray shows the overcoming distance.
The navigation among the different scenes occurs through buttons reacting to the user's actions. To visually enhance the interaction, the black buttons change their color to light brown while selected, turning white once clicked.
The user interface is kept simple and consistent throughout the virtual experience aiming to create a reference point assuring the user the possibility to get to the home scene and quit the game anytime. In all the scenes, the users find a panel providing information together with the "next scene," "home," and "exit" or" repeat audio" buttons close to the starting position.
The "next scene" button allows the user to take their own individual time to explore the scene and move forward once ready.

Fig. 136. Oculus Quest 2, Head mounted display and controllers

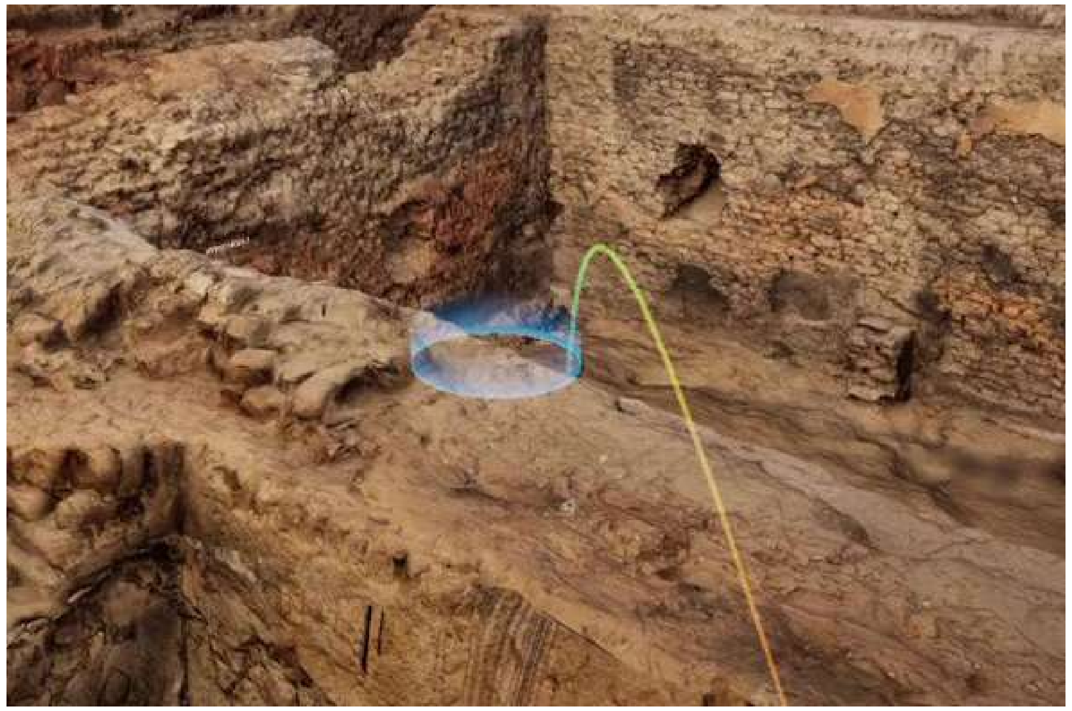

Fig. 137. Navigation in VR, teleportation

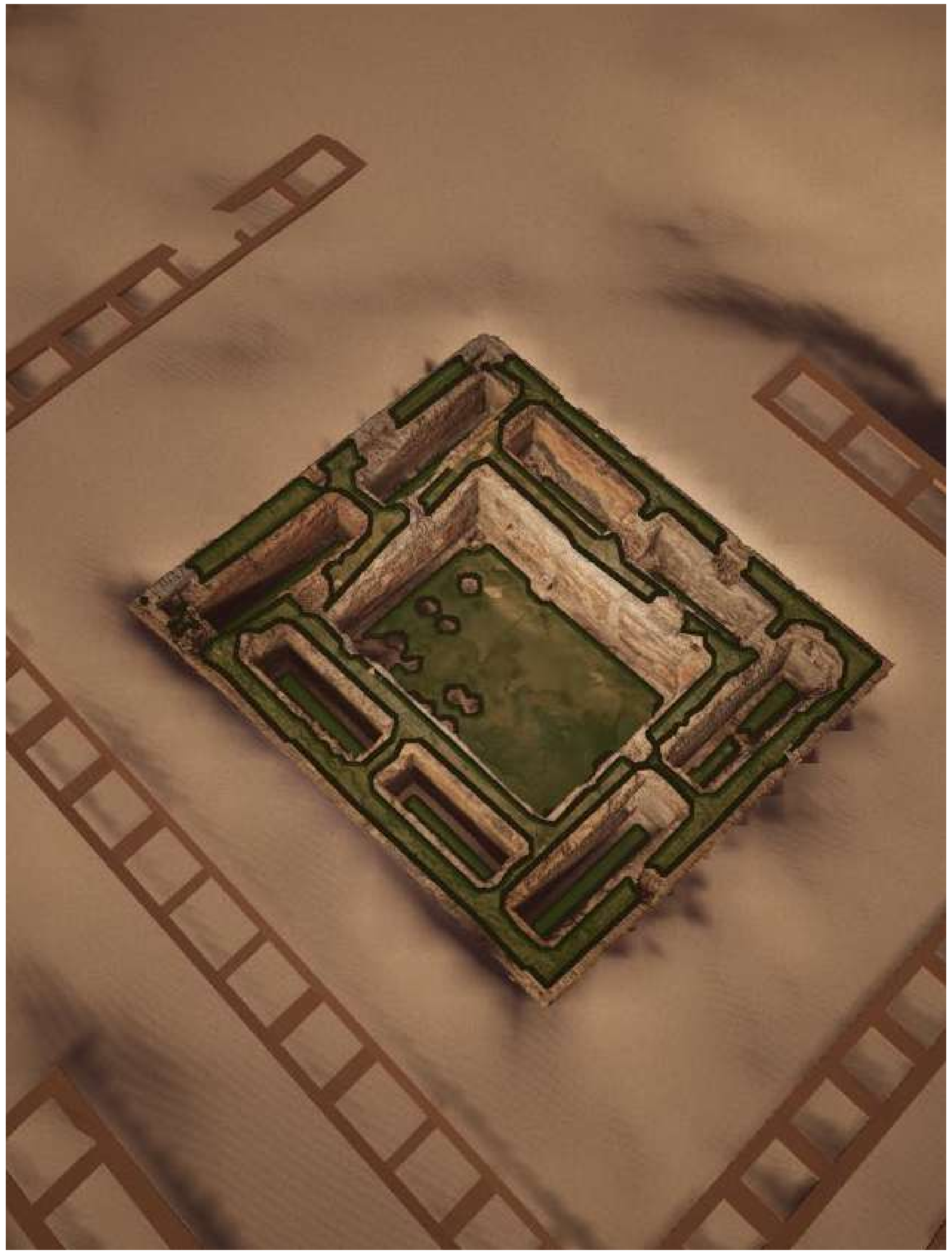

Fig. 138. Navigation surfaces highlaghted by the green color

Fig. 139. User interface

5.7.9 fire simulation

The fire was created using FluidNinja VFX Tools by Andras Ketzer (2019), simulating fire and smoke and exporting it to flipbooks. The flipbooks enabled the creation of animated materials, which were then applied to planes set in the reconstructed scene.
The visual effects were then coupled with the sound of fire.

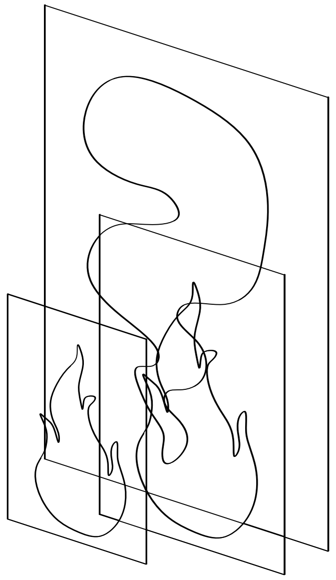

Fig. 140. 2D Panels displaying the fire simulation arranged in the 3D space

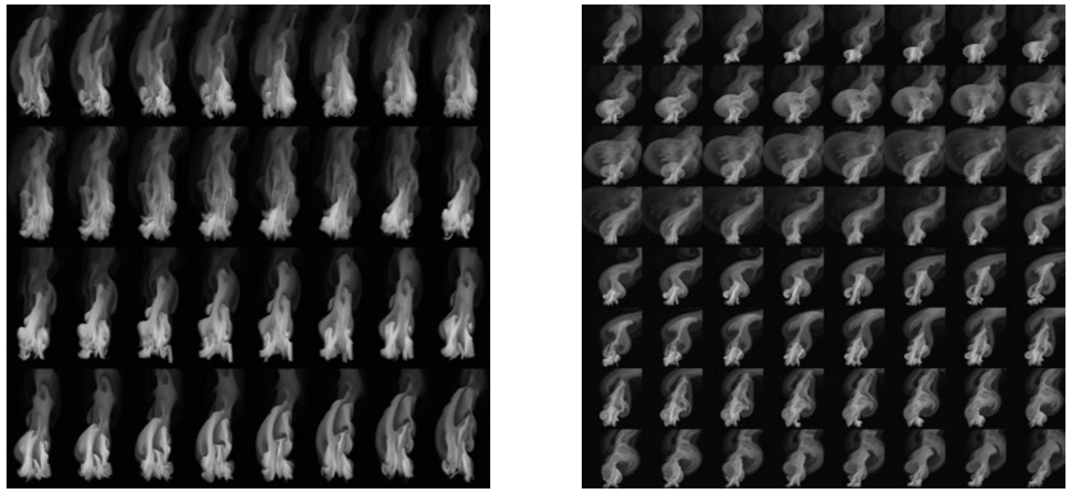

Fig. 141. Flipbook of the fire simulation realized in FluidNinja

Fig. 142. Arranged fire and smoke in the main chamber

5.7.10 scenes

The sequence of the scenes follows one linear direction, meaning the user can only move forward, eventually returning to the main set. The whole experience shares the same display order: the users get to the first scene of one of the three different reconstructed hypotheses from the main scene. This first scene provides orientation, clarifying the direct subjects and picturing the protagonists while performing their activities. The second scene presents the cause of the fire, either by accident or on purpose, showing the fire getting out of control. The third scene shows the fire taking over the central role, spreading over the tomb or the cemetery. The shelter and the tomb robber's sets share the same third fire scene since both take place inside the burial chamber. The three hypotheses bring to the same fire analysis scene, allowing the users to explore the grave more profoundly each time, noticing details they missed previously. A voiceover briefly explains the narrative in the visualizations of the three fire hypotheses.

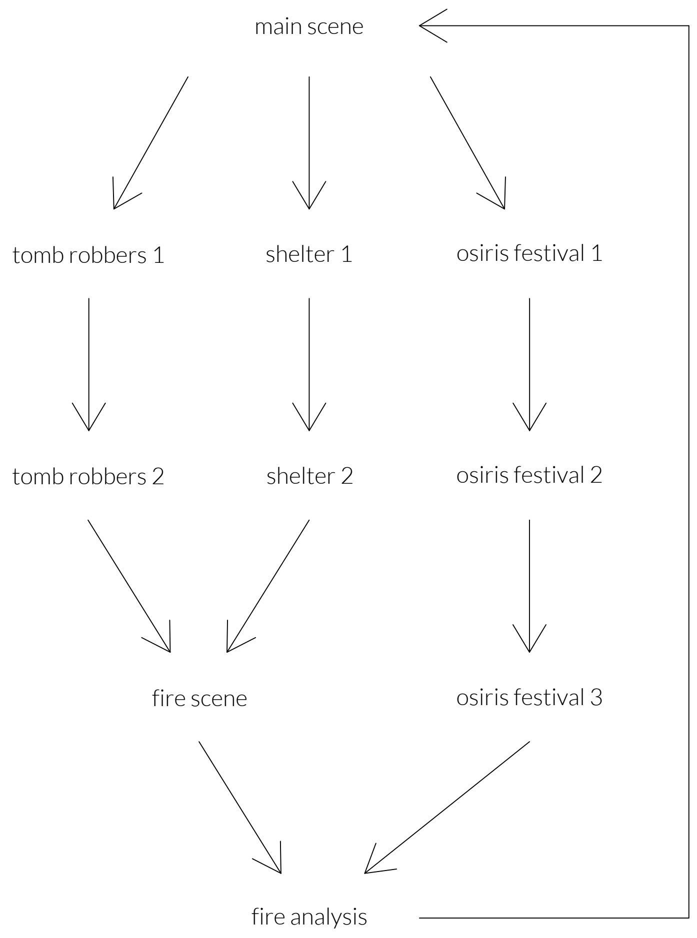

Fig. 143. Scenes connections

Fig. 144. In the next page: main scene, the tomb of Meret-Neith

Fig. 145. Button leading to the visualization of the Osiris Festival hypothesys

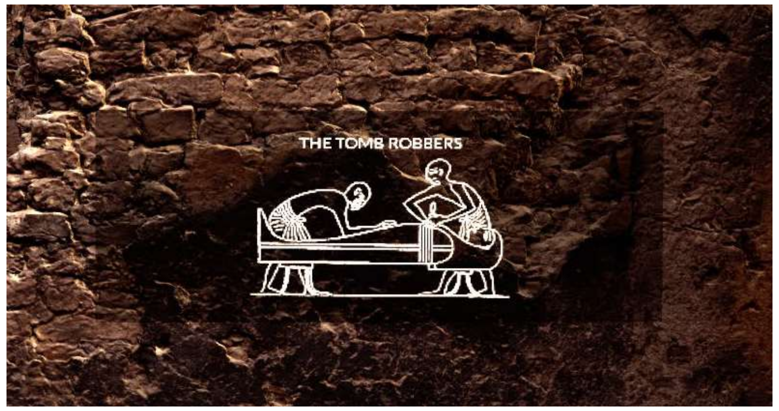

Fig. 146. Button leading to the visualization of the tomb robbers hypothesys

Fig. 147. Button leading to the visualization of the shelter hypothesys

5.7.10.1 main scene

In the main scene, also the starting scene, the users find themselves in the reconstructed archaeological site of Umm el Qa'ab.
The cemetery is represented in its actual state; the graves are covered in the sand showing just part of the upper crown. The great mountains and the desert, together with the characterizing sound of sparrows, seek the creation of an atmosphere in which the user feels immersed.
The visitors are free to walk around the tomb and explore every chamber. Information about the Royal Cemetery and Queen Meret-Neith's grave is provided on panels immediately near the starting position. Three buttons located on the wall of the main chamber take the users to the three different scenes exploring the fire causes.

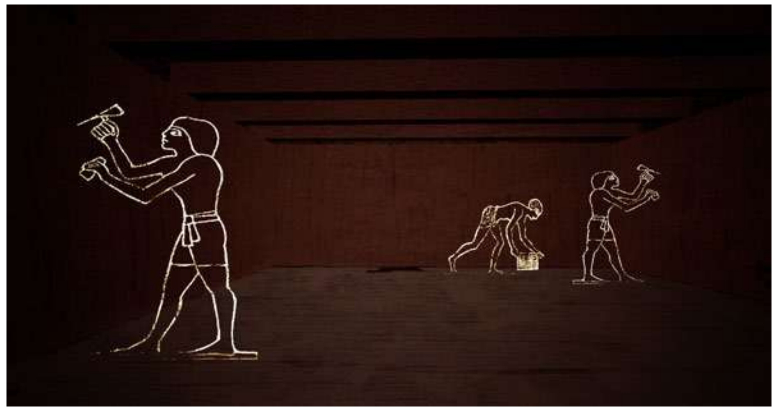

Fig. 148. First scene: the robbers break into the tomb

Fig. 149. Second scene: the robbers set the tomb on fire

Fig. 150. Indoor fire scene

5.7.10.2 the tomb robbers

The tomb robbers' hypothesis consists of a sequence of three scenes.

By clicking on the button showing the tomb robbers, the users find themselves inside the reconstructed wooden shrine in the tomb's burial chamber. Various figures are represented while hitting the walls to break them and stealing valuable goods. The loud sound of tools hitting wood contributes to the immersive atmosphere. The second scene shows figures deliberately setting fire to the tomb and running away with the stolen items. Eventually, the users find themselves inside the burning chamber, showing large flames, smoke, and burning walls, free to walk around to observe the spreading of the fire.

Fig. 151. The tomb robbers first scene: the robbers break into the tomb

Fig. 152. First scene: the vagabonds cook inside the tomb

Fig. 153. Second scene: the fire gets out of control

Fig. 154. Indoor fire scene

5.7.10.3 the shelter

The shelters' hypothesis consists of a sequence of three scenes.

By clicking on the button showing the figures cooking, the users find themselves inside the reconstructed wooden shrine inside the tomb's burial chamber. Figures are represented while cooking on a small fire, providing wood, and sitting around. Characterizing kitchen sounds contributes to the immersive atmosphere. The second scene shows the fire growing bigger and getting out of control. Eventually, the users find themselves inside the burning chamber, showing large flames, smoke, and burning walls, free to walk around to observe the spreading of the fire.

Fig. 155. The shelteer, second scene: the fire gets out of control

Fig. 156. First scene: the procession takes place at the Royal Cemetery

Fig. 157. Second scene: one of the tombs takes fire

Fig. 158. Outdoor fire scene

5.7.10.4 the Osiris festival

The Osiris festival hypothesis consists of a sequence of three scenes.
By clicking on the button showing the procession's bark, the users find themselves outside the tomb amid the annual parade honoring the god Osiris. Figures are shown following the Neshmet-barque, carrying goods and, some of them, fire. The sound of the wind conveys the feeling of an extremely windy day. The cemetery is shown in its supposed original state, with sand tumuli covering the graves. In the second scene, the users notice a small fire starting near one of the tumuli covering the royal tombs. The third scene depicts the fire spreading all over the cemetery because of the strong wind burning all the graves at once.

Fig. 159. The Osiris Festival, second scene: one of the tombs take fire

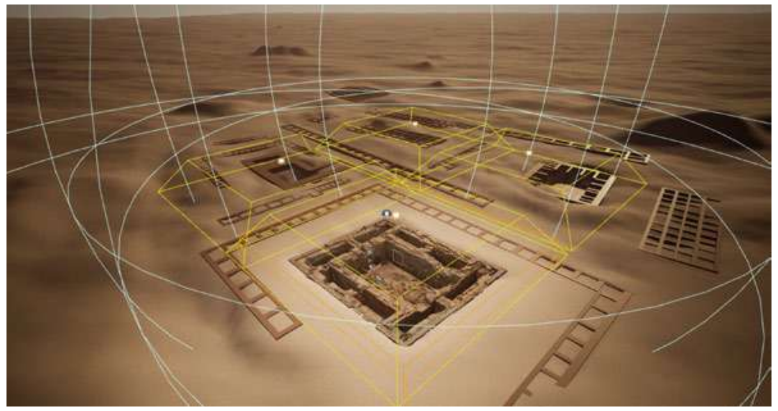

Fig. 160. Lighiting of the fire analysis scene

Fig. 161. Discussion panel

Fig. 162. Grabbable artifacts

5.7.10.5 fire analysis - discussion

The scene following the three different fire scenes allows the users to analyze the burning and reflect on the happenings. The tomb is represented in its actual state, illuminated by artificial light sources to avoid direct shadows. White lines mark the burning signs on the walls highlighting them. The reconstructed found artifacts are spread around the tomb, highlighted by white marks, ready for the users to grab and take a look at them. Some thoughts and considerations about the hypotheses of the fire happening are reported on a panel to start a discussion about it, bringing the users to reflect on it and develop an opinion.

Fig. 163. Fire analysis: east wall of the main chamber with highlighted fire traces

Fig. 164. VR interaction with the reconstructed jar

5.7.11 application export

Two applications were eventually exported: one for Windows and one for Android.
The Android application could be directly installed on the HMD without needing a computer. However, this format proved to be inadequate for this project. First, the application should preferably max 2 GB big, a limitation that compromises the quality of this project's main subject, the tomb; and second, many features, such as color correction, fog, and other elements that help create the atmosphere, are not yet supported by a VR Android application. After a massive simplification of the photogrammetric model of the tomb and all the scenes in general, the application was installed directly on the Oculus Quest 2. It was particularly unstable, slow and impposible to enjoy, especially since its flickering would create nausea.
The Windows application runs on Windows laptops and computers. To enter the virtual experience, the users need to access the computer from their Virtual Reality glasses, in this case with the Oculus Link App. The limitations regarding the size of the assets are much higher and, contrary to the Android version, it supports many more features. The application proved stable, displaying the assets without compromising the quality and offering a more significant level of immersion. The quality of the experience depends, of course, on the power of the computer on which it is running; the level of quality is, however, extremely better than the one of the Android application.

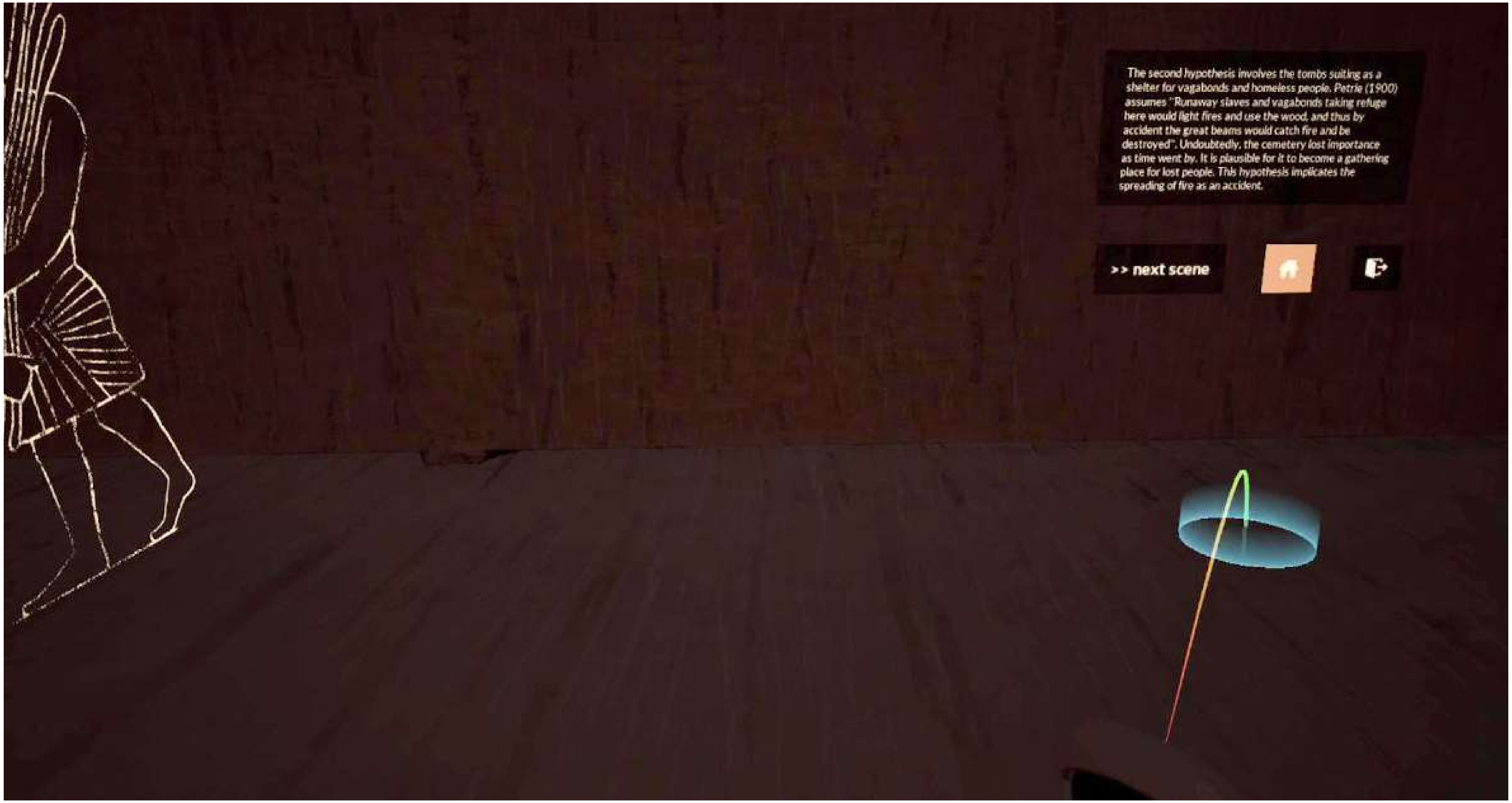

Fig. 165. VR viewport of the shelter scene

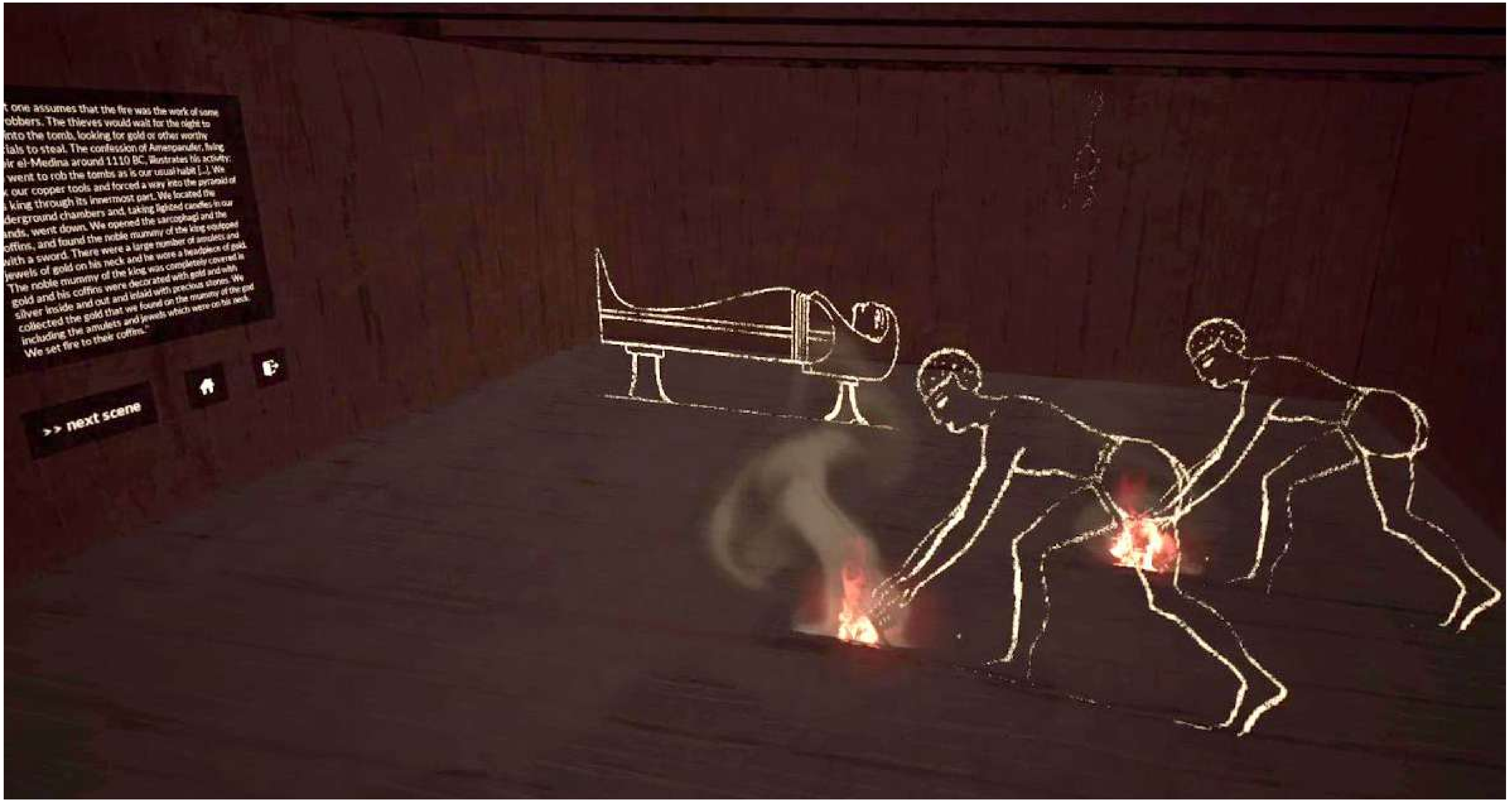

Fig. 166. VR viewport of the tomb robbers scene

Fig. 167. VR viewport of the indoor fire scene

Fig. 168. Aereal view of the reconstructed site and superstructures

6 conclusion

The main challenge of this thesis project has been the attempt to overcome distances, them being physical, cultural, and temporal, by connecting visitors of the current generation to an object that is by its geographic location in the desert, culture, and era far away from nowadays life.

The first step to reaching a connection to the subject has been to recreate the presence feeling of actually being inside the tomb, in its natural location, the Sahara desert, surrounded by high mountains, characterized by its still atmosphere, the sound of the wind, and the birds chirping.

The data acquisition process seeking the photogrammetric reconstruction of the tomb faced many challenges, given the particularity of the subject and its unique location. After a testing process, the team preferred to shoot with the iPhone instead of the camera since such a small, light, and compact device fitted perfectly the necessity to climb around the tomb reaching every corner. It had, of course, its limits; the light adaptation of the camera compromised the color reproduction. Due to the abrupt changes in the camera exposition, the white balance was only partially accurate since the camera exposition on which the color checker was based was not constant throughout all the pictures. The colors needed, in fact, to be harmonized through the color correction tool directly inside of Reality Capture.

Another massive problem, especially during the second campaign, was the poor heat resistance of the iPhone, which had to be frequently cooled down with the help of an icebox. Once the device reached the maximal temperature, it would suddenly shut down, preventing the proceeding of the shooting.

The spreading of the markers helped in the reconstruction of the model, providing Reality Capture with features with very strong contrast, essential for the alignment process and scaling of the model to the actual size. During the second campaign, using markers, which remained fixed in the same position throughout the campaign, proved to be a significant help. They had to be removed at the end of it, meaning for the further excavation of the subsidiary chambers, the absence of very points, referencing their position to the main structure. The setting of control points, accurately measured in altitude, latitude, and longitude, would significantly help the correct scaling of the reconstructed object, also serving as a reference point for the relation between it and its surrounding.

The time factor caused the most significant problems; the tomb was, in fact, never entirely empty. The chambers shooted during the first campaign were, during the second campaign, filled with sand. The software erroneously partly reconstructed the sand, which needed to be removed in post-production. It was impossible not to use all the photos picturing part of the sand since it is visible in most of the wall-crown images. A solid excavation strategy needs to be developed together with the archaeologist team, defining the occurrence of the work in a way where the shooting object and its surrounding are entirely free.

The massive amount of collected data resulted in difficult handling; the pictures had to be divided into four different SSD (2TB each). The data processing was very time-consuming.

The resulting original model, having 285 Million triangular faces, proved impossible to handle since no devices were available to take such an enormous size. The texture had to be reduced to 25% of its original resolution to be even calculated. The model had to be massively reduced to be correctly displayed on today's devices of common use. This questions the creation of such an extensive and accurate model, which is not effectively accessible. The documentation purposes, however, are also aimed at the future, requiring so the best possible quality in the data acquisition, ready for sounder use with the come of more potent devices.

The development of the VR experience in UE5 presents similar challenges to those mentioned above. The tombs model needed to be simplified to 8.9 Million triangular faces, and its texture udims had to be reduced from 8K to 4K resolution, compromising reproduction quality. Furthermore, Virtual Reality does not yet support practical features that would increase the assets' quality. One of them is the recent virtualized geometry system Nanite, available in Unreal Engine 5, but only for developing computer games. Nanite enables an intelligent render of the detail of only the perceived geometry creating an automatic level of detail.

This project regards only the tomb of Queen Meret-Neith. However, it could potentially expand to the whole cemetery, featuring the reconstructed models of the other tombs, showing further steps in researching the causes and dating of the fire since almost all the tombs burnt. It could also serve as a base for visualizing other historical aspects like the excavation process or the Osiris cult. As the archaeological research progresses, it could win new insights into the causes and fire spread, which should be updated in the scenes. In this case, creating a new scene and revising the navigation buttons will be necessary. Creating a library of elements sharing the already used colors and style could simplify this process. The discussion aspect in the fire-analysis scene only serves, as it is, as a cue; it could be enhanced by implementing a live scientific and non-scientific discussion board where users could post their opinions and comments.

The application export proved to work better on a Windows device than on Android. The Android application, which could be directly installed on the HMD, required a further reduction of the tomb's model but revealed itself unstable and impossible to enjoy since its flickering would create nausea. The application is today only accessible via Windows Laptop through the Oculus Air Link application. The application could now be ready to download on a museum website but not, however, not usable by anyone, making the Metaverse aspect not yet ready. With the increase of power in the future of Virtual Reality Glasses, this aspect will be improved. This thesis means to be part of the ongoing effort to build the Metaverse, investigating ways to visualize ancient architectural heritage suitable to the current digital media.

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