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Abstract: Underground space has widely been used through history, provided either by natural or by dug cavities that were used as storage for farming production. In particular, cereals have constantly been present in the Mediterranean cultures. Their preservation was crucial in the Mediterranean grain trade for local and urban growth.
The main goal of this multidisciplinary study is to analyse the typological and architectural characteristics of underground Mediterranean granary structures. It also discusses the excavation process for building a silo, focusing in a study of the Valencian Silos at the Spanish Mediterranean shore. The Valencian silo-yard was essential for the socio-economic city development in the 16th century. This is the first research performed on this subterranean ensemble, by searching through historical documents and using a non-destructive technique (NDT) as Ground Penetrating Radar (SIR-3000, GSSI) with 100 MHz and 400 MHz antennae. The composition soil was obtained for hydrogeological characteristics by geotechnical tests. Besides, laser scanner and GPS surveys were carried out for mapping the silo-yard in detail.
Since the Valencian silos are a relevant example of subterranean engineering storage, we were able to carry out a comparative study of significant Mediterranean silos (from Algeria, Italy, Jordan, Malta and Turkey) by reviewing documentation. As a result, these underground spaces share numerous features, as type of terrain, excavation process, geographic location, morphology, dimensions, sealing system, usage, etc. These similar features illustrate that a subterranean grain storage stereotype is present in the Mediterranean region heritage.

# Understanding subterranean grain storage heritage in the Mediterranean region: the Valencian Silos (Spain)

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**Abstract**

Underground space has widely been used through history, provided either by natural or by dug cavities that were used as storage for farming production. In particular, cereals have constantly been present in the Mediterranean cultures. Their preservation was crucial in the Mediterranean grain trade for local and urban growth.
The main goal of this multidisciplinary study is to analyse the typological and architectural characteristics of underground Mediterranean granary structures. It also discusses the excavation process for building a silo, focusing in a study of the Valencian Silos at the Spanish Mediterranean shore. The Valencian silo-yard was essential for the socio-economic city development in the 16$^{th}$ century. This is the first research performed on this subterranean ensemble, by searching through historical documents and using a non-destructive technique (NDT) as Ground Penetrating Radar (SIR-3000, GSSI) with 100 MHz and 400 MHz antennae. The composition soil was obtained for hydrogeological characteristics by geotechnical tests. Besides, laser scanner and GPS surveys were carried out for mapping the silo-yard in detail.
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**Highlights**

- Multidisciplinary study has defined the main Valencian silo characteristics.
- GPR has been used for underground architectural analysis: inner structure.
- Comparative study shows main Mediterranean silos share numerous features.
- Silo construction process has been proposed for the Mediterranean region.
- Mediterranean silos are a very vulnerable underground heritage to preserve.

**Keywords**

Subterranean grain storage; Mediterranean silo features; underground architecture; ground penetrating radar; 3D laser scanner model

## 1. Introduction

From far-off times, underground space has been used to satisfy human requirements (Dunkel, 1985; Fuentes et al., 2006; Labs, 1976; Sterling et al., 1983). Habitation and grain storage have been two of the main activities associated to subterranean structures. Many examples can be located all over the world, as housing caves and silos, especially around the Mediterranean Sea (Dunkel, 1995; Erdem, 2008; Miret, 2005). In particular, the Iberian Peninsula has a large tradition in subterranean spaces, as natural caves, troglodyte habitation, mining works, galleries beneath fortresses, crypts, wells, cisterns, wine cellars, silos, recent roads, railway or hydraulic tunnels (Aranda, 2003; Flores, 1984; Juncà, 1998).

Despite the importance of underground grain storage for wheat preservation and population subsistence, silos have gone unnoticed or undocumented through the history of the Mediterranean countries. This paper helps to understand the characteristics and building techniques of these subterranean structures by analysing the 16th century Valencian silos (Spain) and comparing them with other Mediterranean underground grain storages.

Cereals were outstanding in the religion and mythology of the ancient Mediterranean societies. Wheat was the raw material for obtaining bread, which was an intrinsic element in the religious rites. Their significance took in from the myths of Prometheus and the grain goddess Demeter until the Christian Eucharist (Ostrovsky, 2007). Bread was also the staple food for all social classes. Underground grain storage was already used from the Neolithic period. This praxis expanded considerably during the Iron Age. Despite the fact that Romans imposed the grain storage in barns and large earthenware jars, subterranean granaries were still in use (Miret, 2009; Valls, 2014).

In the Middle Ages, subterranean grain storage reached its peak. Silos were employed as subterranean warehouses for groceries conservation and especially for cereals preservation. Due to the great expansion of sea trade, these underground structures were profusely excavated all over the Mediterranean lands. So, small farming silos coexisted with large fossae created for big cities consumption. Large-scale silos built during the medieval period were still in use until the 19th century for saving cereals in case of crop failure or fluctuating price of grain (Hyde and Daubney, 1960; Miret, 2009). These reasons were crucial for the urban growth of Valencia, considering it was the capital of the former Valencian Kingdom and one of the most important Mediterranean cities.

During the 15th century, Valencia became a great trading power, taking advantage of the commercial expansion in the Mediterranean Sea. Valencia geostrategic situation allowed business deal of imports. Wheat was brought in from Castile (Central-Spain) using terrestrial transport, as well as from Sicily through shipment (Braudel, 1953; Guiral-Hadziiossif, 1989; Salvador, 1972). Following this purpose, the large-scale underground Valencian grain storage was constructed in a place (Burjassot) near the city, only 5 km away from downtown, in 1573 (Fig. 1). This location was selected owing to favourable economic, geographical, topographic and geological aspects. It was a civil project undertook by the Valencia city council, due to (Expósito, 2005; Valls, 2014):

- Shortage of wheat.
- Seasonal crop failure.
- Fluctuating price of cereals.
- Economic losses stemmed from bad conditions of grain conservation in downtown barns.

These subterranean granaries were excavated on the top of a small flat hill. This topography prevents rainwater accumulation. Besides, its elevated position allowed the excavation of underground structures without reaching groundwater table.

Silos were dug in a clayey soil that presented nodules of carbonates and intercalations of limestone crust substrates. It is a really suitable type of terrain for underground grain storage facilities. It has some advantages as the easiness of excavation, the consistency and the hydrothermal conditions for wheat preservation as it has been stated in several studies about the Mediterranean granaries (Benítez et al., 2004; De Nicoló, 2004; Miret, 2009). It presents key biological factors as low oxygen atmosphere, uniform low temperature and low moisture content, really appropriate for underground grain storage (Dunkel, 1995; Miret, 2009).

Nonetheless, at the beginning of the 20th century, the Valencian silos fell in disuse because of the 1936-39 Spanish Civil War and the introduction of new industrial techniques. Since then, the architectural underground ensemble completely lost its original use and it led to evolutionary deterioration.

The present study shows a comprehensive inventory of subterranean silos for analysing the foremost typological characteristics, materials and methods in the Mediterranean region. For this purpose, the Valencian silos have been taken as an example.

Underground characterisation of cultural heritage sites usually requires a multidisciplinary approach involving historical documentation and a variety of techniques, especially non-destructive techniques for preserving the integrity of the historical structures. Concerning this research purpose, we implemented a combined use of non-destructive techniques with historical archive data to define as much of the Valencian silo-yard features as possible, regarding morphology, dimensions, socio-economic, construction process and hydrogeological site features.

Combination of non-destructive techniques has been widely applied to corroborate historical archive information features (Barilaro et al., 2007; Conyers and Connell, 2007; Pérez et al., 2000; Sutton and Conyers, 2013) and map unmarked subterranean features (Costanzo et al., 2014; Fiedler et al., 2009; Leucci and De Giorgi, 2005; Moropoulou et al., 2005). Laser scanner is currently the quickest and most powerful tool to generate completed 3D models of a variety of subterranean spaces (Abellán et al., 2014; Buchroithner and Gaisecker, 2009; Fanti et al., 2013; Fekete et al., 2010; Lam, 2006; Pejić, 2013). Moreover, it was necessary to find a non-destructive way to rationally focus the subsoil study while ensuring complete covering of the silo-yard. Ground Penetrating Radar (GPR) has long been used as a survey tool in mapping and examining natural underground structures (Alfares et al., 2002; Anchuela et al., 2009; Hausmann and Behm, 2010; Jaw and Hashim, 2013; Pueyo-Anchuela et al., 2009; Słowik, 2013; Yang et al., 2011) or man-made buried structures (Cataldo et al., 2012; Doolittle and Bellantoni, 2010; García et al., 2007; Hansen et al., 2014; Ramírez et al., 2008) due to high resolution imagery, fast data acquisition and cost effectiveness in large areas.

## 2. Material and methods

The majority of large-scale, underground grain storages have been documented thanks to archaeological excavations. Nevertheless, in Europe, a few examples of these subterranean structures still remain with their original architectural conditions, as Silos of Valencia, Spain (Valls, 2014), Il-fosos of Floriana, La Valletta-Malta (Hyde and Daubney, 1960; Dandria, 2010) and Fossae da grano of Cerignola, Italy (Pergola, 2011).

A first stage of the research involved an exhaustive review of historical documentation in the Municipal Historical Archive of Valencia. Several manuscripts, historical maps and images were consulted in order to find information about the construction evolution and the different uses of the underground ensemble. Following this initial phase, GPS, laser scanner and Ground Penetrating Radar (GPR) surveys were carried out in the whole silo complex. There was an urban-scale topographical survey without silo-yard elements, so GPS and laser scanner surveys were carried out for mapping the silo-yard in detail. It helped to georeference silo lids, to measure the silo-yard and to determine silo internal shapes and dimensions. A GPR survey was performed using a GSSI SIR-3000 equipment with 100 MHz and 400 MHz centre-band frequency antennae for modelling the silo-yard subsurface and detecting underground anomalies. Besides, geological layers were analysed in laboratory in order to study their petrologic characteristics and the main lithological shifts that affect the subterranean structure state of conservation.

Likewise, we compared our results with documentation of several underground grain storages around the Mediterranean Sea. This study revealed the existence of quite a lot of similarities between them, concerning location, terrain, shape, sealing system, architectural ensemble elements, etc. (De Nicoló, 2004; Expósito, 2005; Martins et al., 2007; Miret, 2009; Sigaut et al., 1979, 1981, 1985; Vigil-Escalera et al., 2013).

## 3. Architectural assessment of the Valencian silos (Silos of Burjassot)

### 3.1. Typological characteristics

As a result of the GPS and laser scanner surveys, we determined that the Valencian silos comprises a total built area of 6,175 $m^2$ and that it is composed of 3 warehouses, a well, a small church and 41 visible underground grain storages located beneath a 73x70 m square.

However, the historical documentation analysis confirmed that at least 4 more pits were dug. So a GPR survey was performed to detect hidden silo evidences. The GPR study with 100 MHz antenna derived evidences for the existence of 7 more underground granaries. It allowed us to determine the total number of visible plus hidden subterranean granaries (a total of 48 silos) and their location. Each silo position was defined by GPS. Figure 2 shows a detailed map of the Valencian silos, where the visible and hidden silo relative coordinates were well-fixed.

The dimensional and morphological features of inner underground spaces and the tunnelling connection, which was excavated during the Spanish Civil War, have been determined thanks to the laser scanner study (Fig. 3). This 3D modelling let us elaborate a silo-model of the underground grain spaces of Valencia.

Figure 4 shows the dimensions and the architectural elements of a traditional silo in the Valencian subterranean complex. The standard silo morphology is bottle-shaped with a wide chamber and a narrow cylindrical neck at the top. It is 4-8 m in diameter and 5.5-12 m deep, including the neck. Its capacity ranges from 30 $m^3$ to 260 $m^3$. The entrance to the underground space consists of a small-sized circular mouth of 60-70 cm diameter. The neck is a small narrow downward corridor of 0.80-1.00 m deep.

Apparently, the base of the Valencian silos is flat as many other examples of medieval silos previously studied in archaeological excavations (Vigil-Escalera et al., 2013). However, the GPR prospection carried out in this area using a 400 MHz antenna revealed the presence of convex surfaces at about 50 cm depth beneath the current floor level (Fig. 5). So the present base is the result of several levels of compacted soil that have caused a flat surface. The former base might be built in this shape for expelling the damp generated in the underground storage space. This way, drainage was produced around the circular base.

In order to provide a complete hydrogeological characterization, a geotechnical survey was carried out inside silos. Laboratory tests confirmed evidences that landslide in the ground of silos was due to the expansiveness of clays. The test method for one-dimensional swell pressure of a soil in consolidometer (UNE 103602:1996) established 445-705 KPa swell pressure values for the terrain in Burjassot. These soil properties made that rainwater seeping was an inconvenient for wheat preservation and for underground structure stability. For this reason, the whole surface of the esplanade was covered with 15-22 cm-thick flagstones. Besides, the whole enclosure was border on a 90 cm masonry wall. This construction delimited the site and held back the lands where silos were excavated.

3.2. Excavation process: building a silo

The historical documentation confirms that the construction of the Valencian silos started at the end of the 16th century, when the Renaissance was setting up in Valencia. However, medieval techniques and materials were still in use and also medieval crafts –as blacksmiths, stonemasons, carpenters, etc.- were working up to this time. Silos were excavated following traditional medieval construction techniques. Craftsmen had to break up stones in a quarry, transport the materials to the construction site, forge iron instruments, shape lids and ashlars, excavate the cavities for silos or prepare mortars (Baixauli, 2001; Castillo and Martínez, 1999; Municipal Historical Archive of Valencia; Iñúrria, 2005; Valls, 2014).

Many authors have described excavation work to build underground granaries (Sigaut et al., 1979, 1981, 1985; Vigil-Escalera et al., 2013). In this case, the data obtained in the study implemented in the Valencian silos let us define a nine-step excavation process for a silo construction, as shown in Figure 6. As stated above, silo excavation was made using traditional medieval techniques and tools. Auxiliary implements as plumbs and compasses were also employed (Bessac, 1980; Miret, 2009).

In this process, the first step consisted in choosing the optimum terrain-location. Our geological and geotechnical studies demonstrated that the ground in the Valencian silos is a clayey soil with intercalations of limestone crust substrates (Valls, 2014). Many authors agree that this is the most appropriate ground for this purpose (Benítez et al., 2004; De Nicoló, 2004; Iarussi, 1986; Miret, 2009; Pergola et al., 2001). Laboratory tests corroborated that this type of ground is consistent and easy to excavate. It also was proved that it has the suitable hydrothermal conditions for optimum wheat preservation (Blanes, 1987; Miret, 2009).

Once the site was selected, the mouth was opened and the neck was built by using bricks in order to reinforce this area. Silo neck building work was one of the most solid tasks. By analysing the inner space of the silos, walls and vaults are only covered with lime mortar. However, the area next to the entrance is reinforced with a cylindrical frame built with bricks. This frame has been proved to have a twofold function: structural and hydrothermal. It served as the basis for supporting the limestone closure items (limestone lid and curb). Besides, it was absorbent enough to drain the vegetal moisture of the wheat (Iarussi, 1986).

The subterranean grain storage was hollowed out on the ground with a bottle-shaped section. As shown in Figure 6, silos were dug in several phases. Inner surfaces (vaults and walls) were covered with mortar as depth increased. The lining material used in these silos is a 1.5-2 cm-thick lime mortar. It was set for waterproofing the storage space and allowing moist grain absorption (Iarussi, 1986; Miret, 2009).

However, the historical documentation confirmed that consolidation work was made during the 18$^{th}$ and the 19$^{th}$ centuries. So a GPR survey was carried out to locate the reinforced areas in the underground structures. The GPR study with 400 MHz antenna detected evidences of bricks and holding mortar under the lime mortar surface of the walls, as shown in Figure 7.

The opening was covered with a hemispheric lid that protected the internal space and expelled rainwater. The standard model of the covering system of our research is shown in Figure 8. However, different lid shape solutions have been found in other Mediterranean underground grain storage, as circular and flat stone lids or mounds of soil over wooden slats (Dandria, 2010; De Nicoló, 2004; Hyde and Daubney, 1960; Iarussi, 1986; Miret, 2009; Pergola et al., 2001).

Lastly, the silos were sealed with an oil-based bitumen joint between the lid and the curb. This joint was protected from the outside with a gypsum mortar sealing cordon. Figure 8 shows the general construction details of a standard model covering system.

## 4. Comparative study of Mediterranean silos

Selected Mediterranean silos have been studied by different authors (Ayoub, 1985; Dandria, 2010; De Nicoló, 2004; Hyde and Daubney, 1960; Iarussi, 1986; Miret, 2009; Pergola et al., 2001; Peters, 1979; Vignet-Zunz, 1979). So we were able to compare the Valencian silo example with the most representative underground granaries in the Mediterranean region (Fig. 9). As a result, we have found out that the Mediterranean silos share quite a lot of typological, geological and structural characteristics between them.

The main Mediterranean underground grain storage features are summarized in the issues below:

i. <u>Hydrogeological features:</u>

   The Mediterranean silos were excavated in high lands (as hills or mountains) for avoiding phreatic stratum and rainwater accumulation.

   Geological studies concerning the Mediterranean silos reach the same conclusion: subterranean granaries were excavated in a clay terrain with intercalations of limestone. The clay terrain is absorbent enough to regulate the soil damp and therefore, to assure the preservation of grain inside silos. Moreover, limestone upper substrate acts as a waterproof layer. Nevertheless, some pits were exclusively dug either in clay (e.g. Altinova and Ouarsenis) or in limestone (e.g. Floriana).

   Owing to clay absorbency and limestone waterproofing, most of the Mediterranean silos have flat bottoms. However, the Valencian silos were provided with a drainage system in the base consisting in a convex surface. Alternative drainage systems were built in the Maltese fossae. The Florian silo base is composed of a beaten earth layer over a drilled floor, below which is a drainage pit (Dandria, 2010; Hyde and Daubney, 1960). In this case, drainage pits were necessary since granaries were excavated in a porous marine limestone soil (globigerina limestone rock) (Rothert et al., 2007). Other resources were used in the underground granaries located in Gozo Citadel and Hartha. In these examples, the drainage technique consisted of a concave silo bottom.

ii. <u>Typological and structural features:</u>

   The whole Mediterranean silos were made by excavation, using traditional techniques and tools, and employing auxiliary implements as plumbs and compasses. However, in some cases, it was necessary to reinforce the curved structure with construction materials as bricks or ashlars. This structural reinforcement could have covered the total surface of vaults and walls (e.g. Rimini, Cerignola or Gozo Citadel) or just been localized in a specific unstable area (e.g. Valencia).

Inner surfaces of silos (walls and vaults) were usually covered with lime mortar. This lining material absorbed the damp generated in the underground storage space, expelled the clay moisture and also made ensilage work easier. When inner surfaces were waterproofing enough any wainscot was used, but a bottom drainage system was required for collecting the water generated inside the subterranean chamber.

Regarding morphological aspects, the bottled or belled shapes are the most common form among the silos excavated around the Mediterranean Sea. These kinds of shapes could contain large amounts of cereals and only a small percentage of it was in contact with the inner surfaces, which were the feeblest points due to the vicinity of natural terrain.

Besides, the whole Mediterranean silos have circular-shaped mouths. Mouth diameters range from 0.60 to 1.00 m, so they were wide enough to allow a person pass through.

Underground grain storage required the use of a sealing system over the mouth of silos. All around the Mediterranean Sea, subterranean granaries were closed up in order to expel rainwater. A mound of soil over straw or wooden slats was a sealing system that was profusely employed. However, silos were also closed with limestone flat or hemispheric lids on the top.

Beside silo mouths some identification elements were used to distinguish one silo from another. The recognition signs varied from stone posts (e.g. Foggia, Cerignola and Rimini) to identification marks over the lids or curbs (e.g. Valencia and Floriana).

iii. Socio-economic and geographic features:

The underground granaries were located close to main population consumption areas (as cities or villages), important trading ports or routes for an easy supplying (e.g. Valencia, Rimini and Hartha). They were usually hollowed out in a delimitated area forming a silo-yard. It could be demarcated or even protected with walls (e.g. Valencia and Gozo Citadel). Occasionally, silos were scattered inside the houses, along the streets or around the village (e.g. Rimini and Hartha).

City population supplying required the excavation of a high number of silos (approx. 50-150). This amount of underground granaries guaranteed the survival of citizenry. Nonetheless, vast quantity of silos (approx. 400-800) not only was thought for people provision but also for trade. An exception might be the 400 silos located in Ouarsenis (Algeria), which belonged to a tribe.

Moreover, we may take into consideration the dimensions of silos. Most of the Mediterranean granaries have large sizes, especially when they are close to cities or villages. However, when subterranean silos were related to tribes or small hamlets, they were small-sized silos (e.g. Altinova and Ouarsenis).

iv. Usage features:

The Mediterranean silos had two uses. They could have a public use for city supplying and for particular or civic trade; either they could be used by individuals. Occasionally, the limit between public and private practice was not so explicit.

The underground grain storages in the Mediterranean region were commonly under public management. Silos could be run exclusively by the local government (e.g. Valencia) either could be rented for individuals under public administration (e.g. Foggia and Cerignola). Scattered subterranean granaries were associated to private usage, so each family could have one or two silos for own-use and consumption (e.g. Rimini).

As a result, Table 1 illustrates the main characteristics of the most representative examples of the Mediterranean silos regarding their morphology, capacity and their silo-yard extent.

## 5. Conclusion

In this research, we have integrated historical documentation studies with a non-destructive technique (GPR), laser scanner and GPS surveys and geotechnical tests. The archive documentation was useful in providing historical data but, in most cases, there was with lack of detailed information and confusing findings. The laser scanner has shown itself to be a useful and effective tool in defining the morphology of these subterranean granaries with 3D modelling. This technique offered high geometric accuracy and permitted calculating the volume of silos. The GPS survey allowed us to obtain exact relative coordinates and establish accurate GPS positioning in order to find the connection between the hidden and the visible zones of the silo-yard. Moreover, the GPR technique enabled us to find unknown buried features, establish the exact number of silos that were excavated in the silo-yard and define the internal silo structure. The geotechnical tests provided helpful information on hydrogeological features of the ground for understanding the reason why this place was chosen for the construction of the silo-yard. As a result, we have established the geological and underground building features of the Valencian silos.

Silos are a valuable source of information to learn about the cereal conservation techniques that have been present in the Mediterranean culture. This study allowed us to compare the Valencian typology with other subterranean granaries in the Mediterranean region. We found out that they all share numerous features.

The whole Mediterranean granaries were made by using traditional excavation techniques. They were usually dug in a consistent clayey soil with intercalations of limestone. The Mediterranean grain storages were situated in high lands due to hydrogeological features. They were close to main cities and important trading ports or routes. Generally they had a public use and were managed by civic administration, although silo private usage was also widespread. They were ordinarily used for citizenry consumption and for cereal trade. The standard morphology consisted in a bottle or bell-shaped pit with a wide chamber and a narrow cylindrical neck at the top of the cavity. The subterranean granaries were closed up on the top for solving waterproof requirements. And they sometimes had recognition marks for the identification of each silo.

Owing to the high number of coincidences among the underground Mediterranean granaries, we have come to the conclusion that the silo construction methodology was very similar in the Mediterranean region.

Despite the ethnographical value of these underground granaries for the Mediterranean culture, they have lost the original use and threaten to disappear. The industrialization of grain conservation process, with silos over the surface, made these underground spaces fall into disuse. So, most of them are currently in an advanced state of deterioration or part of them had even been demolished.

As seen above, the combined use of new technologies with historical documentation is a particularly effective methodology for studying subterranean silos in the Mediterranean region and launching new research lines:

- structural analysis of the underground entities for future structural restoring or consolidation,
- thorough study of waterproof and drainage systems,
- comprehensive comparative research on silo construction process and their socio-economic usage,
- 3D modelling of the underground spaces for providing virtual tourism and visualizing scenes from impossible viewpoints in the real world.

We conclude that restoration, museum adaptation or declaration as Site of Cultural Interest could be a way to enhance this kind of underground architecture, as it has already been done in cultural sites. An alternative strategy for guaranteeing the preservation and revalorization of this subterranean heritage could be to create an underground grain storage Mediterranean network association for scientific documentation exchange and development of rehabilitation programs to raise public awareness and provide public education. Tourism and cultural activities in these underground spaces would help to preserve them and to understand the huge meaning of this subterranean heritage in the Mediterranean region.

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Figure 1. General view of the Valencian underground architectural complex: Silos of Burjassot.

Figure 2. Detailed map of the Valencian Silos. It shows the 48 silo location: 41 visible and 7 hidden silos (the last ones were detected by the GPR survey); and building elements: 1- Main entrance (16th c.), 2- Chapel, 3- Warehouses, 4- Well, 5- Greek cross sculpture, 6- Yard, 7- Secondary entrance (19th c.), 8- Wall.

Figure 3. A view of the Valencian Silos with the representation of six underground spaces (1, 2, 6 and 7) made by using laser scanner technique. The 3D laser scanner modelling represents the inner space of six accessible silos and their projection on the silo-yard surface.

Figure 4. The Valencian silo model with the main dimensions and the description of the elements.

Figure 5. (a) Radargram of the profile P2 (400 MHz antenna) that shows the basement of the silos 6, 7 and 2. (b) Sections of the silos 6, 7 and 2 with the overlap of the radargram (P2) obtained by the GPR survey. Present flat base level and former convex surface are identified.

Figure 6. Model of a silo construction process derived from this study.

Figure 7. a) Interior images of the silos. 1- Silo 41. 2- Silo 7. 3- Silo 6. b) Radargram of the profile P65 (400 MHz antenna) that shows the wall of the silo 1.

Figure 8. Front view and cross section of the lid sealing system derived from this study of the Valencian silos.

Figure 9. Location of the main large-scale underground Mediterranean silos which have been compared in this study.

Table 1. Characteristics of the most representative underground granary examples in the Mediterranean region.

## Graphical Abstract

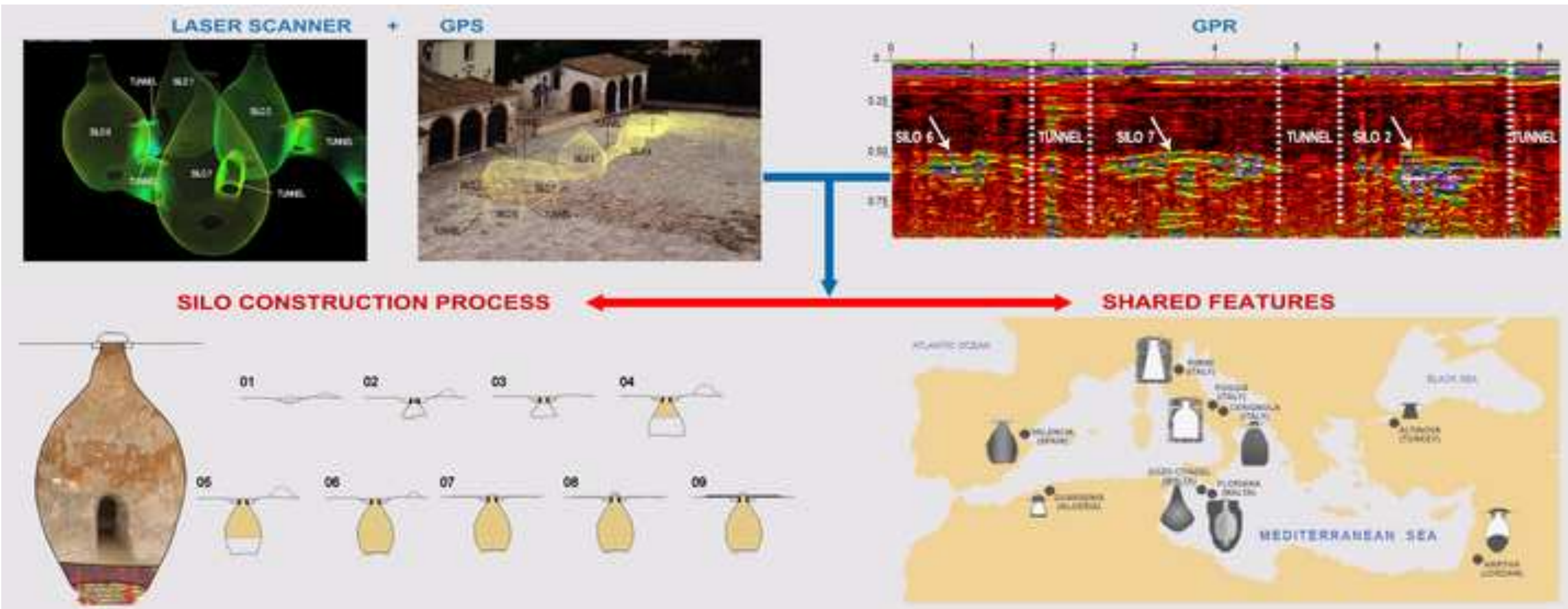

Figure 1
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Figure 2
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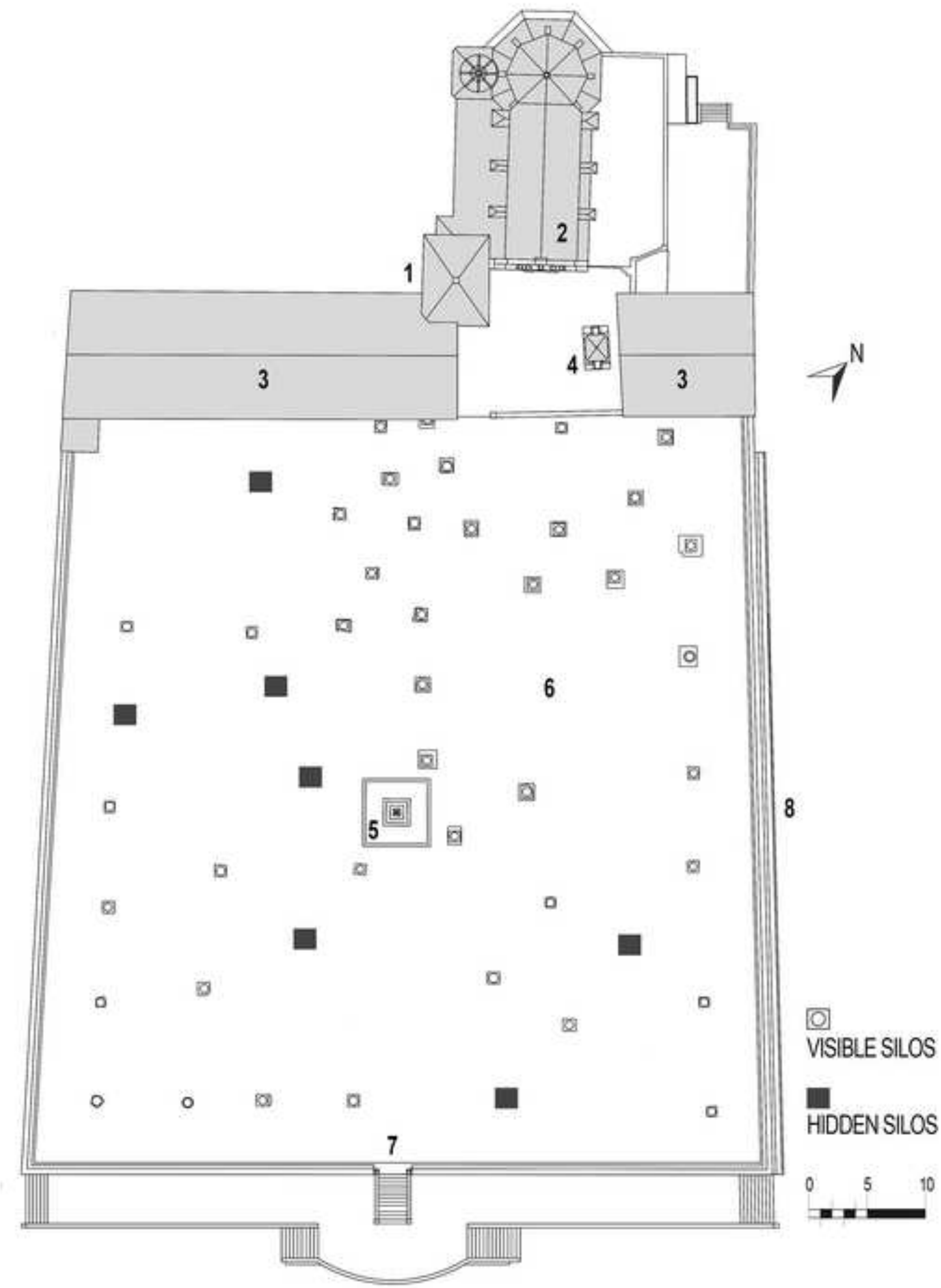

Figure 3

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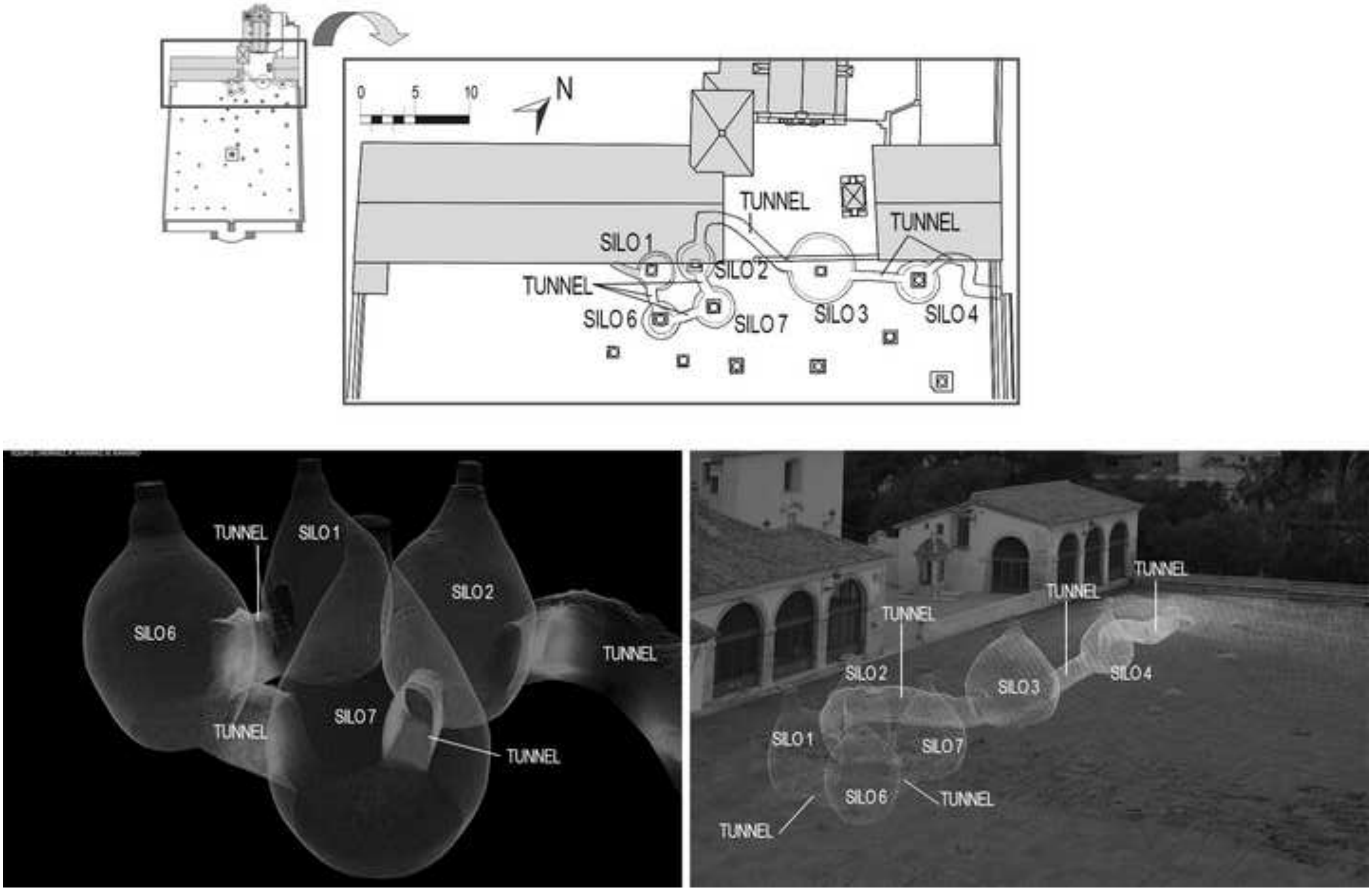

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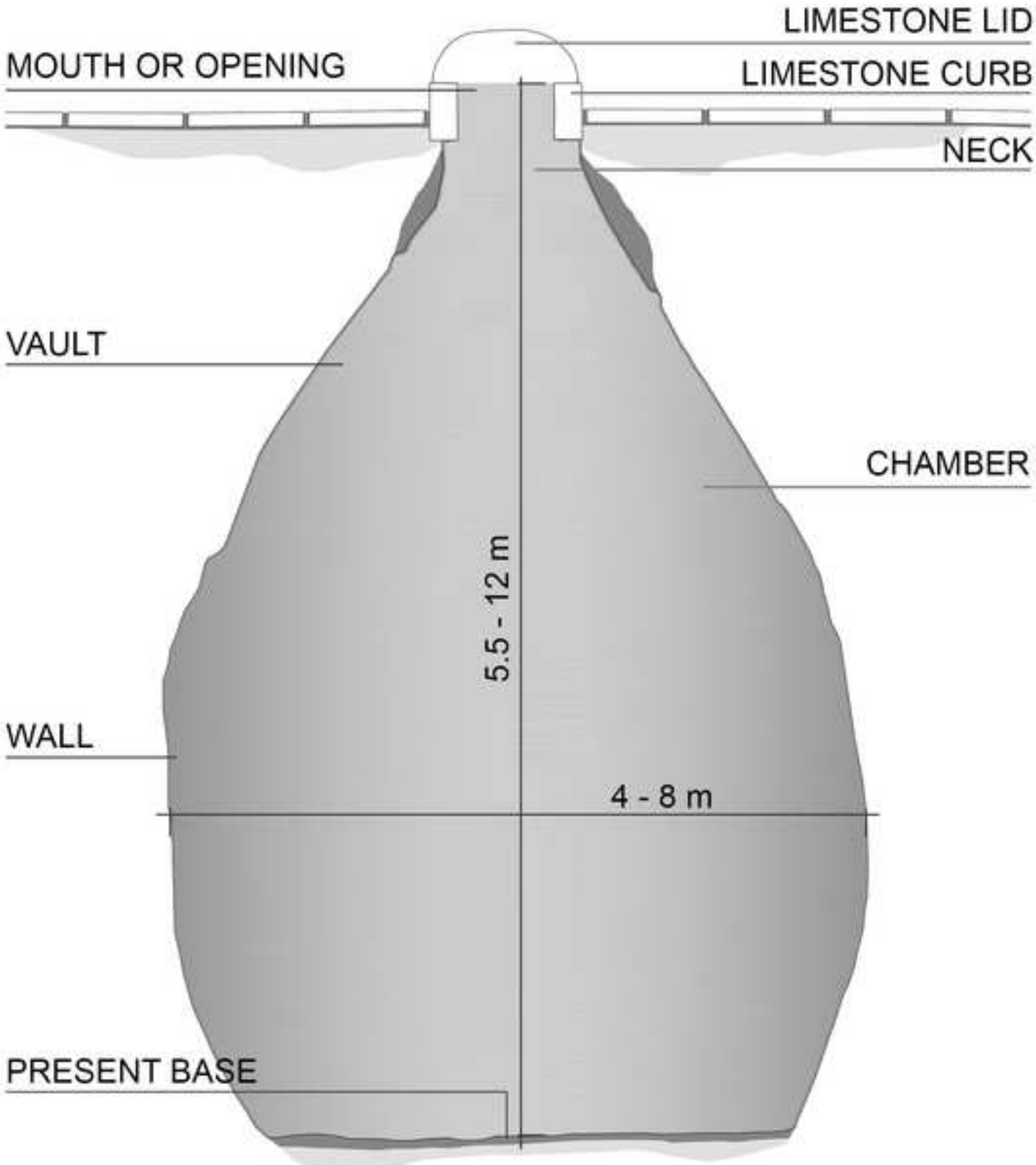

Figure 5

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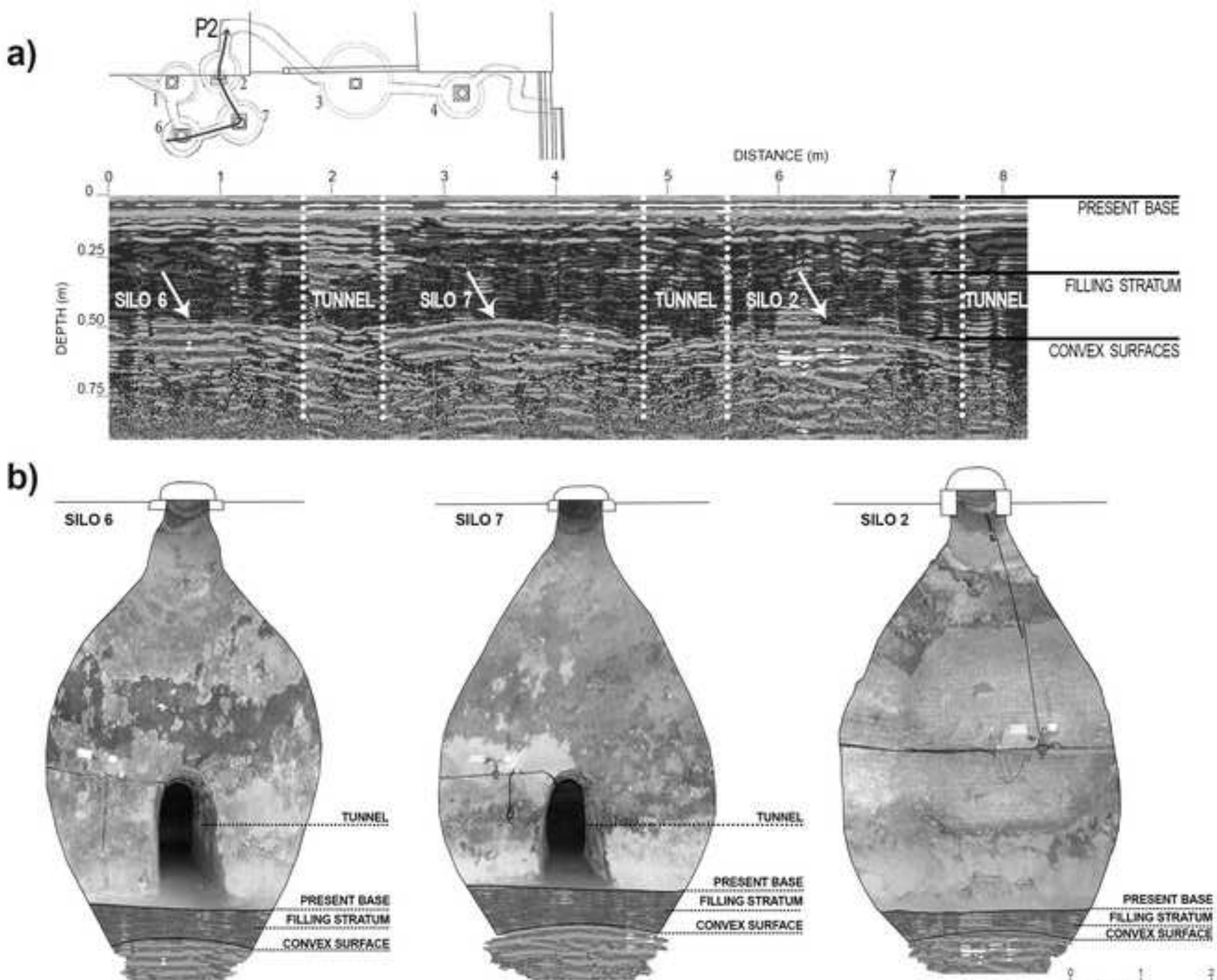

Figure 6
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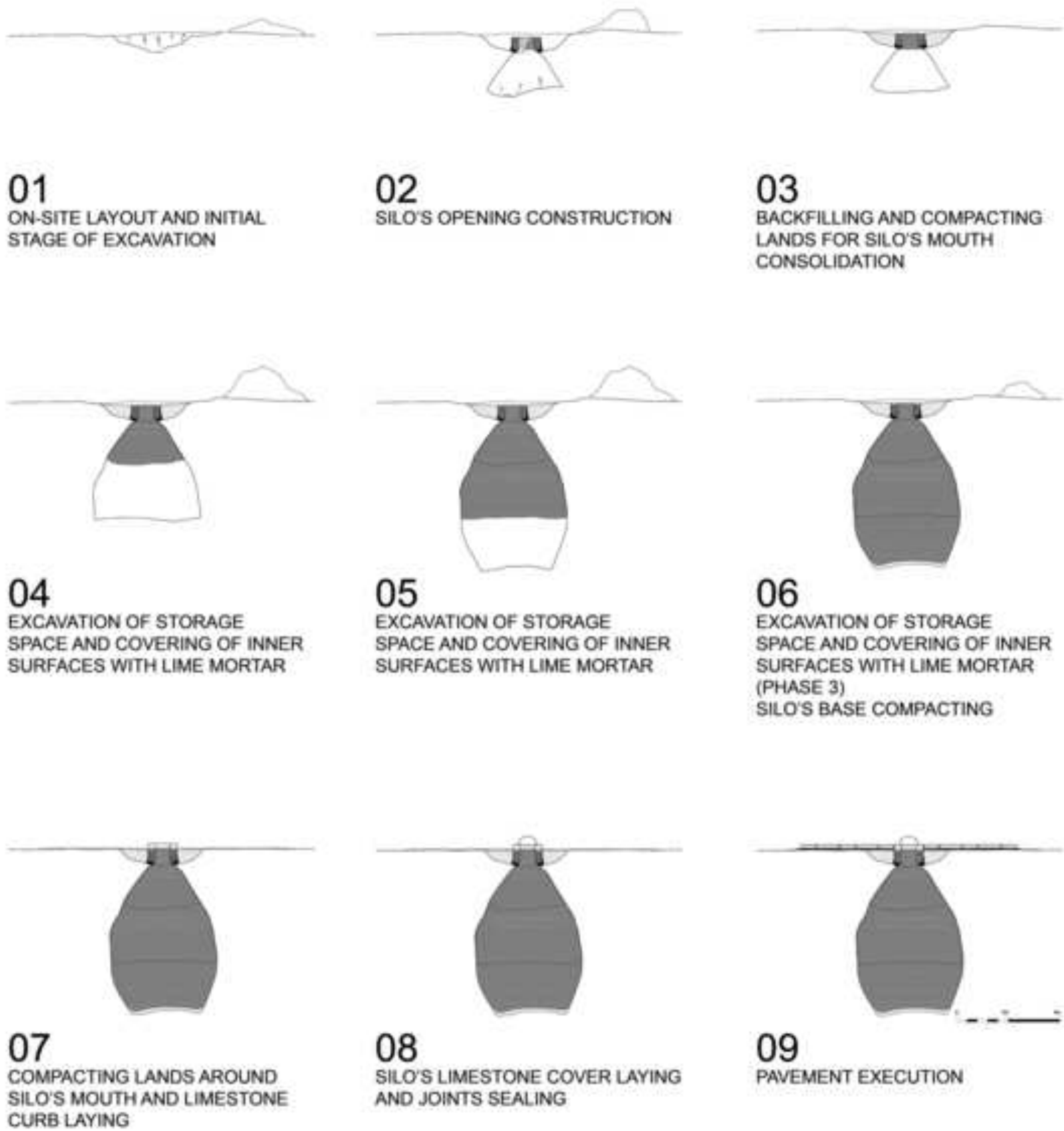

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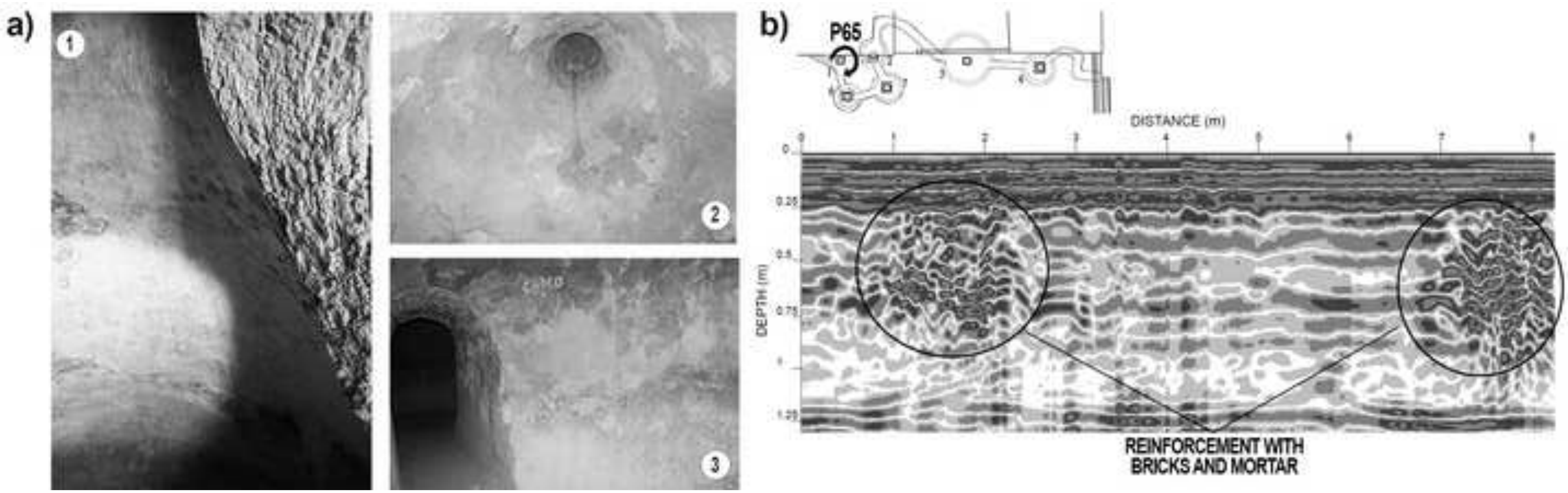

Figure 8
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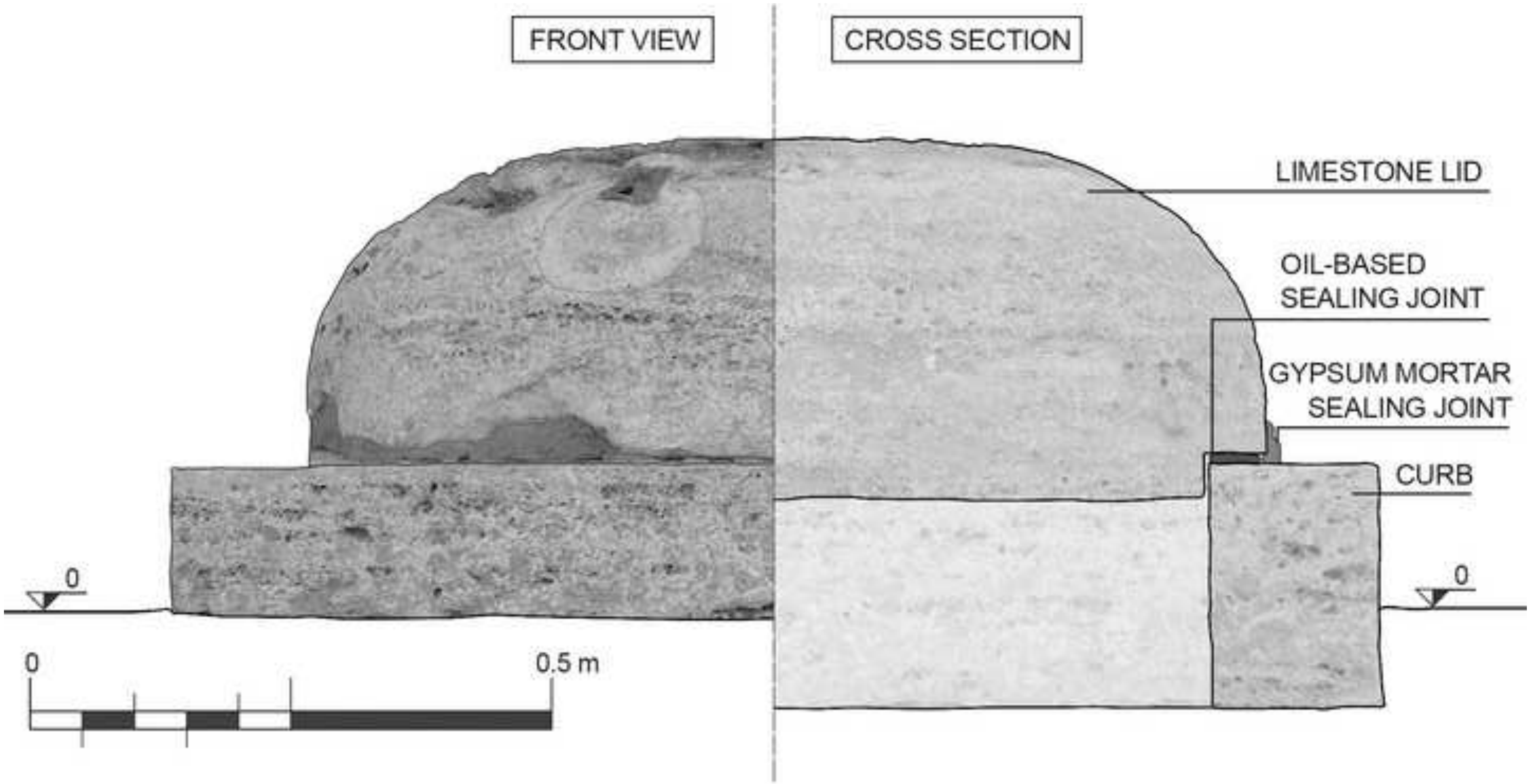

Figure 9

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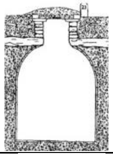
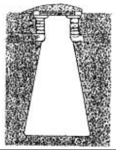
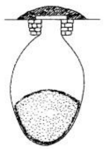
**Table 1**

| LOCATION | MORPHOLOGY | DIMENSIONS (m) | | SOIL | INNER LINING MATERIAL | COVERING ELEMENTS | NUMBER OF SILOS | EXTENSION | |
|---|---|---|---|---|---|---|---|---|---|
| | | Height | Diameter | | | | | Scattered | Gathered |
| BURJASSOT, VALENCIA (SPAIN) |  Bottle-shaped | 5,5 - 12 | 4 - 8 | Clay with limestone crust substrates | Lime mortar | Hemispherical limestone lid | 41 | | X |
| FOGGIA (ITALY) |  Bell or bottle-shaped | 6 - 10 | 4 - 6 | Clay with limestone crust substrates | Lime mortar | A mound of soil over wooden slats | 880 (Demolished) | | X |
| CERIGNOLA (ITALY) |  Bell or bottle-shaped | 4 - 7 | 4 - 8 | Clay with limestone crust substrates | Lime mortar | A mound of soil over wooden slats | 625 | | X |
| RIMINI (ITALY) |  Bell or truncated cone-shaped | 13 - 15 | 8 - 10 | Alluvial soils composed of clayey loams | Lime mortar | A mound of soil over wooden slats | 128 | X | |
| FLORIANA (MALTA) |  Flask or bottle-shaped | 9 | 4,5 | Globigerina limestone rock | None | Circular or square flat lids | 76 | | X |
| GOZO CITADEL (MALTA) |  Flask or bottle-shaped | 8 - 11 | 5 – 7,5 | Globigerina limestone rock and blue clay | Lime mortar | Circular or square flat lids | 3 | | X |
| HARTHA (JORDAN) |  Oval-shaped | 6 - 7 | 4 - 5 | Limestone and marls | None | A mound of soil and a layer of straw over a flat stone | 18 | X | X |
| ALTINOVA (TURKEY) |  Truncated cone or cylindrical-shaped | 1 – 1,5 | 1 approx. | Clay soil | Lime or gypsum mortar | A mound of clayey soil with cut straw | (Unknown) | | X |
| OUARSENIS (ALGERIA) |  Bell or truncated cone-shaped | 2,5 approx. | 1,5 approx. | Clay soil | Lime mortar | A mound of soil over straw | 400 | X | X |