PROBLEMS OF ROOFING OF EARLY MINOAN THOLOS TOMBS: THE CASE OF KAMILARI A THOLOS TOMB IN THE WESTERN MESARA PLAIN*

Introduction

The Minoan tholos tomb (known also as the Mesara-type tomb)[1] is a stone-built circular structure, widespread in the Mesara plain during the Early Minoan period, with some re-use during the Middle Minoan and Late Minoan periods. These circular structures, not covered by soil and therefore visible above ground, usually had a small entrance on the east side; annex rooms were at some point added mostly on the east side, together with other structures, such as rectangular funerary buildings, *peribolos*-walls, paved area, altars and platforms. Archaeological excavations have shown that Minoan tholos tombs have been found isolated or clustered in groups. They have been used over several centuries, for multiple burials, with primary and secondary burial practices attested within the main chambers and the external rooms.

Although a number of these circular buildings show traces of a corbelled roof, the argument of a stone vault has been discussed by various scholars in the past years often with open or not unanimous conclusions[2]. Aside from the scholars who deny the existence of any vault, those who have argued for a vaulted roof have suggested several solutions (stones or lighter and perishable materials, such as mud bricks or wood), each of them supported by defined arguments, but each interpretation has always avoided the discussion of a possible true vault, since its first appearance must be placed in the Mycenaean period.

The present article will try to explore once again the question of the vaulted roof by examining the case of Kamilari A Minoan tholos tomb. Thanks to the good state of conservation of the walls, preserved at a significant height in some parts, the following analysis will try to verify whether the tholos tomb had a vaulted roof or not, and to argue about possible reasons for its collapse. The following analysis does not aim to extend the hypothesis of roof profiles to all Minoan tholos tombs, especially if one bears in mind the peculiar state of preservation of Kamilari tholos A as well as the fact that it was one of the latest buildings of this type to be constructed at the beginning of II millennium BC.

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[1] Goodison - Guarita 2005.

[2] For a good summary see Treuil 1983, pp. 435-440; Belli 1984, pp. 120-122 and Warren 2007.

The article is divided in two sections. The first part is devoted to the presentation of the problem of roofing of Minoan tholos tombs through archaeological and ethnographical examples. The second part deals with the discussion of the false and the true vault systems and the analysis of possible roof profiles and collapse mechanisms of the vault.

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The vaulted roof problem: the archaeological research

None of the numerous Minoan tholos tombs has been found with a complete vault[3]. Although many examples provide information about the architectural structure, the poor preservation of their walls and their reduced height often provide little evidence about the roof. It has also been claimed that in those cases where a mass of fallen stones over the burial level has survived, the amount of stones would have never been sufficient to constitute an entire vault[4].

The only technical study of the structural mechanism, among other things dedicated to the Mycenaean tholoi, concluded that the Minoan tholos tombs were not domed in stone[5]. Two scholars considered crucial for their analysis of the absence of a covering earthen mound together with the thickness of the external wall argue that, in the absence of an earthen mound, the ratio of the thickness of the wall to the radius of the tomb must be 0.53[6].

Regarding the Minoan tholoi, researchers have proposed three ways of roofing: corbelling with stones, a flat roof of perishable material and without vaulted, and corbelling with mud bricks. Such a variety of suggestions should not surprise: already in 1976 O. Pelon could affirm that «*la diversité des hypotheses traduit bien la caractère ambigu des données archéologiques disponibles*»[7].

As regards the first hypothesis, S. Xanthoudides was the first who favoured a stone vault[8]. Afterwards, many others considered a variety of aspects and conditions, such as the amount of stones fallen inside the tomb and the slightly in-sloping cylindrical lower section[9]. Particularly, the excavations of Kamilari[10], Myrsini[11] and Archanes Tholos[12] C have progressively shown the existence of monuments showing a full stone vault.

The second hypothesis did not find many proponents and was followed by a general rejection of a stone vault in contraposition with the Mycenaean tholos tombs. R. Seager was the first to think about the Minoan tholos tombs as open air circular structures in juxtaposition to the LM III tombs of a Mycenaean inspiration[13]. This is the interpretative line followed by many other scholars (A. Wace, J. Pendlebury) who have variously expressed the opinion that the Minoan tholos tombs exhibit less careful execution and more primitive features compared to the Mycenaean ones[14].

[3] For a recent catalogues of the tombs see Panagiotopoulos 2002, pp. 164-168; Goodison-Guarita 2005.

[4] That is for instance also the case of Kamilari A: Belli 1984, p. 122. See also Branigan 1970, p. 39.

[5] Cavanagh-Laxton 1981, pp. 131-132.

[6] Cavanagh-Laxton 1981, p. 127, table 3.

[7] Pelon 1976, p. 57.

[8] Xanthoudides 1924, pp. 70 and 91.

[9] Paribeni 1904; Evans 1921, p. 70; Alexiou 1960; 1960-61; Levi 1961-62, p. 11.

[10] Levi 1961-62.

[11] Platon 1959, p. 373.

[12] Sakellarakis 1972; Papadatos 2005.

[13] Seager 1907, p. 131.

[14] Wace 1931; Pendlebury 1939, pp. 64-65.

Differently, E. Stefani, as regards Ayia Triada Tholos A, accepts the existence of a full vault only admitting a wooden framework sustaining it from inside[15]. G. Karo considered a full stone vault only for the later monuments, where he accepts a full vault made of stone and light material, such as clay[16]. Sp. Marinatos accepted a stone vault for the Krasi and Vorou B tholos tombs, but otherwise he suggested a roof composed by wooden beams, branches and earth[17]. Similarly, K. Branigan has suggested for the earlier tombs a light roof made of horizontal timber beams below a stone layer that could have been easily removed when the internal chamber needed periodically to be fumigated[18]. He has also interpreted the projecting slabs on the external wall as scales to reach the top of the tomb and to facilitate the removal of the roof. However, he also admits that later tombs, such as Kamilari and others of MM I, could have been fully vaulted in stone[19]. Following this, P. Warren expressed the opinion that the vault, as it was described by Branigan, needed a wooden pillar to be sustained[20]. Nevertheless, the study by K. Branigan is quite remarkable for having been the first comprehensive study of the evidence after several decades and before the work by O. Pelon. The British scholar also firstly pointed out the need to look for archaeological evidence in support of the vault hypothesis, described in four points: a collapsed vault, a corbelled superstructure, the thickness and height of the stone walls, and the external support for the walls[21].

As far as the third hypothesis is concerned, the first scholar to suggest a vault made of lighter material and specifically mud bricks was G. Glotz[22]. Similarly, S. Hood, after a long analysis concluded that only the smaller tholos tombs were completely vaulted in stone, whereas the larger ones were built with mud or mud-brick domes on stone foundation[23]. Clearly, the third hypothesis functions as a solution in between, influencing a group of scholars who have admitted the possibility of the existence of several solutions. O. Pelon, for instance, accepts the idea that tombs up to 6 metres in diameter were vaulted in stone, whereas tombs above 6 metres of diameter – such as Kamilari A – had a conical framework of timber to support an outer layering of stone[24]. Similarly, P. Belli, though admitting the incomplete character of the archaeological documentation, considers the case of tholos tombs A and B at Platanos and concludes that the first tombs might have had a vault made of mud-bricks, while a mass of fallen stones inside tholos B was not sufficient to support a complete stone vault[25]. Following this argument, Belli considers also at Kamilari tholos A an insufficient volume of stones to guarantee a full vault[26].

More recently, Pelon in a new revision calculates the *indice d'instabilité* on 61 cases and concludes that two techniques of construction did develop contemporarily as early as EM I on Crete: one with a full stone vault (for the tombs of type I and II) and the other with a vault made of mud-bricks (for the tombs of type III)[27].

LUCA GIRELLA

[15] STEFANI 1930-31, p. 150.
[16] KARO 1922, col. 1750.
[17] MARINATOS 1929, pp. 136-137; MARINATOS 1930-31, p. 168.
[18] BRANIGAN 1970, pp. 28-55.
[19] BRANIGAN 1970, pp. 28-55.
[20] WARREN 1972, p. 240.
[21] BRANIGAN 1970, p. 38.
[22] GLOTZ 1952, p. 157. But also DESHAYES 1969, pp. 620-621; TREUIL 1983, pp. 435-440.
[23] HOOD 1960. Among the Italian ones BELLI 1984, pp. 121-122. See *infra*.
[24] PELON 1976, pp. 55-63.
[25] BELLI 1984, pp. 121-122.
[26] BELLI 1984, p. 122.
[27] PELON 2004, p. 183. For the explanation of the three types distinguished, *ibidem*, pp. 174-175.

The vaulted roof problem: the cases of Lebena and Archanes Tholos C

A significant contribution to the issue of the vaulted roof has been provided by two important case studies: tholos II at Lebena/Gerokampos and Tholos C at Archanes/Phourni.

Already in 1960 St. Alexiou had declared the opinion that tholos II at Gerokampos was fully vaulted in stone[28]. According to the Greek scholar, the other two tombs (IB and III) were also vaulted in stone, based on the preserved height of their walls[29]. More recently, P. Warren has commented upon the final publication of the Lebena cemetery[30] and has come back to the issue of a stone roof for tholos tomb II. In particular, he argues that «*Lebena Tomb II, like Kamilari Tomb I, makes what appears to be a decisive contribution to understanding the construction techniques of the roofing of Early-Middle Minoan round tombs, with its stone corbelled vault*»[31]. Decisive for such an interpretation was the discovery that parts of the fallen stone vault were preserved during the excavation «*like a row of inclined books*»[32] (*fig. 1*). Moreover, the careful excavation report seems to demonstrate the existence of a previous original vault (likely dated to EM I, the period of its construction) collapsed on the floor but left in situ, with burial inhumations located near and on top of it[33].

Tholos C at Archanes/Phourni was built directly on the rock in EM IIA. Two burial phases have been distinguished: in the first phase burials were deposited directly on the floor, whereas after an EM IIB gap, in EM III and MM IA burial containers (*larnakes* and 1 *pithos*) were introduced. Other burial buildings (namely 9 and 5) added in EM III or MM IA functioned as buttresses. During MM IB and MM II tholos C is no longer in use, while Building 9, erected in front of Tomb C, blocks its entrance. Finally, the tomb collapsed in MM IIB-IIIA, likely during a large earthquake which destroyed a large part of the cemetery. The tholos has well preserved walls that reach the height of 2 and 2,20 m; its diameter is of 3,5 m. Architectural considerations have clarified that the tholos had a fully corbelled stone roof[34], as already hypothesised by its excavator, Y. Sakellarakis[35]. In particular, the evidence that reinforces such an hypothesis is the following: (1) the preserved height of the wall[36], (2) the overhanging of the stones in the upper part of the wall (the calculated corbelled overhang is of 0,40 m which gives to the tomb diameter a reduction from 3,5 m at the base to 3 m at the highest point), (3) the difference in the stone used in the wall construction (large and irregular in the lower part, while they are smaller and flat on the upper part where they are placed with a slight overhang)[37], (4) the identification of these smaller and flat stones fallen inside the tomb, in the upper part of the soil fill[38] (*fig. 2*).

A recent study by C. Papadopoulos based on the virtual reconstruction of the Phourni cemetery at Archanes has offered new insights on the history of tholos C[39].Virtual representations are here used as an alternative way of documenting the excavated strata and facilitating a three dimensional perception of the buildings. The purpose is not «*to create the exact representations of the ancient structures, as the available evidence does not contribute to such*

[28] Alexiou 1960, p. 226.
[29] Platon-Davaras 1960, pp. 509 (Tomb III) and 510 (Tomb Ib).
[30] Alexiou-Warren 2004.
[31] Warren 2007, p. 14.
[32] Alexiou-Warren 2004, p. 15, pls. 26-27; Warren 2007, p. 10, figs. 2.3-5.
[33] Alexiou-Warren 2004, p. 15, pl. 27C; Warren 2007, p. 10, fig. 2.6.
[34] Papadatos 2005, p. 6.
[35] Sakellarkis 1972.
[36] Papadatos 2005, p. 6.
[37] Papadatos 2005, p. 6, fig. 3A, pls. 1B, 2-3.
[38] Papadatos 2005, 6, pls. 4B, 5A, 6A.
[39] Papadopoulos 2010.

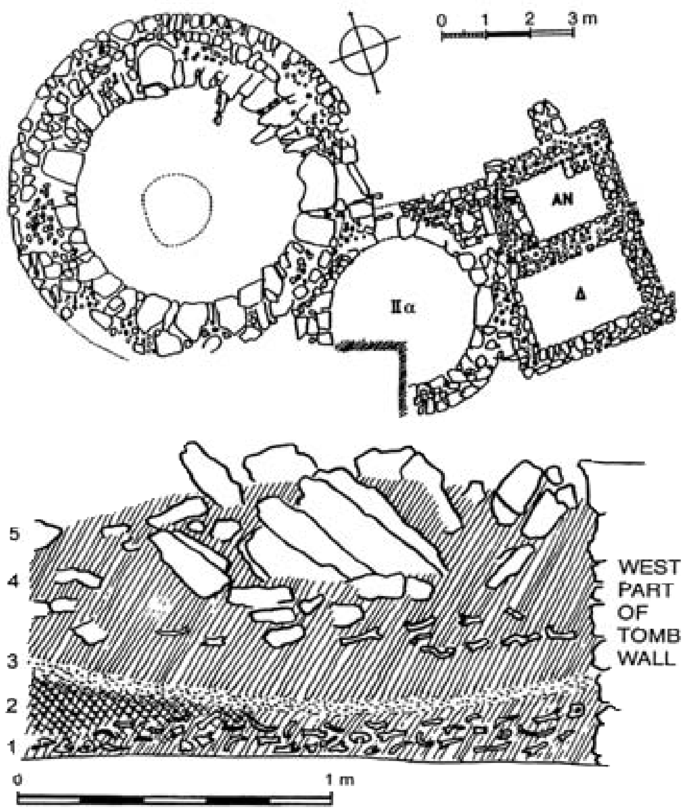

Fig. 1 – Lebena: plan of Gerokampos tholos tombs II and IIa and the section viewed from the north with on top (num-ber 5) the fallen vault stones from tomb IIa (after Alexiou-Warren 2004).

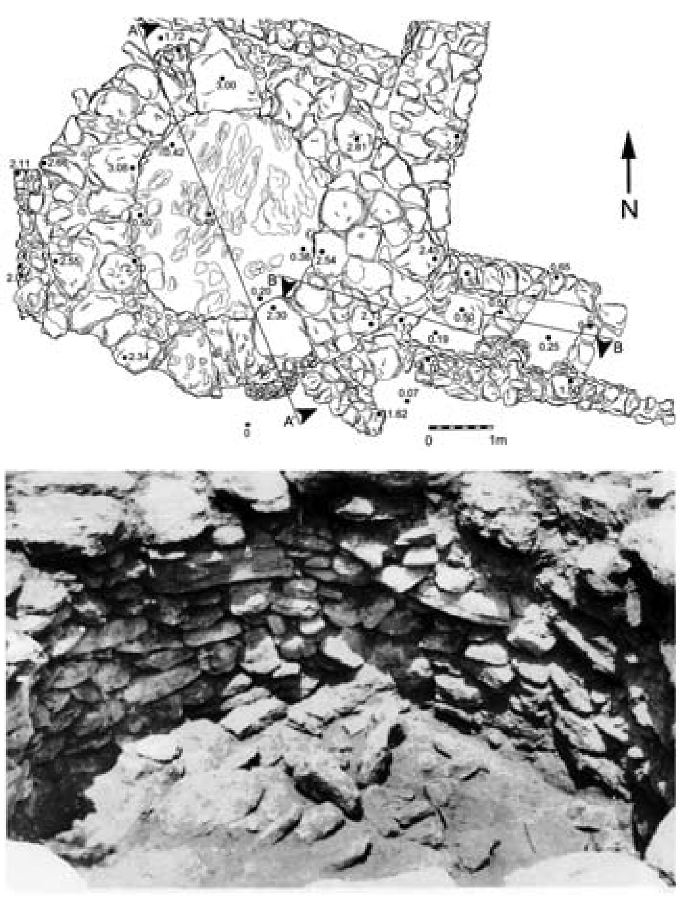

Fig. 2 – Archanes/Phourni Tholos C: general plan of the tomb and view of the interior with the stones from the collapsed roof (after Papadatos 2005).

an approach, but to give the observer a sense of ancient structures»[40]. Quite inspiring in this work is the approximate illumination study produced in order to observe the perceptual differences and the practical role of natural and flame illumination[41]. As regards tholos C, the scholar indeed explores the possibility that only during the second phase (EM III - MM IA) the tholos was fully vaulted in stone, whereas in the first one (EM IIA) he suggests the existence of a light roof made of perishable material[42].

Although the scholar is aware of the 'hard' evidence for a vault made of stone, he has decided to create alternative versions as well, «*in order not only to observe the visual impact, but the difference in the illumination of the interior as well, if any, based mainly on the fact that inadequate evidence from the preserved structures make researchers propose alternative methods for the roofing of these constructions*»[43]. The possibility of a roof not made by stone is assumed for the first phase of the tholos tomb when burials were placed directly on the ground. This aspect would speak in favour of the existence of wooden pillars inside (to sustain the roof system made of other material) and the introduction of the burials from the roof (with the periodical opening of the roof). The two alternative reconstructions therefore are: (*i*) a rectangular roof made of wooden beams and pressed earth[44]; (*ii*) an entire earth structure with layers of stones set in mud around the edge of the wall head, a hypothesis based on the parallels from Lemba Lakkous during the Chalcolithic period (3800-2500 BC). As noted by Papadopoulos, such a structure however would have required parallel wooden beams, supported by a vertical thick timber support, and layers of reeds laid over the rafters, to create a stable and dense surface for the positioning of earth[45].

LUCA GIRELLA.

The vaulted roof problem: the ethnographic parallels

As noted by Branigan, the vaulted roofing system has a long tradition in modern Crete where circular houses or huts with vaulted stone roofs are called *mitata*[46]. S. Xanthoudides was the first to observe these peculiar constructions on the upland of Nidha and their similarities with the construction of the tholos tombs[47]. Subsequently, Warren and Branigan have considered this issue[48]. *Mitata* are particularly common on the upland plains of Mt. Ida, especially Nidha, and the Madares high-altitude pastures of the White Mountains[49]. They are used by shepherds as temporary dwellings and also as cheese dairies during the summer period. Being circular and corbelled buildings, the *mitata* offer a valid comparison for the construction of Cretan tholos tomb (*fig. 3*). In particular, Warren points out several dimensional and architectural similarities between the two building types, with particular attention to details of construction details[50], such as: the interior corbelling of the vault, the stone working with the preference for slab and wedge-shaped in the roof construction of the *mitata*[51], the doorway and

[40] PAPADOPOULOS 2010, p. 143.
[41] PAPADOPOULOS 2010, pp. 51-55.
[42] PAPADOPOULOS 2010, pp. 17, 62-65, 85-86.
[43] PAPADOPOULOS 2010, p. 17.
[44] PAPADOPOULOS 2010, figs. 8-9, 33.
[45] PAPADOPOULOS 2010, p. 8, figs. 10-12; THOMAS 2005.
[46] BRANIGAN 1994, p. 65; SYRMAKEZIS1988.
[47] XANTHOUDIDES 1924, p. 136.
[48] BRANIGAN 1994; WARREN 1973; 2007.
[49] SYRMAKEZIS1988.
[50] A good synthesis of the evidence is in WARREN 2007, p. 14.
[51] Similar according to Warren to those found fallen on the floor of Lebena Tholos II: WARREN 2007, 14.

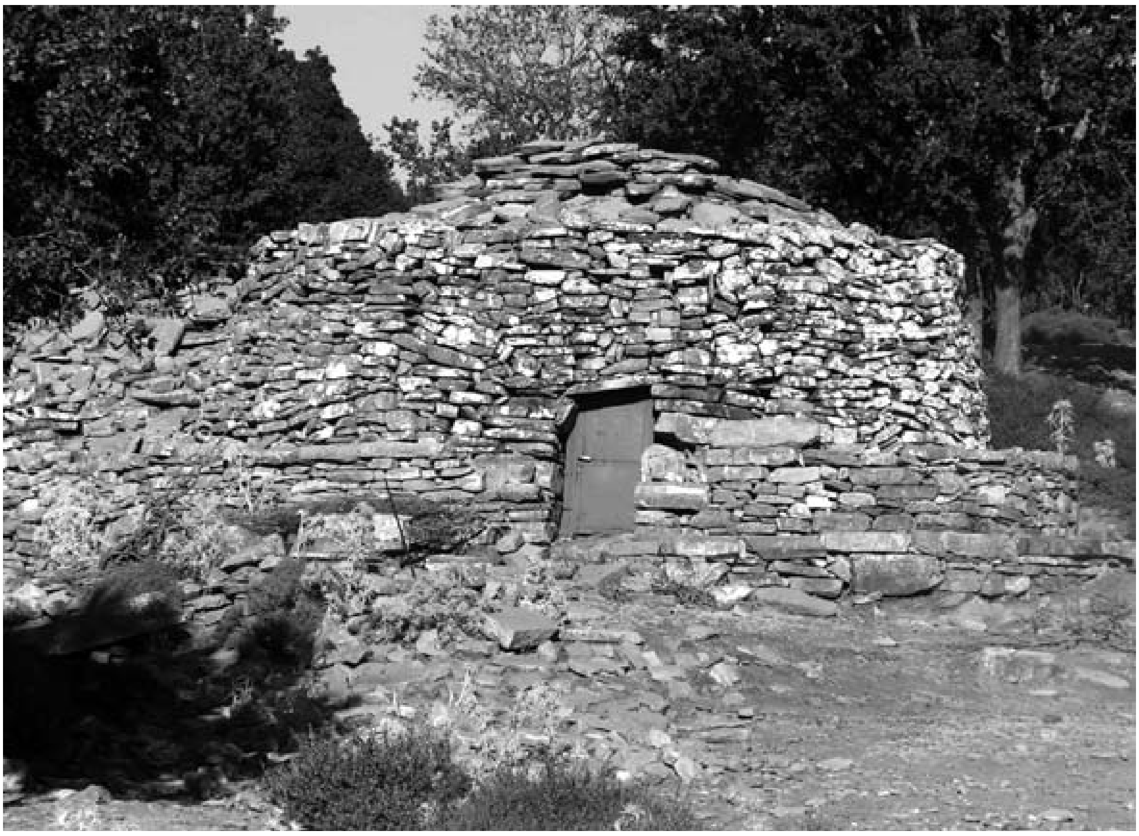

FIG. 3 – MITATO IN ZOMINTHOS AREA WITH THE VIEW OF ITS ROOFING TECHNIQUE.

entrance passage of the *mitata* made of a strong lintel stone and upright monolithic slabs or orthogonal blocks. On the contrary, other authors have stressed both the absence of chronological continuity and the difference in the construction of the walls, namely the use of dry-stone technique for the *mitata* and the earth, clay and small stones for the tholos tombs[52].

On the same wave, Branigan examined a small vaulted stone hut about 6 km south of Vryses Apokoronou[53]. Although the structure offered several differences to the *mitata* of Nidha, it has points of comparison, such as the construction of a foundation course of large boulders above which small stones are used, and the use of rock buttresses and/or an additional 'skin' around part of the diameter[54].

Although the issue of comparing the building tradition from the III/II millennium BC Cretan tholos tomb to the relatively modern constructions of *mitata* remains open[55], the useful point of these ethnographical comparisons might be that the modern buildings reflect respons-

[52]PELON 1976, p. 60; BELLI 1984, p. 123.

[53]BRANIGAN 1994, pl. I.

[54]BRANIGAN 1994, pp. 66-67. The use of thickening one side of the tomb by the use of additional skin walls is for instance noted at Chrysokamino A, Vorou A and B, Apesokari A and B, Kouses.

[55]This aspect has been stressed by several scholars: PELON 1976, p. 60; BELLI 1984, p. 123; WARREN 2007, p. 15; PAPADOPOULOS2010, p. 7. As suggested by Warren, if any case for derivation can be proposed, circular building like *mitata* might be common in Crete during Hellenistic and Roman times, when is documented for the first time the use of the mountains for summer pasturages. WARREN 2007, p. 15 following CHANIOTIS 1999, pp. 188-205.

es to specific needs and constructional concerns related to the natural resources available for use as building materials. It is for instance of value that the almost invariable characterisation of the *mitata* roofs, conical in shape, with loosely arranged slab-shaped and wedge-shaped stones that, aside from giving an interesting suggestion to the roofing system of the Cretan tholos tomb, is particularly suitable for the draining off of rainwater and melted snow[56].

Useful insights can be offered by the corbelled domes common in rural areas on the borders between Spain and Portugal, used for stores, wells, drying places, wine cellars and granaries. Using mostly dry-stone techniques, the walls of these constructions are erected by bonding stones without cement or mortar. In the *chozos* usually the section is triangular and the vault quite conical, whereas roofs can be protected from the rain by a layer of soil[57]. In the *barracas*, in the inner province of Cataluña, the vault is corbelled with horizontal and overhanging layers of stone, while on the top of the dome maybe found a horizontal stone plate[58]. Other similar constructions, occurring in many varieties from one area to another, are *pozos* (common in the inner region of Aragon, Valencia, Cataluña ad Andalucïa)[59] and the *ponts* in the Baleares islands[60].

Any of these analogies cannot prove a direct link to the construction of Cretan tholos tombs, however it can be used as a good parallel to visualize the solutions about the vault system and to observe similar structural responses. Moreover, it has been observed that the corbelled domes of Crete, Spain and Portugal, as many other in the Mediterranean, are mainly the result of agricultural activities and transhumance economy. This particular aspect should be taken into consideration when thinking about Cretan communities during III millennium BC and their size and social composition. Unfortunately, aside from very few studies, such as those focused on the Ayiopharango valley, links between tombs, community, kinship groups and landscape are not fully understood[61].Thanks to the study of the physical environment and the distribution of graves and potential cultivable land, the survey of the lower catchment of the Ayiopharango valley has demonstrated the division of the valley in smaller landscape units, each one associated with several related families sharing the use of a single communal tholos tomb. Therefore, a comprehensive study of the Cretan tholos tombs, from its construction to the communal use for burial and ritual purposes, must embrace a broader approach which includes the study of physical environments and the relationship between settlements and natural resources. In this sense, because Cretan tholos tombs were built in response to constructional needs, it is useful to consider the relationship between communities and available local resources to better understand tholos tombs, human settlement and sustainability.

LUCA GIRELLA

Kamilari tholos tomb A: the context

Tholos A is known by the name of the low hill, Grigori Koryphi, on top of which the tomb is still visible today inside the archaeological fence. Kamilari tholos A is placed about 1.5 km

[56] VALLIANOS 1985, p. 54; and noted by WARREN 2007, p. 14, fig. 2.11. See also PAPADOPOULOS 2010, figs. 4-5.
[57] MUÑOZ MUÑOZ 2006; JUVANEC 2008.
[58] MARTÍN I VILASECA 1990; CASTELLANO CASTILLO 2001.
[59] RIVAS 2004.
[60] CALVIÑO CELS 1999.
[61] BLACKMAN-BRANIGAN 1977.

FIG. 4 – AERIAL VIEW OF THE KAMILARI THOLOS A (AFTER MYRES, MYRES, CADOGAN 1992).

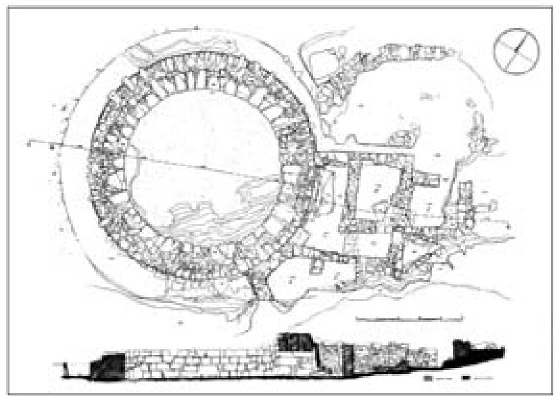

FIG. 5 – PLAN AND SECTION OF KAMILARI THOLOS A (AFTER LEVI 1961-62).

north of the modern village of Kamilari and about 2 km south-west of the Ayia Triada Villa. The tomb was discovered and excavated during summer 1959 and belongs to a group comprising two other circular tombs; Kamilari tholos B (Mylona Lakko), placed approximately 200 metres north of Kamilari A[62], and Kamilari C, about 150 metres to the south-east[63].

Kamilari tholos A is composed of three main complexes (*figs. 4-5*): a main circular chamber, five external rooms and an open-air space to the north delimited by an enclosure wall[64]. The circular chamber has an internal diameter of 7.65 metres with walls constructed of roughly worked blocks, and large stones on the inside face. The doorway is located on the east side as in almost all the tholos tombs of southern Crete. Five annex rooms were built east of the main chamber: a so called antechamber, room α, that connected through a corridor with two other rectangular spaces, rooms' β and γ. To the south two other small rooms (δ-ε), the first of which is almost circular, were built against the rock. Finally, an external area, a kind of courtyard known as '*recinto delle offerte*' (offering fence) obtained by smoothing the natural rock, apparently remained an open space during the whole life of the tholos tomb[65].

Several details are useful for the following analysis:

1. The tholos tomb lies directly on the rock, likely smoothed and regularized at the time of construction. Like all the other Cretan tholos tombs it was probably not entirely covered by soil and therefore visible above ground. As with several other tholos tomb, Kamilari A is built against the rock face (quite visible on the south), possibly with the intention of using this as a sort of natural buttress or counter-force. A foundation trench, which must have been filled with earth upon completion of the building construction, is still visible on the south[66] (*fig. 6*).

2. The walls are better preserved on the southern side with 7 courses of blocks and they reach a height of 2,07 m, whereas only 4 courses are preserved on the northern part (*figs. 7-8*).

3. The circular chamber has an internal diameter of 7.65 m; however, the recent survey of the structure has demonstrated that the chamber is slightly oval along the east-west axis with a reduced diameter of 7.35m (*fig. 9*).

[62] LEVI 1961-62, pp. 107-110.
[63] ALEXIOU 1957; BRANIGAN 1976; PELON 2004, p. 160.
[64] LEVI 1961-62, pp. 9-19.
[65] Preliminary work about the new project of publication of the tholos tomb are GIRELLA 2001; 2013, in press; CALOI 2011; TRIANTAPHYLLOU-GIRELLA forthcoming.
[66] LEVI 1961-62, fig. 5.

Fig. 6 – Kamilari tholos A: view of the western wall with stones projecting outward from the outer masonry and rest of foundation trench (SAIA B/7778, Courtesy Italian Archaeological School of Athens).

Fig. 7 – Kamilari Tholos A: view of the southern inner wall (SAIA B/7247, Courtesy Italian Archaeological School of Athens).

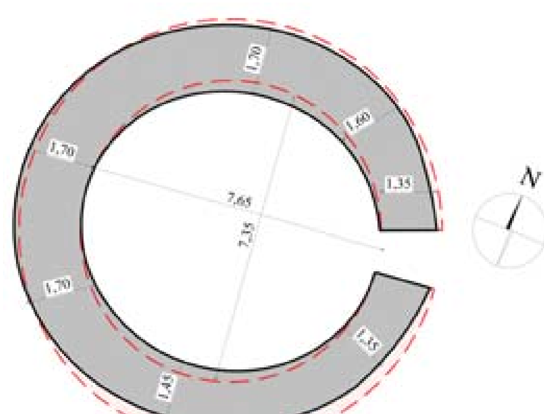

Fig. 9 – Kamilari Tholos A: plan of the chamber masonries as surveyed (solid black line) compared to the perfectly circular geometry.

Fig. 8 – Kamilari Tholos A: view of the north-east inner wall (C/8546, Courtesy Italian Archaeological School of Athens).

Fig. 10 – Kamilari Tholos A: a) photo of the fallen stones taken during the excavation, from SE (SAIA B/7167, Courtesy Italian Archaeological School of Athens); b) view from E (SAIA B/7171, Courtesy Italian Archaeological School of Athens); c) close-up view of the fallen stones in the central part of the tomb (B/7174, Courtesy Italian Archaeological School of Athens); d) view of the collapsed stone from N (SAIA B/71789, Courtesy Italian Archaeological School of Athens).

4. Similarly, the wall thickness is about 1.70 m along the western part of the wall ring, but it varies significantly along the circumference, with a reduced thickness of 1.35 mat the entrance door.

5. The walls are built with two side leaves and filling material. The arrangement is characterized by large and almost regular stone blocks along the inner face and smaller and irregular elements on the external facade (*fig. 6*)[67]. Horizontal bed joints are clearly visible on the inner masonry leaf and the texture of the masonry is neatly arranged. The overlaying layers of stone element are linked with earthen mortar; small and medium size stone wedges guarantee the compaction of the texture[68]. As observed in other tholos tombs (Kamilari B, Ayia Triada B, Kalathiana) the majority of facing stones are large enough to span half the width of the wall. The core of the masonry is made of stone rubble of variable size[69].

6. The beginning of the curve of the external profile is observable commencing at the second course and is quite visible on the southern part where seven courses of stone blocks are preserved.

7. Several slabs, of almost regular shape (0.80/0.90 × 0.65 m), project from part of the circumference. They are placed at different levels along the circumference but not at the door sides[70].

8. The masonry of the adjacent walls is arranged completely differently. It has one single leaf, bed joints of mortar and repointed in a few sections. The small chamber masonries have no interlock with the tholos masonries, but they are simply arranged beside the outer leaf.

[67] Levi 1961-62, figs. 9-10, 13.
[68] Shaw 2009, pp. 56-57.
[69] Shaw 2009, p. 57.
[70] Levi 1961-62, fig. 10.

9. As in several other tombs (Lebena, Platanos B), at Kamilari A a large flat slab (1.32 × 1.12 m) was found on the northern area, close to the '*recinto delle offerte*', and interpreted by Levi as the capstone of the full stone vault[71].

The issue of the roofing vault at Kamilari was firstly discussed by its excavator. In particular, D. Levi used the massive layer of almost regular dressed stone brought to light inside the tholos as supporting argument of a stone vault[72]. Moreover, he stressed the point that, aside from the quantity of the stones found, the cubic volume of which he did not calculate, a key factor was the preservation of progressive and superposed superimposed concentric rings that shaped the possible vault. The photos of the fallen stones taken during the excavation show a slightly higher concentration of the stone material in the centre of the chamber with a progressive reduction towards its perimeter[73] (*fig. 10*). According to Levi's reconstruction of the tomb's history, the stone vault remained standing until a large fire lit by looters[74]. Although after the removal of the fallen stones a large archaeological layer appeared with mixed human bones, offerings, and large traces of fire and charcoal[75] (piles in several points of the circular chamber or largely along the perimeter), Levi was convinced that the fire that burnt the grave was not due to the rite of cremation or purification, but rather caused by the torches the looters had used to rob the tomb or poles that they may have put at their disposal to support the crumbling vault. Torches and poles, better than any other hypothesis, explain for Levi the presence of coals left from the fire, fire that may have hastened the collapse of the tomb[76].

On the contrary, Branigan and Pelon have observed that the occurrence of burnt timber under the fallen stone layer might support the theory of a wooden roof[77]. A similar conclusion was reached by P. Belli who, by calculating the cubic volume of the stones layer found in the circular chamber, observed the impossibility of a full stone vault, otherwise completed hypothetically by a mud-brick structure[78].

Admittedly, at Kamilari A there can be no doubt that the stones used to face the wall were very carefully worked, but whether this vault was entirely built or incomplete needs to be verified. Most of the facing stones have properly cut face and are cut into the shape of either a rectangle or a wedge. Furthermore, in the case of Kamilari and Lebena the excavators rightly drew attention not only to the fallen stones but to the *nature* of the stones and to the way in which they had fallen. A notable number of stones at Lebena seem to have been wedge-shaped and were found to have fallen like a 'row of leaning books'. Both these features are strongly suggestive of a collapsed corbelled structure[80]. A final argument used by Levi to

[71] Levi 1961-62, fig. 15.

[72] Levi 1961-62, pp. 11, 104-105, figs. 11-12.

[73] Levi 1961-62, figs. 11-12.

[74] Levi 1961-62, pp. 21-22.

[75] Botanical and dendrological analysis have been carried out by Maria Ntinou on charcoal samples collected by Doro Levi in 1959 and those collected by the present author together with the human bones dug out in 2009: Triantaphyllou-Girella forthcoming.

[76] Levi 1961-62, p. 22.

[77] Branigan 1970, p. 54; Pelon 1976, pp. 56-57. But Branigan 1993, pp. 53-55, fig. 3.11, he opts for a corbel-vaulted tomb.

[78] Belli 1984, p. 122. Levi mentioned indeed one mud-brick found along the north wall of the circular chamber (Levi 1961-62, p. 34) but he considered it as the remnant of a partition wall used in the chamber to divide depositional areas of skeletons. There is no picture of the mud-brick unfortunately. For the use of partition walls inside tholos tombs see the case of the tomb at Kaminospilio: Pelon 1994, pp. 162-163, fig. 15.

[79] Alexiou-Warren 2004, pp. 12, 15, 18, 21, pl. 27A.

[80] Warren 2007.

Fig. 11 – Kamilari Tholos A: large stone slab identified as the keystone of the vaulted roof found outside north (SAIA B/7248, Courtesy Italian Archaeological School of Athens).

accept a stone vault was the large flat slab identified as the keystone of the vaulted roof found north of the tomb, re-moved by looters in antiquity to enter into the tomb[81] (*fig. 11*). On the function of this large stone block, however, the interpretation given by Levi is hard to accept. The dimensions of the block are not compatible with its use in a stone vault which would have necessitated lighter dressed stones on its upper part, while the bizarre explanation of its removal to facilitate looting suggests a different interpretation. Due to its similarities with the stone door found in situ in room α at the entrance of the main circular chamber, it is, indeed, possible that it was used as a vertical architectural element, like a second door related to an entrance toward the area known as '*cortile delle offerte*'. Interestingly, the attentive survey of the offering courtyard masonry fence wall highlights the presence of a series of stones of remarkable size all inclined with respect to the horizontal plane (*fig. 12*). Due to their firmness and particular arrangement this alignment of stones is very unlikely to represent the original disposition of the stone in the masonry (given that the texture is different elsewhere), but is probably the remnants of an overturned wall, possibly a pillar. If this interpretation is true, it would corroborate the hypothesis of the presence of a further

Fig. 12 – Kamilari Tholos A: view of the large wall W of the external courtyard. Visible behind is the large stone slab (SAIA C/6659, Courtesy Italian Archaeological School of Athens); b) close-up view of the wall masonry from E (SAIA C/6670, Courtesy Italian Archaeological School of Athens).

[81] Levi 1961-62, p. 21, fig. 15.

entrance to the funerary complex (the pillars being the doorposts) and would justify the position of the slab at the time of excavation and of the use of the slab either as entrance closure or threshold. Such an hypothesis, however, would allow us to re-interpret the origin and the function of the circular wall closing the open air area on the west.

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The Kamilari tholos tomb: Reconstructive hypotheses

In this section the structural response of possible roof vaulting systems is introduced and the archaeological data (angles, size of masonry units, block mutual interlock, possible roofing systems and finishing, collapses, etc.) are critically re-analyzed in order to highlight possible evidence of a special type of vaulted roof[82]. Far from expecting to unveil the original configuration of the possible dome of the Kamilari tholos, the aim of this study is rather to analyze the consistency of the hypothesis of a stone dome for the tholos, by taking into account both the archaeological data and the possible structural behaviour allowed by the special technical measures adopted in the tholos construction.

Corbelled domes vs true vault structural models

Two structural models were considered: the *corbelled dome*, otherwise known as the false vault, whose behaviour was well known at the time of construction of the Kamilari tholos, and the *true vault*, whose spread was later likely introduced by Mycenaean builders. The latter model is considered in this analysis as it is possible that the first tentative and pioneering examples of true vaults were already erected in the Early Minoan. In this scenario, Kamilari might be representative of a transient period in which construction expertise was fast developing toward the fine Mycenaean constructive art. In the following analysis the difference between false and true vaults is first discussed and the details and possible technical precautions required for their correct functioning is commented upon.

The *corbelled vault*[83] is the spatial extension of the *false arch*[84], bridging an opening through the progressive overlap of offsetting masonry blocks, having a horizontal arrangement of courses[85]. Concentric masonry courses meet at the dome key and the last gap is usually bridged with a flat stone. A corbelled vault is modelled as a series of stand-alone vault slices, lacking any mutual connection to the adjoining ones (*fig. 13*). Corbel vault slice stability is guaranteed by the sole vertical dead loads of both the masonry and a possible tumulus, assumed as acting like point loads located at the correspondent gravity centres. Equilibrium is guaranteed at each overlaying masonry course as long as the restoring moment is larger than the overturning moment with respect to rotation about the hinge identified as shown in (*fig. 14a*). The ratios between the resisting and overturning moment

[82] The details of all analytical and numerical studies can be found in Palmieri *et al*. 2012. The following presentation is a synthesis of this study.

[83] Como 2013, 203-207.

[84] Heyman 1982.

[85] Benvenuto-Corradi 1990.

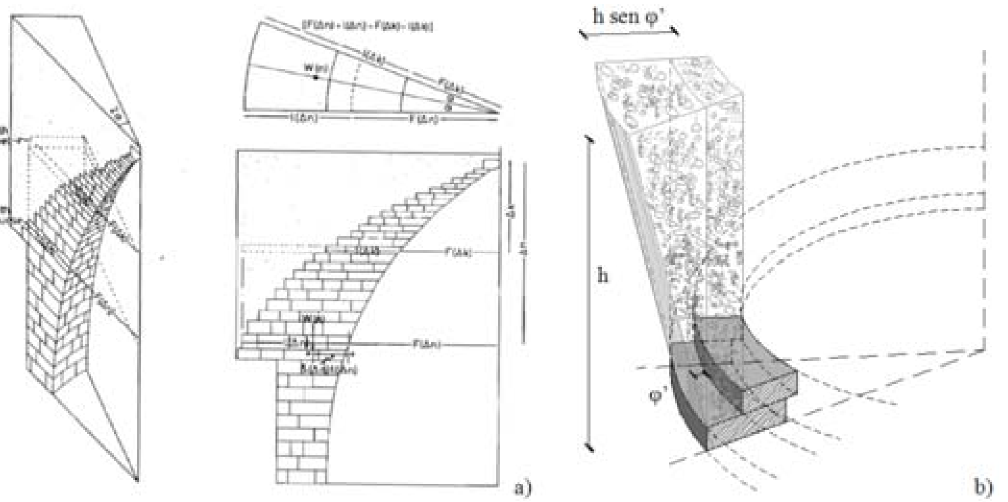

FIG. 13 – A) FALSE VAULT OR CORBELLED VAULT BEHAVIOR: INDEPENDENT VAULT SLICE CONSIDERED IN THE STRUCTURAL CALCULATION (AFTER CAVANAGH – LAXTON 1981, FIG. 10, P. 121). AN 8° OPEN ANGLE IS ASSUMED IN THE ANALYSIS. B) SHAPE OF THE TUMULUS VOLUME AT EACH OVERLAYING BLOCK LAYER.

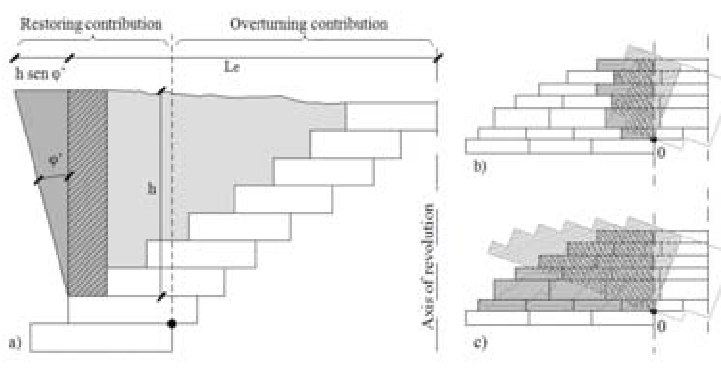

FIG. 14 – A) EQUILIBRIUM TO ROTATION AT THE BASE COURSE ABOUT THE HINGE (BLACK DOT IN THE FIGURE): THE WEIGHT OF THE STRUCTURE PORTION TO THE RIGHT OF THE DASHED LINE CONTRIBUTE TO THE OVERTURNING MOMENT, WHEREAS ALL VOLUME TO THE LEFT CONTRIBUTE TO THE RESTORING MOMENT; B) PORTION OF MASONRY INVOLVED IN THE OVERTURNING MECHANISM IS MUCH SMALLER THAN C) THE PORTION THAT WOULD BE MOBILIZED IF THE HORIZONTAL COURSE WAS COMPOSED BY MONOLITHIC STONES.

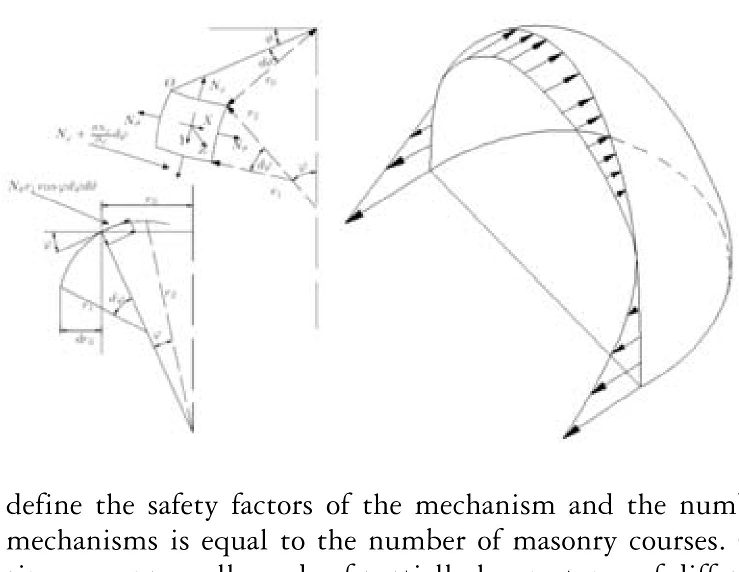

FIG. 15 – TRUE VAULT BEHAVIOR. MEMBRANE STRESSES AND PARALLEL STRESSES DISTRIBUTION, HIGHLIGHTING THE CHANGE IN THE SIGN ALONG THE MERIDIAN (AFTER HEYMAN 1995).

define the safety factors of the mechanism and the number of the possible overturning mechanisms is equal to the number of masonry courses. Given the texture of the tholos ring masonry wall, made of partially hewn stones of different sizes bridging the thickness of the wall, the restoring moment is jeopardized and the portion of masonry involved in the mechanism (*fig. 14b*) is much smaller than the portion that would be mobilized if the horizontal course was composed either by monolithic stones or by through-stones bridging the entire cross section (*fig. 14c*). Corbel vaults stability usually requires thick walls or a tumulus to counteract the effects of gravity loads, which would otherwise tend to collapse the vault inwards.

In *true vault* behaviour, the structure is subdivided into meridian slices and parallel rings which concur to the stress transferring, thus the major novelty with respect to the false vault behaviour is the introduction of parallel actions resisting part of the meridian lateral thrust[86] (*fig. 15*). When considering a true vault behaviour, different analytical solutions for shell structures can be addressed depending on the adopted set of hypotheses[87]. Given the uncertainties of the geometric model and the mechanical properties of the material, basic analyses were carried out and meridian and parallel stresses were calculated with reference to the classic membrane theory[88] by unrealistically assuming homogeneous linear elastic behaviour of the materials, thus neglecting the «no tension» behaviour of masonry. With this assumption, given the shape, the thickness of the vault, and the set of applied loads, both meridian and parallel stresses were easily obtained.

In the case of true vaults subjected to sole axial-symmetrical dead loads, meridian deformation is contained by the confining actions of the parallels; in other words, parallels resist to the portion of the radial thrust which is not transferred by the meridians. Accordingly, meridians are subjected only to compressive stresses, which increase from the key to the imposts of the vault, whereas parallels are subjected to compression in the upper part of the vault and to traction in the lower part. The change of sign of the parallel stresses occurs at a colatitude angle of about 52° in a semi-spherical dome, at a smaller angle in lancet domes, and at a larger angle in depressed domes[89]. When traction parallel stresses exceed the almost negligible tensile resistance of the masonry, cracks open and divide the lower part of the vault into flying buttresses subjected to eccentric actions, given that the confinement of the parallel is lost. Equilibrium is still possible as long as the centre of pressure lies within the meridian cross section edges. Beyond this limit a dome can still find equilibrium if a *tumulus*, confining the meridians, thus substituting the parallel actions, is adopted.

Finally, in true vaults, the masonry courses are usually arranged with a slight tilt inward for the compressive action in the meridian to be normal to the bed joints. In this particular case, given the horizontal masonry bed joints, equilibrium to sliding along each horizontal bed joint is guaranteed only as long as the horizontal component of the compression action in the meridian at the given joint ($R_f = N_\Phi \cos\Phi$) is smaller than the friction resistance along the bed joint ($R_f = N_\Phi \, sen\,\Phi$), possibly increased by the passive thrust of the tumulus ($R_p = (K_p \, Y_T h) \, A_L$, where K_p and Y_T are the passive thrust coefficient[90] and the specific weight of the tumulus respectively, and A_L is the contact lateral surface of the block with the tumulus). Therefore equilibrium to sliding must be carefully verified by enforcing: $N_0 < R_f + R_p$).

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[86] HEYMAN 2013; COMO 2013, pp. 183-189.
[87] COMO 2004.
[88] BELLUZZI 1980.
[89] SALVADORI-HELLER 1986.
[90] RANKINE 1857.

<u>*Surveyed details and technical arrangements corroborating the hypothesis of a vault for the Kamilari tholos*</u>

Considering these two possible structural models, it is interesting to reconsider the archaeological data, from a structural point of view. As a matter of fact, the survey of some architectural details drives the attention to the possibility of a covering structure entirely made of stone. Evidence corroborating the idea of a vault system are:

1) *Remarkable thickness of the tholos masonry wall*. The relevant wall thickness, ranging between 1.35 m and 1.70 m, as well as the relevant amount of material adopted in the construction, are compatible with a thrusting roofing system, such as a vaulted structure, whereas they are unlikely to be associated to non-thrusting or light roof structures. Based on this observation, the hypothesis of wooden elements sustaining the possible vault along the crown is rejected as a propping system would either reduce or eliminate the lateral thrust applied to the ring wall;

2) *Reduced thickness of the adjoining room walls*. These walls are contemporary or immediately subsequent to the tholos construction time, and are built with the same technique but with a significantly reduced thickness of approximately 0.50 m. The use of different wall sections in adjacent structures may be the result of a conscious construction choice resulting from the different characteristics of the neighbouring roofing systems. In this scenario, the reduced cross section size appears to be compatible with possible lightweight overlaying structures, or even with no coverage;

3) *Stone projecting outward from the outer masonry face.* The stones projecting from the outer surface of the wall with a constant horizontal and vertical spacing (80-90 cm and 50 cm, respectively), could have been conceived and served as special elements improving adherence between a possible stabilizing earthen mound (either complete or partial) and the masonry wall, as well as to increase bond of the earthen backfill laid between the outer masonry leaf and the foundation trench. This hypothesis is coherent with the assumption of an earth *tumulus* stabilizing the possible vault[91]. However, it is worth noting that

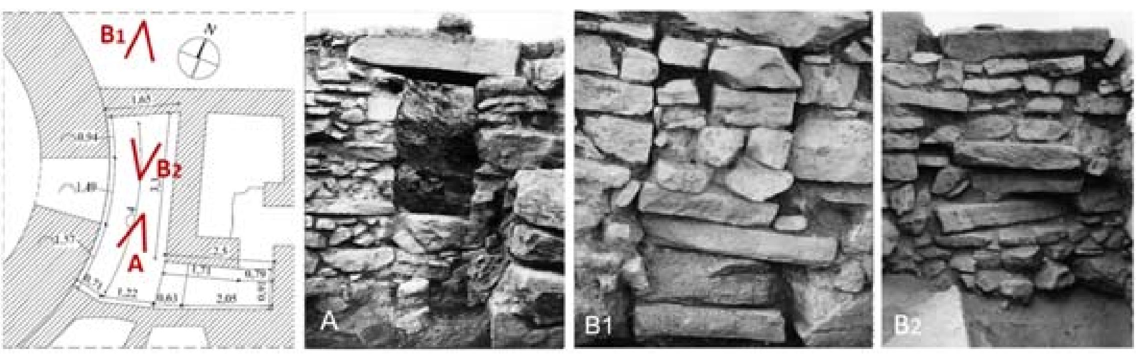

FIG. 16 – VIEWS OF THE TRANSVERSE WALLS OF THE ADJACENT ROOMS ± AND ¥: NO BUTTRESS ACTION IS PROVIDED BY THESE WALLS TO THE CHAMBER RING MASONRY GIVEN THE LACK OF MUTUAL INTERLOCKING AND THE SIGNIFICANT WEAKENING INTRODUCED BY SEVERAL OPENING (ONE HAS BEEN CLOSED IN A SECOND TIME – B IN THE FIGURE).

[91] LEVI 1961-62, p. 12. Likewise, Levi has interpreted the stones as ladders to assist the builders for the construction of the vault: *Ibidem*, pp. 111-12.

the hypothesis of the *tumulus* can hardly be sustained considering that it could not extend along the full perimeter of the tholos given the presence of the adjacent rooms and the offering courtyard. Neither the *tumulus* confinement action could have been substituted by the three transverse walls of the adjacent rooms: these walls are too thin, lack any interlocking with the tholos masonries and are weakened by several openings which make them unable to behave like massive buttresses (*fig. 16*).

As for the role of the projecting stones, doubts arise when considering that they were surveyed also along the masonry ring portion facing the offering courtyard, where no *tumulus* could be located. This may suggest an alternative hypothesis of the projecting stones as necessary to sustain a possible thick coating layer at the base, protecting the masonry extrados from the severe weather conditions and serving as a water proof finishing;

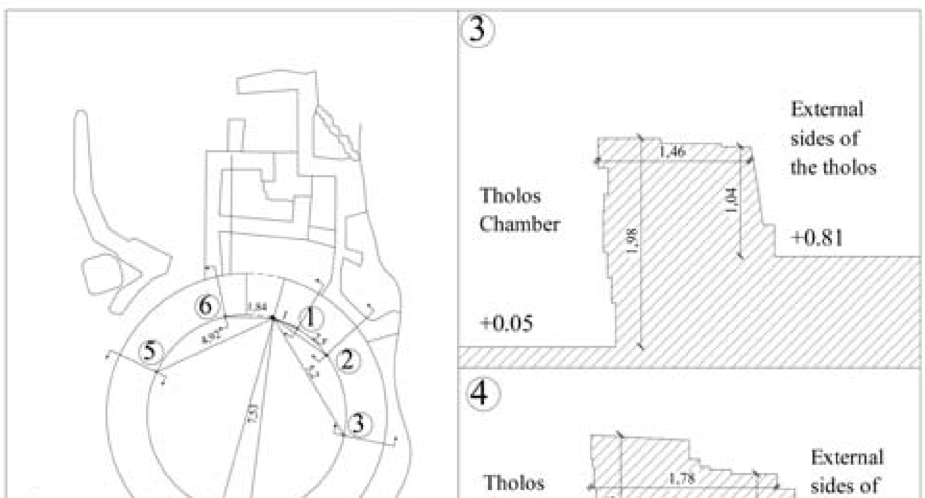

FIG. 17 – ON SITE SURVEY OF THE MASONRY CROSS SECTION SHOWING A PRONOUNCED SLOPE INWARD OF THE THOLOS RING WALL.

4) *The ring wall thickness varies along the height at each course*. As a result, the external and internal masonry leaves of the ring wall show a pronounced slope inward (*fig. 17*); the outer wall leaf inclination is more pronounced than the internal one. Such a tapered arrangement, which proves a clear awareness in the construction of the tholos chamber wall, is missing in the adjacent room walls, where the walls are approximately vertical, and is compatible with the presence of a vault having a tapered cross section. Interestingly, the survey shows varying inclination along the circumference. The inward inclination of the ring wall is much less pronounced close to the entrance and this could be compatible with the onset of a slight rotation of the wall at the base for unconstrained horizontal thrust, provided that the thin adjacent room walls are incapable of behaving like massive buttresses;

5) *The extensive use of wedge stones* of variable size, increasing compaction of both vertical and horizontal joints of the ring wall masonry inner leaf, might have ensured the proper transmission of the meridian and parallel compressive stresses associated with «true dome» behaviour. Interestingly, such an expedient is adopted neither in the adjacent room walls nor in the external leaf of the chamber wall, corroborating the hypothesis of a vault made from a single thick leaf, strengthened at the base by the double ring, the filling material and possibly a small earthen mound. Besides the presence of stone wedges among the blocks, the offset of the vertical joints strengthens the structure along the meridians. Double-height stones bridge overlaying block courses of the inner leaf and strengthen the masonry by allowing the distribution of possible parallel stresses. All these features ensure unity to the dome structure, and are more likely to entail a true vault structural behaviour, rather than a false vault made of independent radial slices;

6) *The extended crack pattern of one of the large stones* composing the entrance lintel might be the result of the excessive overlaying supported load.

Further evidence of the possible presence of a stone vault can be deduced from the literature analysis. Significant information was collected from available documents, in-situ surveys and archive photographs. Important evidence concerns the stratigraphy and the profile of the crumbled stone mound, discovered during the excavations of the archaeological site, piled in the centre of the tomb after the collapse of the upper ring masonries (either vaulted or not) (*fig. 10*)[92].

The pictures taken during the excavation before the removal of the stone mound portray a tapered mound profile, having its maximum height at the tholos centre, whose height progressively reduces at the ring wall perimeter. The stones are displayed concentrically, corroborating the hypothesis of a stone vault. The «archaeological layer« has an opposite tapered profile with a maximum 0.40-0.50 m thickness along the perimeter of the tholos and a reduced height at the tholos centre[93]. The stones piled in the tholos after the collapse are of small size and irregular geometry, thus they are apparently different from the large semi-hewn elements used in the internal ring wall leaf. Based on these observations, given the geometry of the tholos, the profile of both the stone mound and the archaeological layer, the «net volume» of the stone was computed as equal to about 56 m^3 (the «gross volume» being 70 m^3)[94]. The net vol-

[92]See also Levi 1961-62, figs. 11-12.
[93]Levi 1961-62, figs. 24, 28.
[94]Palmieri *et al*. 2012.

ume was then deducted from the volume necessary to restore the uneven ring wall masonry layers up to the extrados of the lintel. The updated net volume was estimated as equal to 39 m^3. Finally, by considering the presence of voids between the stones the «available volume of stone« for the construction of the possible vault was then calculated as equal to 27 m^3.

Under these circumstances, it is therefore important to point out that the estimated available volume of stone does not corroborate the assumption of a stone vaulted structure overlaying the ring masonry wall above the lintel level, unless a significant tapering of the masonry with the height is considered. Furthermore, as surveyed on the archaeological site a possible *tumulus*, if present, could have been only partial, given the presence of the courtyard and the adjacent rooms, and of reduced height given the particular topography of the surrounding landscape).

Structural analyses: from the analyses of a series of vault layouts inherited from the literature to the proposal of a possible vault profile

Various shapes of the possible vault profiles were analyzed by assuming corbelled vault and true vault behaviour. In the false vault model, vault slices having 8° open angle were considered, whereas in the true vault model the whole vault structure was taken into account. Unlike previous studies focusing on the behaviour of Mycenaean tholoi, where a

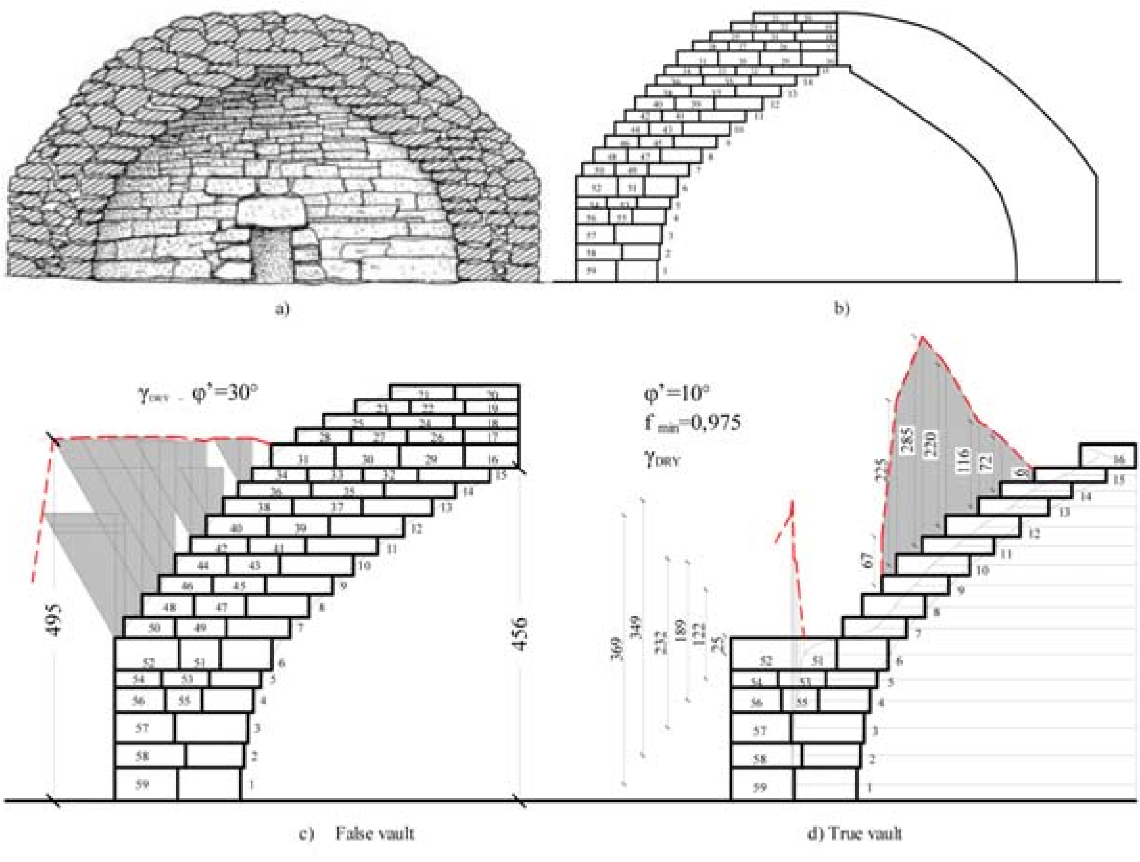

FIG. 18 – A) BRANIGAN'S RECONSTRUCTIVE HYPOTHESIS (1993, FIG. 3.11). B) SIMPLIFICATION OF THE BRANIGAN'S VAULT HYPOTHESIS AS ASSUMED IN THE STRUCTURAL MODEL (ELEMENTS NOS.1-59 ARE CONSIDERED IN THE FALSE VAULT BEHAVIOR, NOS. 1-16 IN THE TRUE VAULT MODEL). C) MINIMUM HEIGHT OF THE TUMULUS ENSURING EQUILIBRIUM FOR MINIMUM VALUES OF THE PARAMETERS IN THE CASE OF *FALSE VAULT* BEHAVIOR (WHERE INDEPENDENT VAULT SLICES ARE MODELLED AS IN FIG. 13A) OR D) *TRUE VAULT* BEHAVIOR (WHERE NUMERICAL ANALYSES ARE CARRIED OUT ON THE FULL VAULT, AS IN FIG. 15B).

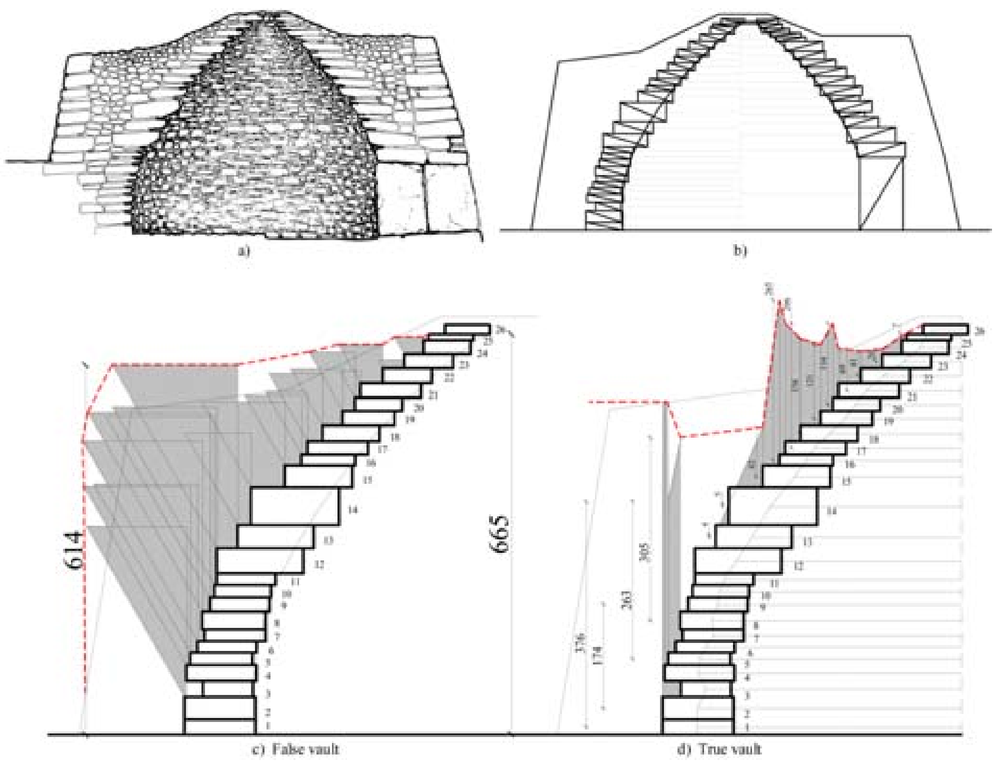

FIG. 19 – A) *MITATO* CROSS SECTION (AFTER SYRMAKEZIS1988, FIG. 2); B) *MITATO* VAULT PROFILE STRUCTURAL MODEL; C) MINIMUM HEIGHT OF THE TUMULUS ENSURING EQUILIBRIUM FOR MINIMUM VALUES OF THE PARAMETERS IN THE CASE OF *FALSE VAULT* BEHAVIOR (WHERE INDEPENDENT VAULT SLICES ARE MODELLED AS IN FIG. 13A) OR D) *TRUE VAULT* BEHAVIOR (WHERE NUMERICAL ANALYSES ARE CARRIED OUT ON THE FULL VAULT, AS IN FIG. 15B).

defined set of data was assumed and derived from the surveys[95], in this case given the lack of data a sensitivity analysis approach was necessary. For each given geometry and structural model, parametric static analyses and a sensitivity study were carried out for varying a set of parameters governing the structural behaviour, namely: *(i)* the specific weight of the possible tumulus, which was considered in dry $Y_T = 1.6kN/m^3$ or wet conditions $Y_T = 1.9kN/m^3$, unless differently specified; *(ii)* the ground friction angle', alternatively set equal to 0-10-20-30°; *(iii)* the friction coefficient along the bed-joints set equal to 0.975-1.65-2.34, where the extreme values were selected as an average between the friction coefficient at «first detachment» ranging between 1.5÷3 and the friction coefficient «during the displacement» ranging between 0.68÷0.78[96].

Preliminary analyses were carried out with reference to geometries inherited from the literature, namely: Branigan's reconstructive hypothesis, and the *mitata* roofing system profile. While the first hypothesis is applied to the case of Kamilari tholos A, the second one is based on a schematic representation of the Cretan *mitata* and not referring to any specific building[97].

Branigan has proposed for the Kamilari tholos a massive stone vault, assuming the structure to behave like a false vault (*fig. 18a*)[98].The *mitato*, made with large stone slabs

[95] COMO 2004.
[96] COLOMBO 1955; COLOMBO-COLLESELLI 1996.
[97] SYRMAKEZIS 1988, p. 11, fig. 2.
[98] BRANIGAN 1993, pp. 54, fig. 3.11.

dry assembled in thick and slightly inwards tilting masonry walls, has a quite interesting almost conical covering system (*fig. 19a*). There are some similarities, which make the *mitata* solution worth studying in order to identify formal and structural analogies for the possible covering system of Minoan tholoi, despite the lack of chronological continuity and the improvable constructive art continuity, also evidenced by the difference in the materials[99]. Interestingly, a similar observation was made by Papadopoulos, concerning the possible covering of the Tholos C in the Archanes/Phourni cemetery, in which the ethnographic reference to the *mitato* roof system was proposed as a possible solution[100].

Similarities can be summarized as follows: *(i)* the *mitata* diameter to masonry thickness ratio is similar to that of the Minoan tholoi (the external diameter ranging between 6-10 m, the internal between 3.5-6.5, thus the thickness varying between 1-1.9 m); *(ii)* the offset of overlaying courses starts at the wall base, resulting in a progressive inward inclination of the masonry; *(iii)* the texture of the masonry with horizontal bed joints, radial semi-hewn stones displayed in two concentric ring leaves and small wedges to induce compaction (the most relevant difference being the use of earth instead of clay mortar as binding material and to fill the interstices); *(iv)* the neatly arranged inner leaf; *(v)* the main entrance opening bridged by two-three lintel slabs.

With reference to the false vault behaviour, a first set of analyses was carried out by considering the absence of the tumulus; in a second set the stabilizing contribution of a complete horizontal tumulus extending up to the vault key was studied; and finally in a third set of analyses the optimal profile of a possible tumulus stabilizing the structure was derived by evaluating the minimum tumulus height at each masonry course necessary to guarantee equilibrium[101]. For both geometries and for all sets of parameters (Y_T and Φ), the static vulnerability assessment analyses referred to the false vault behaviour showed that stability of the vaults is guaranteed only if a thick tumulus covering the vault is introduced (*figs. 18c* and *19c*). In Branigan's solution the *tumulus* is needed in the inferior zone, the upper portion of the vault being stabilized by the massive masonry (*figs. 18c*); whereas, interestingly, in the case of the *mitato*, the calculated optimal *tumulus* profile corresponds to the actual surveyed profile (*figs. 19c*). It is worth noting that with reference to the *mitata* geometry, the upper masonries actually behave like a tumulus provided that they have no static role, but they simply introduce a stabilizing dead load.

In the case of the behaviour of the true vault, meridian and parallel stresses and the latitude angle where parallel stresses change sign were evaluated for all geometries. The optimal tumulus profile was identified as the envelope of the minimum tumulus heights necessary either to introduce a horizontal thrust balancing possible parallel tensile stresses or to apply a restoring passive thrust where sliding between the courses may occur. Branigan's reconstructive hypothesis was simplified and only the internal masonry blocks were considered as components of the chamber true vault (namely: blocks n. 1 to 16 in *fig. 18b*. It was found that the necessary tumulus height reduces for increasing the ground friction angle and the bed joint friction angle. In Branigan's vault, for minimum values of both the friction angle and coefficient, a thick tumulus is required all along the vault profile (*fig. 18d*). This solution is incompatible with the surveys of the archaeological ruins and the landscape skyline.

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[99] Warren 1973; 2007.
[100] Papadopoulos 2010, p. 17.
[101] Palmieri *et al*. 2012.

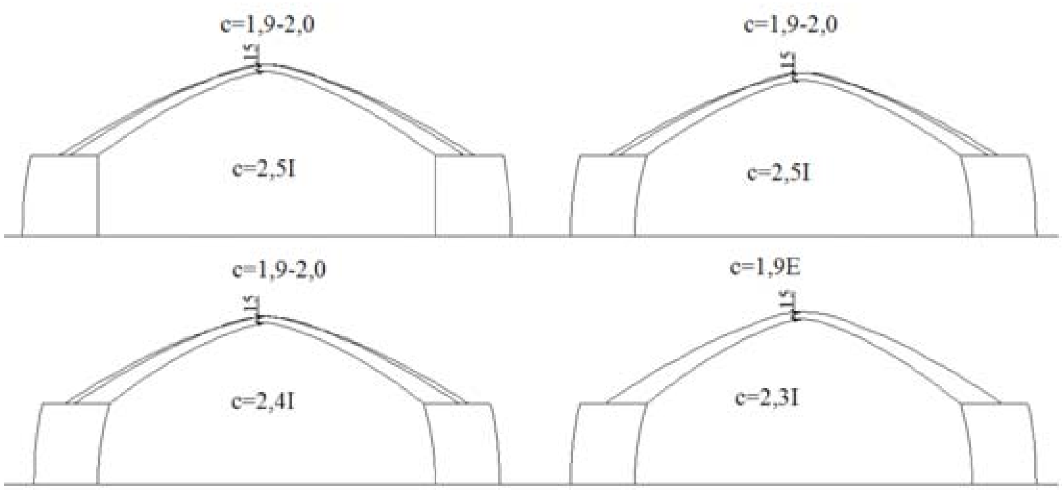

FIG. 20 – EXAMPLE OF DIFFERENT TENTATIVE VAULT PROFILES OBTAINED BY ASSUMING THE INTRADOS PROFILE AS DIVIDED INTO 4 PORTIONS.

In the case of medium friction values, no stabilizing *tumulus* is required in the upper part of the vault, whereas a thick *tumulus* is always needed up to the lintel extrados to stabilize the chamber wall in the lower part. On the other hand, the *mitato* vault shows a better distribution of mass and the true vault behaviour can be established at a reduced value of the friction angle and with a *tumulus* almost corresponding to the *mitato* extrados profile (*fig. 19d*).

As a major drawback of both alternative reconstructive hypotheses, besides the need for a *tumulus* extending along the structure's extrados, the volume of stone necessary for their assemblage is remarkably larger than the estimated available volume of stones (approximately 90 m^3 vs 27 m^3).

With reference to Cavanagh-Laxton's mathematical relationship defining the profile of Mycenaean vaults, further analyses have refined the model proposed in the 80s[102]. Cavanagh-Laxton's relationship defines the intrados and extrados surfaces of the dome through a parameter *c* that remains constant; it is worth noting that this assumption is quite limiting as it results in a continuous curvature of the vault intrados. With reference to Cavanagh-Laxton's relationship a set of internal profile curves was obtained, by assuming: $F(x) = cx^{2/3}$, where *F* is the internal diameter as a function of the height (the origin of the reference system being at the apex of the dome), *c* is a parameter set constant for each tentative profile (*fig. 13a*). Different curves were obtained by varying the parameter *c* from 1.9 to 2.7, as proposed by Cavanagh and Laxton[103]. The thickness of the vault is set equal to: $b(x)=\beta F(x)$, where β is assumed as constant, thus resulting in a constant, progressive tapering of the vault thickness with the height.

In order to overcome the major limitation of Cavanagh and Laxton's relationship, i.e. the assumption of continuous curvature, reference was also made to Buck and co-authors'

[102] BUCK-LITTON-STEPHENS 1993; FAN-BROOKS 2000. [103] CAVANAGH-LAXTON 1981.

model, which introduces a dome change of slope at the entrance lintel, and which can be regarded as an extension of the Cavanagh and Laxton's model[104]. As a further refinement, Fan and Brooks remarks of an initial vertical segment at the base and a further change of slope at the top portion of the vault were taken into account[105]. Fan and Brooks derived their observations from the archaeological evidence they surveyed on the late Minoan tholos of Achladia on Crete, the Mycenaean tholos tomb at Dimini and the *nuraghe* of Madrone, Silanus in Sardinia.

Therefore, in short, the tentative vault profiles (*fig. 20*) were sketched by assuming the intrados profile as divided into 4 portions: *1)* an initial vertical linear segment at the base of the tholos, close to the foundation (as observed by Fan and Brooks); *2)* then a second curved segment extending up to the extrados of the entrance lintel (according to Buck's model); *3)* a third curve defining the largest portion of the dome (with reference to Cavanagh and Laxton's relationship); *4)* and a final change in slope at the very top of the dome (as observed by Fan and Brooks).

Among all the obtained vault profiles a first selection was made by accounting for the reduced available volume of stones to be used in the reconstructive hypothesis. For all values of Y_T and Φ, all structures assumed to behave like false vaults were found to require a tumulus extending up to the vault key. With reference to the true vault behaviour, only for increasing values of Y_T , Φ and f, the tumulus could be removed from the upper part of the vault, whereas for minimum values a complete tumulus was necessary. Weakest points of the structure were identified in the upper part of the vault profile, where the bed joint friction resistance is overcome because of the large inclination of the meridian compressive action, and in the lower part of the chamber ring, where the horizontal confinement to the meridian action is lost and the vault reduces to a series of adjoining flying buttresses. These observations were the basic elements to conceive new geometries.

Identifying possible roof profiles, role of the tumulus and collapse mechanisms

In order to identify possible profiles not needing a complete stabilizing *tumulus* extending up to the top of the vault, new geometries were conceived and investigated by stretching the vault profile upwards, by assuming an abrupt change in the vault thickness at the lintel level, with the sole internal leaf composing the vault, and by introducing a «bottle neck» with an oculus at the vault key (*figs. 21-22*). Both the more pronounced lancet shape of the vault and the «bottle neck» are technical tricks to reduce the horizontal component of the meridian compression force, so that friction is sufficient to satisfy the equilibrium with respect to sliding along the horizontal bed joints in the upper vault portion, parallel stresses are significantly reduced. An interesting possible vault profile in shown in figure 21 and 22. It is worth noting that the proposal of this profile has the sole aim of assessing the consistency of the hypothesis of a stone dome for the tholos, by taking into account both the archaeological data and the possible structural behaviour, and it

[104] BUCK-LITTON-STEPHENS 1993.

[105] FAN-BROOKS 2000.

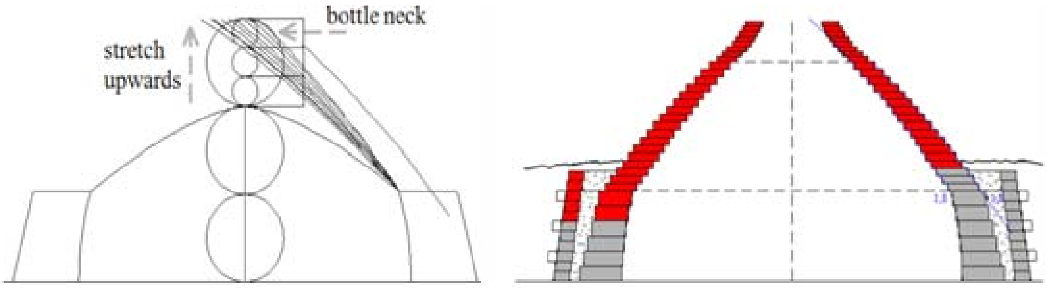

FIG. 21 – SPECIAL GEOMETRY FEATURING A FEW TECHNICAL DETAILS ALLOWING THE STRUCTURE EQUILIBRIUM WITHOUT A TUMULUS IS A TRUE VAULT BEHAVIOUR IS ADDRESSED.

FIG. 22 – KAMILARI THOLOS A: HYPOTETHETICAL RECONSTRUCTIVE HYPOTHESIS OF A POSSIBLE ROOFING SYSTEM. NOTE THAT THE PROPOSED RECONSTRUCTION DOES NOT AIM AT CREATING AN EXACT REPRESENTATION OF THE TOMB, BUT RATHER IT IS PROPOSED AS A POSSIBLE OPTION, WHICH IS COHERENT WITH BOTH THE ARCHAEOLOGICAL DATA AND THE POSSIBLE STRUCTURAL BEHAVIOUR ALLOWED BY THE SPECIAL TECHNICAL MEASURES ADOPTED IN THE THOLOS CONSTRUCTION.

is not at all proposed as the true profile of the dome. The curve is obtained by considering a shape Cavanagh and Laxton coefficient *c* equal to 1.8 for both the intrados to the extrados profile. The particular geometry is coherent with the available volume of stone (29 m^3 vs. 27 m^3).

With reference to the false vault behaviour, a complete *tumulus* is still needed; whose profile is interestingly similar to that of the *mitato* (*fig. 23 a*). By considering a true vault behaviour, parametric analysis results show that the proposed vault layout is stable even without the restraint action provided by the *tumulus*, and for minimum values of the hor-

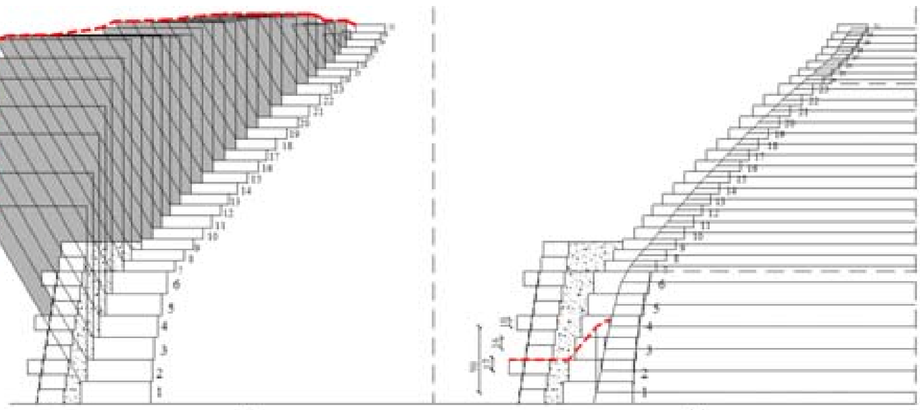

Fig. 23 – a) False vault behaviour. A complete tumulus is required; b) True vault behaviour. No stabilizing tumulus is required.Minimum bed joint friction angle f = 0.975; tumulus friction *angle* Φ = 30°, specific weight in dry conditions $Y_T = 1.6$kN/m^3.

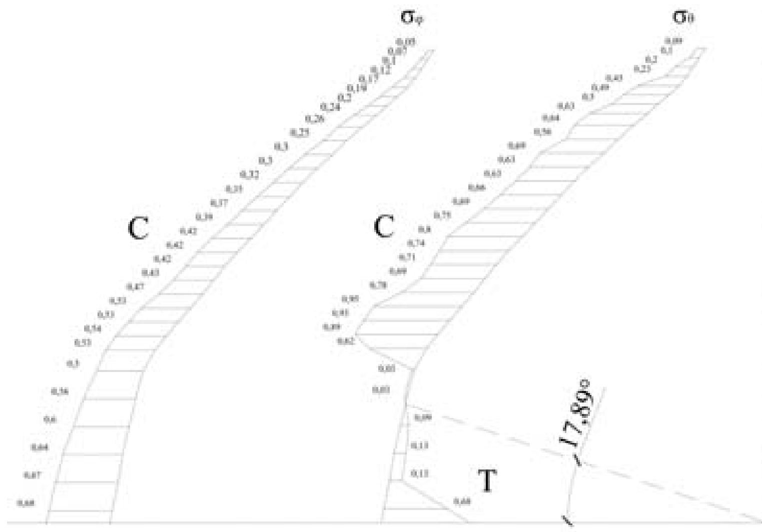

Fig. 24 – True vault behaviour. Meridian and parallel tensile stresses (minimum bed joint friction angle f = 0.975; tumulus friction angle Φ = 30°, specific weight in dry conditions $Y_T = 1.6$kN/m^3).

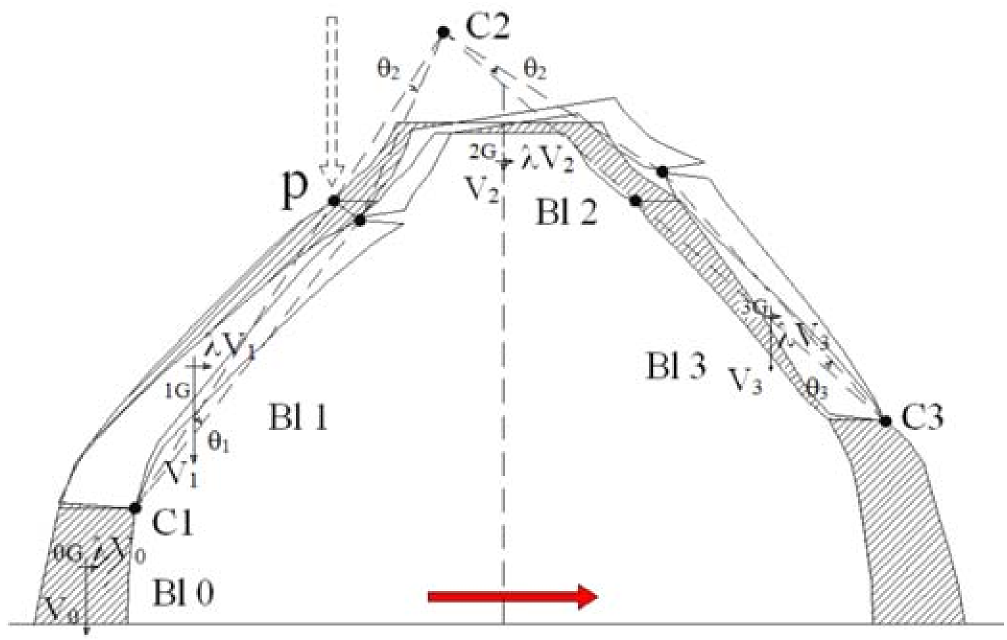

Fig. 25 – Kamilari tholos A: a possible collapse mechanism.

izontal bed joint-to-stone block friction coefficient (*fig. 23 b*).The diagrams of the parallel and meridian tensile stresses shows that possible cracks might propagate up to a height approximately corresponding to the lintel intrados; however, the parallel actions are so small that little confinement is needed (*fig. 24*).The internal masonry leaf can therefore behave like a true vault, having either the outer masonry leaf with the backfill or a partial *tumulus* confining the meridian thrust at the base.

Final considerations regard the possible causes inducing the structure to collapse. Based on the archaeological ruin survey, given the oval actual configuration of the masonry ring and the different height of the masonry, besides the possible collapse induced by the material decay, the possible effect of an earthquake hitting the structure along the South East-North West alignment was considered (*fig. 23*). Limit analysis was applied to evaluate the magnitude of a possible seismic action inducing the collapse. By fixing the position of the hinges C1 and C3 at the extrados of the masonry ruins and by varying the position of the further two hinges, the minimum horizontal action causing the onset of the failure mechanism was found to be equal to 0.15 g, corresponding to an earthquake of medium magnitude (*fig. 25*). Interestingly, a similar mechanism can be onset also by an asymmetrical set of applied loads, such as in the case of a point load of 0.5 t applied in P. Further causes of the possible vaulted system collapse might have been either the leaching of the *tumulus* at the base of the structure jeopardizing the confining action to the meridians or a shear sliding mechanism of the upper part of the vault triggered by an earthquake.

Although there is no doubt about the final destruction of Tholos A, one question however does remain substantially open: accepting the construction of Tholos A during MM IB and its prolonged use without interruptions down to the LM IIIA period, what was the response of the tholos tomb to the earthquake that caused the major destruction of the nearby palace of Phaistos and other areas of Crete at end of MM IIB? It is unfortunately almost impossible to give a definite answer and three hypotheses can be suggested: (*i*) the tholos tomb did survive the earthquake; (*ii*) the tholos tomb was damaged or collapsed after the earthquake and was successively repaired or rebuilt; (*iii*) the tholos tomb was damaged after the earthquake and continued to be used without any reparation. Although the suggested scenarios cannot be corroborated by any proof, our feeling is that the tomb would not have survived the earthquake and that after MM IIB the vault was either repaired or entirely rebuilt. The above analysis has demonstrated that even a medium magnitude seismic event may have induced the collapse of the vault. It is however possible that the damage after the earthquake was not so disastrous, as it was in the palace of Phaistos[106]. The tomb is indeed built on solid stone and this might have resulted in lower seismic with comparison with other buildings resting on deposits of loose-to-medium cohesion soils (such as the foundations of the First Palace of Phaistos, largely overlying previous Prepalatial structures or soils)[107], having lower mechanical characteristics[108].

[106] Riva-Signorini 2001.
[107] We would like to thank Simona Todaro for having discussed this point with us.
[108] Eurocode 8. Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings.

Two further considerations deriving from archaeological data can be noted: firstly, we know that after the MM IIB the tomb was intensively occupied and that also the quantity of MM III grave offerings shows a massive use of the tholos tomb immediately after the MM IIB[109]. Secondly, if we accept that the tomb was repaired or the vault rebuilt after the MM IIB, this event must have happened necessarily between MM IIB and MM III and one effect of this episode might have been the clearing of the previous grave offerings out of the circular chamber to facilitate the intervening works. Following in this, one interesting outcome of this reconstruction is that the enormous deposit of MM IB-IIB pottery found in the external courtyard, especially the deposit massed along the north-west wall[110], could not be the result of periodical deposition since MM IB, but rather the result of one single cleaning operation carried out after the MM IIB seismic event[111].

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Final remarks

The study above presented has analyzed the consistency of the hypothesis of a stone dome for Kamilari tholos A. With reference to different structural behaviour models it has been argued that a complete *tumulus* is still needed to sustain the vault if the false vault behaviour is considered, whereas parametric analysis results show that the true vault behaviour is possible even without the restraint action provided by the *tumulus*, but rather accounting for the confinement induced by the backfill placed between the external chamber wall leaf and the foundation trench.

The insights of a possible vault obtained with the numerical study corroborate the evidences collected during the archaeological ruin survey, the most relevant being:

(i) the remarkable thickness of the chamber wall, which can hardly be associated with a non-thrusting roofing system;

(ii) the inward tilt of the chamber masonries, which might represent the vault profile between the base and the springing section;

(iii) the projecting stone slab at the base, which may have been conceived to improve adherence with stabilizing backfill material;

(iv) the significant volume and the profile of the rubble stone mound as surveyed after the collapse;

(v) the extensive use of wedge stones in the masonry arrangement, which might have been designed to enforce compaction of the masonry courses to favour proper transmission of the meridian and parallel compressive stresses associated to true vault behaviour.

Finally, since this study has pointed out that true vault behaviour cannot be excluded for Kamilari tholos A, a significant argument is now raised again to provide more insight into the fully discussed issue of the Minoan origin of the Mycenaean tholos tomb[112], with particular

[109] Girella 2013.

[110] Levi 1961-62, fig. 107.

[111] It is also worth of noting that the evidence of MM IB and MM II grave offerings in the circular chamber is very scanty, Levi1961-62, 54-55.

[112] Hood 1960; p. 168; Pelon 1970, pp. 183-223, 442- 453; Branigan 1970, pp. 158-160; Kanta 1997. For a mainland origin of the Mycenaean tholos tomb see the discussion in Dickinson 2005, p. 53.

regard to the area of Messenia, where the most ancient mainland tholos tombs can be traced at the end of MH period[113]. Although this issue would deserve an analysis on its own, we would like to stress some points, especially from a structural point of view. One of the main arguments of Cavanagh and Laxton against the Minoan origin of the LH tholos tomb was «*that the Minoans did not vault their own tombs until a period of strong Mycenaean influence, indeed of probable Mycenaean rule on the island*»[114]. It is now clear that, beside the EM cases of Lebena and Archanes, Kamilari tholos A shows the existence of a significant improvement of the technical constructions during the Protopalatial period, especially as regards the increased diameter of the inner chamber that leads the artisans to adopt specific arrangements. Therefore, the later construction of the Kamilari tholos tomb (not before MM IB) coupled with the possibility of a true vault roofing system, represents a significant chronological argument suggesting the possible Minoan root for the Mycenaean tholos tomb at the end of Middle Helladic period. Of course, this argument necessitates a specific investigation, also in consideration of the relationship between Crete and Messenia since the end of Middle Helladic period[115].

Under these circumstances and the perspective of the above presented analysis, a comparative remark between Mycenaean and Minoan true vault constructions might be significant, as it allows us to identify some major difference. For their specific details, Mycenaean tholoi can be regarded neither as false vault nor as a pure true vault, but rather as lancet domes confined at the base. A key difference between Kamilari and the typical structure of the Mycenaean tholoi is indeed the different way to interpret the reinforcement in the weakest point of the construction, corresponding with the tholos entrance: in Mycenaean tholoi the massive transverse walls of the *stomion* have the double role of buttress against the horizontal thrusts of the dome and the *tumulus*[116]; whereas in the Kamilari tholos three thin transverse walls lacking any interlocking with the tholos masonry ring and weakened by several openings are certainly unable to behave like massive buttresses (*fig. 16*).

The evidence of this lack of horizontal confinement can also be found in the inclination of the ring wall; the inward inclination is much less pronounced close to the entrance and this could be compatible with the onset of a slight rotation of the wall at the base for unconstrained horizontal thrusts. Mycenaean tholoi feature several specific arrangements, such as the massive *stomion* transverse wall and roof, the embedment of the wall ring base within a pit excavated in the rock to avoid any loss of shape of the wall ring, the use of the *tumulus* together with precautions to prevent its leaching, the introduction of a triangular opening above the extrados lintel to reduce the lintel supported loads. All these are signs of a incipient art of construction, which allowed the progressive increase in the diameter of the chamber covered with the vault. In the end, these features are not so clearly evident in the Kamilari tholos.

The study presented in this paper, has tried to merge archaeological and structural disciplines to favour a broader perspective in which the archaeological data could be reconsidered; it has also demonstrated that, despite no certain conclusions being drawn, the hypothesis of a stone vault covering Kamilari tholos is as fascinating as actually possible. Interestingly, this

[113] Between the end MH and beginning of LH period can be dated the tholos tomb of Koryphasion, tomb 5 at Koukounara, tomb 4 at Karpophora/Nikitopoulos and the tomb of Kephalovryson: LOLOS 1989, pp. 171-177; ZAVADIL 2013, pp. 44-45, 434-436, 449-453, 461-463, figs. 47, 50, 55.

[114] CAVANAGH-LAXTON 1981, p. 132.

[115] RUTTER-ZERNER 1983, and more recently RUTTER 2005.

[116] COMO 2005.

hypothesis can be regarded as a common thread tying all surveyed elements together, as evidences of a single and uniform project. Conversely, if you deny the possibility of a vaulted roof, then the surveyed constructive elements, such as the thickness or the tilt inward of the wall, the projecting slabs and the wedges seem to become apparently meaningless.

Although the proposed reconstruction does not aim to create an exact representation of the tomb, it nonetheless offers a visual companion for discussing several sets of data. Firstly, it urges us to investigate the problem of roofing of Minoan tholos tombs under a more comprehensive diachronic perspective; secondly, it allows a better appreciation of the sophistication of the constructive techniques and their likely connection with the progressive involvement of Kamilari settlement into the palatial authority as early as MM IB[117]. Thirdly, the study complements the investigation about the relationship of the Kamilari cemetery and its landscape, interpreting the latter not only as the territory shaped by the long use of the area for funerary practices, but also as the mortuary arena resulting from the set of practices that entailed the rearrangement and organisation of the funeral spaces throughout the centuries. In this sense, the study of the Kamilari roof profile and its virtual representation represents a fundamental step to grasp the material and sensorial relationship that the Kamilari community had with its *sepulcrum* otherwise completely lost[118].

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[117] Girella in press.
[118] On this last point see Hamilakis 2013, pp. 129-160.

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ABSTRACT

Problems of roofing of Early Minoan Tholos Tombs: the case of Kamilari A tholos tomb in the western Mesara plain

Due to their reduced state of preservations, the argument of a stone vault for Minoan tholos tombs has been discussed in the past years with open or not unanimous conclusions. Thanks to a special survey carried out during summer 2009 on Kamilari A tholos tombs and the good state of preservation of many architectural parts, the present article wants to explore under a new perspective the issue of the vault system. After the presentation of the problem of roofing of Minoan tholos tombs through archaeological and ethnographical examples, the second part of the paper deals with the discussion of the false and the true vault systems and the analysis of possible roof profiles and collapse mechanisms of the vault. It will be argued that: 1) the true vault behaviour cannot be excluded for Kamilari tholos A; 2) among the possible causes inducing this structure to collapse there is an earthquake hitting the structure along the South East-North West alignment.

Finally, further considerations about the relation between Minoan and Mycenaean tholos tombs are stressed.