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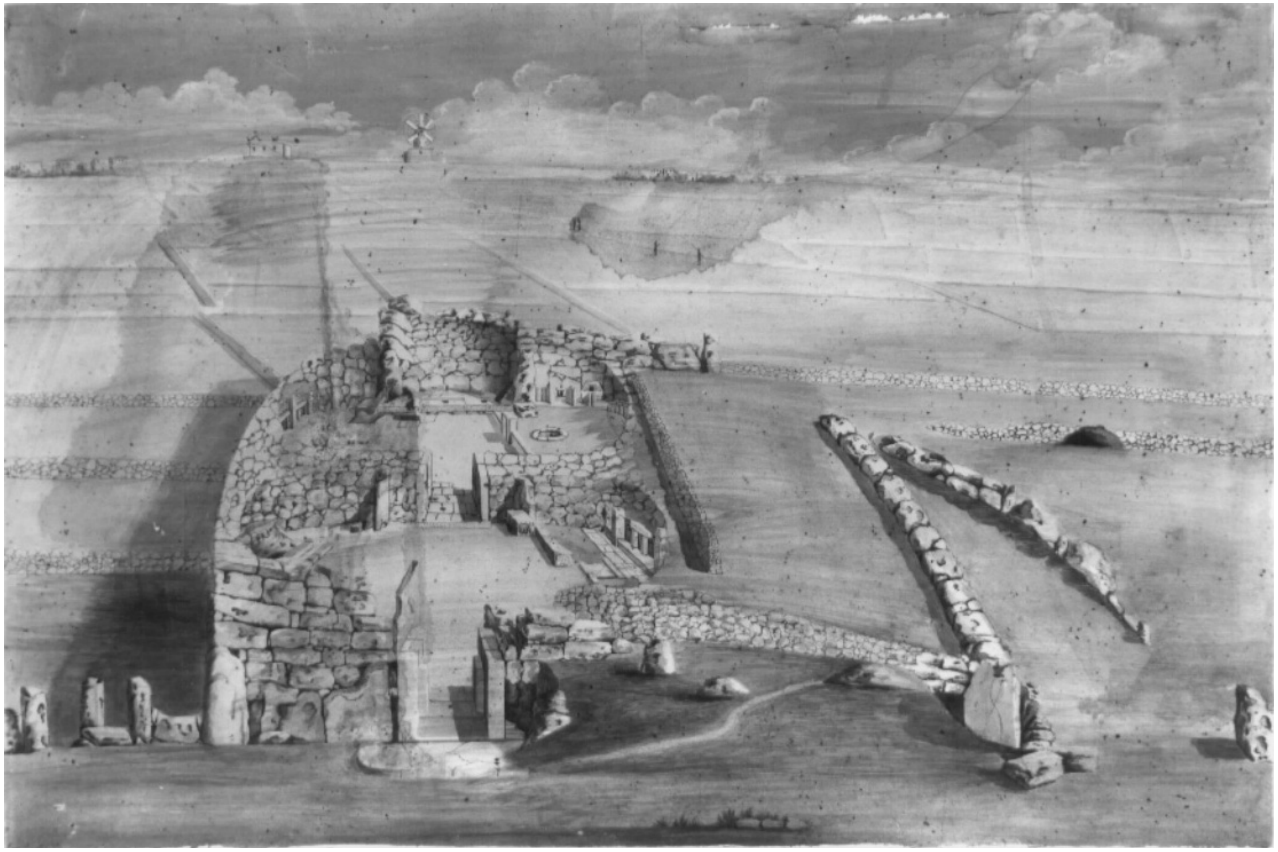

STRUCTURAL SURVEY AT GGANTIJA TEMPLES, GOZO

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STRUCTURAL SURVEY AT GGANTIJA TEMPLES, GOZO

STRUCTURAL ASSESSMENT REPORT

1.0 Introduction

1.1 This is a Structural Assessment Report of the entire structure of the Ggantija Temple Complex, in Xaghra,Gozo. In accordance with the terms of reference, the assessment is required to take into account the nature and condition of the original fabric, the excavation and weathering history of the site, and the tubular steel shoring previously erected at key problematic areas of the complex. The assessment is also required to identify other areas where shoring interventions have not yet taken place, but which require measures to ensure longer-term stability.

1.2 The Structural Assessment Report is also required to include proposals for conservation measures, particularly in the areas which have been shored up, and where the stability of the structure seems to have become dependant on this shoring, in order to enable the removal of the steel tubular shoring, and its replacement with possible, less intrusive, replacements.

1.3 When the Structural Assessment Report is approved, it will be necessary for Terms of Reference to be prepared for the implementation of the recommended interventions.

1.4 The ultimate objective of the Project is to assist Heritage Malta to draw up an intervention strategy for the site, in order to improve its visual aspect and its long-term stability, in the context of a wider plan to erect a Visitor Centre and a Protective Shelter.

2.0 Rationale

2.1 The following rationale is taken from the approved Organisation and Methodology Report, previously submitted.

2.2 The Ggantija Temple complex is one of the four major prehistoric megalithic sites in the Maltese Islands. It basically consists of two temples, adjacent to each other and morphed into one complex. One of these temples is also one of the oldest on the islands, dating back to ca. 3500BC. Although it has the same basic typology as other temple sites, the Ggantija complex is characterized by the use of unfinished (that is, not plane faced) Corallline limestone blocks – with the softer and easier to work Globigerina limestone limited to the portal structures, and decorated elements; as well as by the fact that, (and probably as a consequence to the use of Coralline limestone), the individual megaliths are amongst the most massive that are found in any of the other sites on the Islands. The surviving walls, in both the façade, and inner left apse, are of the order of 7m high. Interestingly enough, however, the Ggantija temple complex can also be considered as one of the best preserved of the major temple sites, because, particularly for the south temple, most of its walls are still standing.

2.3 Various hypotheses have been put forward on whether, and how, the temple apses were roofed over. Other hypotheses have also been proposed on, *inter alia*, the construction methods used, on the significance of the plan shapes, and on the orientation of the temples axes. The assembly of the megaliths to form the apsidal structures seems to have been carried out without the use of bedding mortar at the interfaces. Even if there had been any mortar, distributing the contact stresses, today there is no remaining evidence of any such mortar. The contact surfaces between megaliths have also eroded, so that, in many instances, the transmission of loads from upper to lower megaliths occurs via a reduced number of “aspersions” or point contacts. This is part of the process caused by the exposure to the elements, and in itself explains both the damage that occurs at the contact points where high stresses result, as well as the relative instability of blocks precariously balanced one on top of another.

2.4 This Consultant has studied how the temples behave as a structure, and how various architectural features can throw some light on the way the temples were erected. In general, it can be said that the basic structural module of a prehistoric temple consists of two halves of a “dome” structure, separated by a strong portal structure – which delineates the axis of the temple. The “dome” structure is actually a system of concentric corbelled stone elements that reduce the clear span of the apses so formed, until, according to some hypotheses, the spans can be roofed over by other stone elements, or, perhaps according to others, timber elements. The simplest form of the temple would, therefore, consist of the so-called trefoil plan, that is, a pair of “split dome” apses, and a third apse at the end of the longitudinal axis formed by the portals. The whole would be surrounded by a further ring of stone uprights, enclosing, and probably compressing, (and hence stabilising), the apse structures. Larger temples would be formed by five apses, that is, two pairs of “split dome” apses and the termination apse, or even seven apses. Furthermore, temples also grew by means of adjacent temples merging along a common external wall, and, often, enclosed by a re-configured external stone ring. This is the situation with Ggantija, as it is, say, at Mnajdra.

2.5 The big difference between Ggantija and other temples is that, first of all, the stones forming the apses and corbels are not “squared” or “formed” as in the case of later temples, but basically consist of “boulder” shapes balanced, and fitted together, probably as in vernacular dry coursing (albeit at a much larger scale), into the basic structure typology described above. Secondly, the stones at Ggantija are very large, often considerably larger than at other temple sites.

3.0 Risks of Collapse

3.1 Ggantija consists of two adjacent temples, each with a five-apse system, surrounded by a common outer ring of enormous megaliths, and fronted by the ubiquitous concave façade that characterizes the main temple sites. Sections of the façade of the south temple were identified as at risk of collapse, following a study campaign by researchers from the University of Florence. The scaffolding erected in front of the south façade was intended as an emergency measure to address the real risks of collapse of this façade. Subsequent studies identified other areas at risk, notably in the sides of the termination apse of the south temple – which is one of the highest temple structures still surviving. Emergency props were installed here as well, under the direction of Dr.M.Bonello.

3.2 The north temple is, generally speaking, less at risk. But this is also because its façade structure has collapsed at a time which precedes modern curatorship. Therefore, the scope indicated in the Project correctly identifies four critical areas: 1. the exterior of the South Temple (façade) – where the steel framework is supporting part of the façade of the south building, the corner of which constitutes the highest elevation of the temple complex; 2. the exterior of the South Temple (back wall) – where one of the stretcher megaliths is presently supported by three metal props; 3. the interior of the South Temple – where the scaffolding is supporting unstable megaliths within the inner walls of: (a) the junction between the inner left-hand apse and the back apse, (b) the junction between the inner right-hand apse and the back apse. However, there are other critical areas that need to be looked at, notably the wall at the back of both south and north temple, as well as other parts of the external wall (for example, where a collapse occurred in 2003).

3.3 The basic reasons for the instability are obvious. The integrity of a "dome" structure depends on structural continuity. When parts of the structure collapse, the break in structural continuity places the remainder at a risk of subsequent collapse. In addition, the temple ruin, as it now becomes, is more exposed to weathering actions, notably of the rain and the sun. Significant parts of the Ggantija temples were buried for a large part of their recent life. This exposed the buried parts to infiltration by salt laden waters (sulphates and nitrates from the soil). The movement of water along the ruins of the temple structure had various effects, including leaching of any bedding material between megaliths (if there were any), or of infill material, and erosion of the contact surfaces between megaliths. This further leads to high contact stresses, particularly where the walls are very high, and mechanical damage at the points of contact. The process then accelerates, with stress damage inducing micro-cracks, weathering (flowing rain, migrating salts, temperature gradients) acting on the micro-cracks to lead to loss of surface, leading to other high-stress contact points and so on.

3.4 In addition, as an incomplete structure, whose stability originally depended on structural continuity, particularly of the corbelled apses and roof structure (as a "dome"), the individual stones that make up the structure are no longer held in place by the logic of the structural system, but depend on their own individual equilibrium. The risks that were associated with the façade of the south temple resulted from the fact that the lower megaliths exhibit large voids in the stones themselves, as well as large voids in between megaliths. The margin of safety of the lower, weathered and damaged, stones is difficult to gauge; and, in addition, the stones above, particularly in this location have become similar to a vertical pile of large stones, held in place by whatever tenuous balance of forces still exists. The perception is that, following the erection of the temporary scaffolding, the upper megaliths have leaned outward, and are now resting against the scaffolding. This means that it now seems very difficult to envisage removal or replacement of what was intended as a temporary propping structure, without risking collapse. If the megaliths were more regularly shaped, one could have considered dismantling before removal of the propping structure, and then re-building. However, this seems to be a difficult task in engineering terms, and too risky and too invasive an intervention in archaeological terms.

3.5 A similar situation exists in the interior of the south temple, except that in this case, there is no evidence of extensive weathering of the lower megaliths. One corner between the termination apse and the apse on the left-hand side, is, however, particularly critical since it appears to be detached from both sides, and its equilibrium depends on a precarious contact between the megaliths, and probably, now, on the contact with the propping structure.

4.0 Brief Review of Previous Structural Assessments

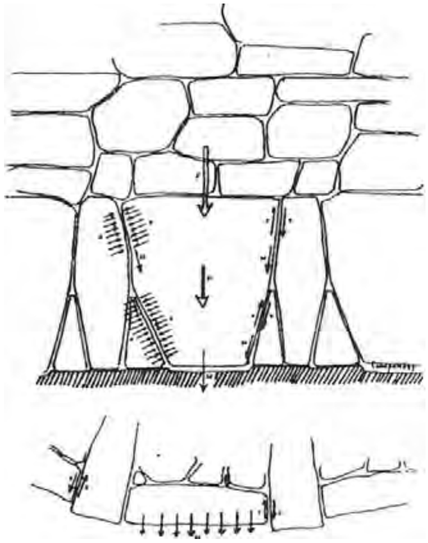
4.1 Systematic scientific assessments of the condition of the prehistoric megalithic temple complexes in Malta and Gozo were started in the 1980's, with a number of projects initiated by the University of Florence in collaboration with the Museums Department. The first studies focussed on the degradation problems of the globigerina limestone used in the temples, (Vannucci, 1985). The first assessment of the construction system and structural degradation issues of the Ggantija Temple Complex was presented in 1987, (Tampone, G., 1987); other studies followed, also on prehistoric megalithic structures, similar to Ggantija: (Tampone, G., 1988), (Cassar, J., 1989), (Tampone, G., 1990), (Tampone, G., 1991), (Tampone, G., 1994), (Torpiano, A., 1994), (Torpiano, A., 1995), (Torpiano, A., 1998), (Torpiano, A., 1999). More recent studies include: (Torpiano, A., 2004), (Torpiano, A., 2011). The studies undertaken by the University of Florence and the Museums Department had already identified the South Façade of the South Temple of the Ggantija complex as in a "dangerous state". The response to this warning was a 1996 project to erect "temporary" scaffolding against part of the South Façade of the South Temple, (Tampone G. , 1994) – see key plan on previous page.

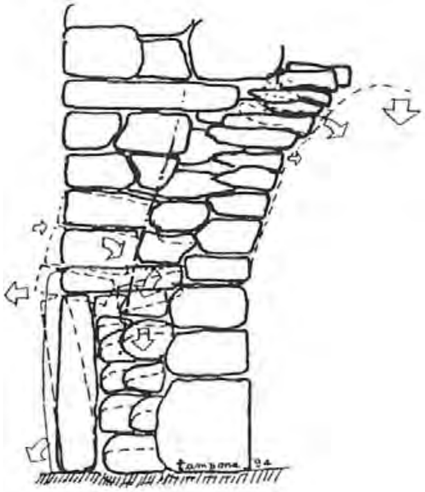
4.2 In December 1999, an Interim Report entitled "Urgent Restoration of Temple Sites", prepared by Dr.A.Torpiano and Dr.M.Bonello, presented an interim assessment of the condition of the major megalithic sites, including, obviously, the site of the Ggantjia Temples, (Torpiano, 1999). This scaffolding is still in place. Later, in 2000, additional temporary scaffolding was erected, also in the South Temple, at the junction between the last, axially-located, apse, (referred to as Apse 7), and the last pair of apses, (Apses 5, and 6) – see key plan on previous page.

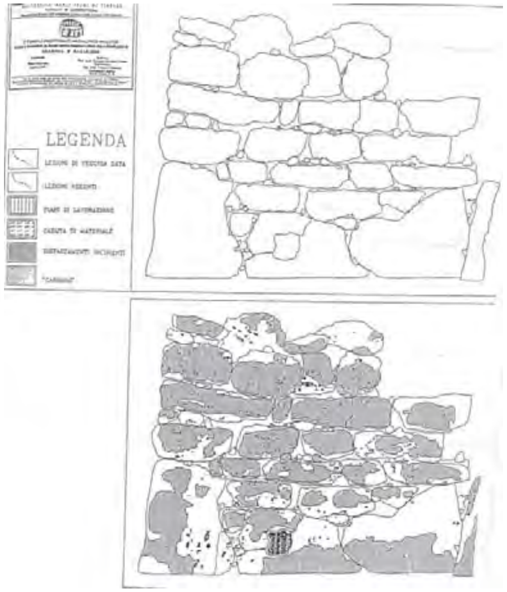
4.3 The Interim Report had noted that all four major prehistoric megalithic temple sites had been effected by collapses between 1994 and 1999, during periods of intense rain, and stormy weather. It was concluded that the link between these collapses and the environmental conditions to which the sites were exposed could not, as a result, be considered as coincidental. The same report proposed some general considerations of the meaning of the terms "integrity" and "stability", which are summarized below. This theme is developed further in the current report.

4.4 In particular, the 1999 Interim Report emphasized that none of the megalithic temple sites could be considered any longer as "structures", but were, more properly, to be considered as ruins. In other words, whatever structural concept they originally conformed to – which seems to have guaranteed a surprising longevity – the situation in these sites was such that practically no structural continuity existed between the various components. Structural continuity is normally the characteristic that permits the application of conventional structural analysis tools. This will be further developed in the current report.

4.5 The Interim Report noted that the integrity of masonry assemblages depended primarily on rigid body equilibrium; in other words, on the existence of a system whereby the actions on each element – in this case, limited to the self-weight of each block, and hence to vertical gravity actions – are transmitted through the sequence of interfaces between the blocks, down to the ground. The interfaces are, however, subject to deterioration mechanisms, which, as will be explored further in the current report, change the nature and extent of the contact surfaces, resulting both in increased, and potentially damaging, contact stresses, and also rotations. Indeed, Tampone, (1994), examines the collapse mechanism of the South Facade of the South Temple, and concludes that it is characterised by small rotations, at the joints, together with cracking as a result of uneven bearing contact surfaces. Collapse results when the contact surfaces of wedged-shaped stones, originally locked against each other, start to “crush”.







4.6 Tampone emphasizes that the assessment of stability of these masonry structures cannot be simply based on rigid body motion, because of the local crushing at the contact surfaces, which renders the blocks equivalent to “deformable” blocks.

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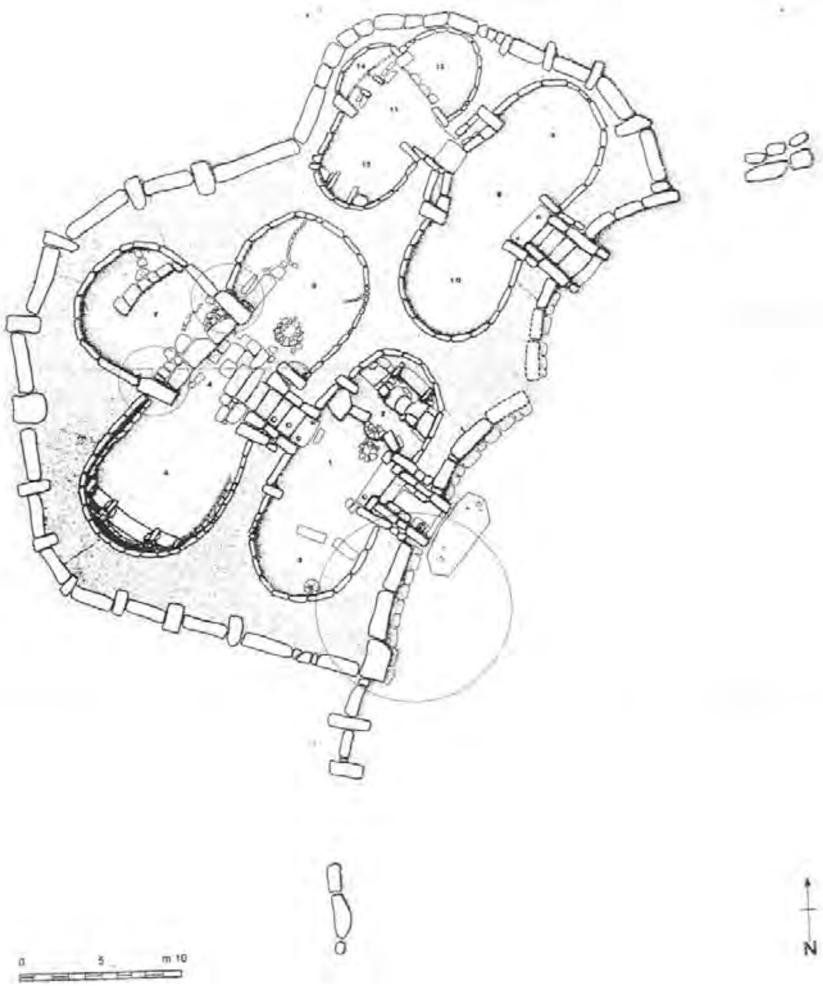

Key Plan, after J.D.Evans, 1971

5.0 Stability of Masonry Assemblages

5.1 Masonry structures are formed by the assembly of discrete solid, or hollow, units, (in this case, very large stone blocks), separated by joints – which may be dry (as in this case), or filled with mortar, or other materials. The stability of masonry assemblies is basically a problem of equilibrium. In the absence of any external agencies, the gravitational weight of each masonry block is balanced by the resistance of the blocks in contact with it. For each block, the system of forces, comprising gravity (acting vertically), and the reactions at the points of contact with adjacent blocks, (together with any external forces, such as wind, or retained soil, or earthquake acting on the individual block), must be in equilibrium for the system to stand up. In other words, the vectorial addition of all forces acting on each masonry block must be zero. The lines of action of these forces must also intersect at a point, in such a way that there is no residual moment of rotation. Rather than 2D closed triangles of vector forces, 3D equilibrium would result in closed tetrahedrons of vector forces. An assembly of masonry blocks is in equilibrium if the “cascade” of such reaction forces, at the points of contact between blocks, can be carried down to the ground.

5.2 The simplest system, in this scenario, is the interface between two blocks, one on top of the other, through which the lower block must provide an equal and opposite reaction to the vertical gravity load from the top one. The upward resisting force in the lower block must necessarily be equal in magnitude to the weight of the upper block. This guarantees equilibrium of forces. In addition, however, the line of action of the self-weight of the upper block, which passes through the geometrical centroid of the block, must be co-linear with the resultant of the upward force, transmitted through the interface; otherwise, a “couple” is set up, with consequent violation of rotational equilibrium. If the interface were a perfectly smooth, plane, surface, the resultant of the upward force could be expected to pass through the centroid of the area of contact - even if the area of contact were smaller than the plan dimension of either block.

5.3 If the area of contact were subject to any weathering processes which (i) reduce the area of contact; (ii) break up the single area of contact into a number of smaller contact areas, then the following considerations could be made.

(a) The reduced area of contact, carrying the same vertical load, will induce higher contact stresses, until, at some stage, such stresses are sufficient to cause material distress, and hence further damage to the contact surface;

(b) The reduced area of contact may not occur symmetrically about the centroid of the original contact area. As a result, the centroid of the contact area changes position with respect to the centroid of the overlying mass – this leads to the creation of disturbing moments, or couples, which can displace the blocks.

(c) If the original contact area is broken up into a number of smaller contact areas, the centroid of the resisting force changes to a different position, depending on the size and distribution of the sub-contact areas. Once again, non-colinearity leads to rotations and displacement.

5.4 If the area of contact were exactly horizontal, equilibrium would be guaranteed even if the contact surface were perfectly smooth and frictionless. If, on the other hand, the area of contact were inclined to the horizontal, the vertical vector representing self-weight, acting at an angle different from 90^o to the area of contact, would develop a vectorial component, of the weight, parallel to such inclined area of contact. Relative sliding could then occur, unless the component of force could be balanced by co-linear frictional forces at the contact interface.

5.5 Friction is normally modelled using Coulomb Law, which contains a constant component which is often referred to as cohesion, and a second component, often referred to as residual friction, which is generally considered directly proportional to the normal load acting on the contact surface.

$$F = \mu R + C$$

The constant of proportionality, μ, is referred to as the coefficient of friction.

The intrinsic magnitudes of both C and μ depend on the characteristics of the surfaces in contact. When two blocks are in contact with each other, as described above, without the presence of any “glue” between them, the term “cohesion” is clearly misleading. It is normally considered to refer to the relatively large asperities that exist on either surface, some of which, more or less, interlock when brought into contact. Relative movement is clearly resisted by the shearing strength of the asperities – which prevents relative movement, even if there is no force acting normal to the surface.

$$F = \mu 0 + C = C$$

When the shearing force increases, it eventually reaches a stage when the asperities preventing movement shear off, bringing the “cohesion” to zero. Any residual resistance to sliding must then be achieved by applying a force normal to the contact surface, bringing the smaller asperities into play.

5.6 The magnitudes of both C and μ, therefore, both depend on the shear strength of the material of which the masonry units are produced – the capacity of the asperities on the surface to resist shearing off - as well as the characteristics of the surface, that is, in simple terms, the amount and type of surface asperities. The most important aspect of the foregoing discussion is that, once the cohesion is overcome – ie when some relative sliding starts – there is a sudden drop in frictional resistance (hence the term “residual” friction), which may or may not be sufficient to balance any component of forces acting parallel to the contact surface.

5.7 Normally, such contact surfaces are neither regular nor plane. It normally happens that a sudden slip creates a different situation in the contact surfaces, whereby some asperities re-engage, and hence provide sufficient additional resistance to stop relative movement. This leads to the characteristic “slip-stick” mechanisms between this type of “rough” materials.

5.8 The process is, yet again, complicated further by weathering processes. The presence of an interfacial layer can have, first of all, the effect of filling the spaces between asperities, and hence of providing some lateral support to such asperities – that is, increasing the ability of the asperities to resist shearing loads. If the weathering process removes such interfacial layer – that is, by washing away mortar, interfacial sand or soil – the ability of the asperities to resist shearing is obviously impaired. Secondly, if, after the removal of the interfacial layer – or when the interfacial layer does not exist – weathering produces any alterations in the state of contact, there will result alterations in the frictional characteristics. In particular, as weathering (this could be erosion of contact surface, or movements/rotations induced by any action) reduces the area of contact between the two surfaces, the obvious result is the reduction of the “amount” of asperities that can interlock, and that would need to be overcome to allow sliding. It could also be hypothesized that, as the area of contact reduces, the normal stress carried by the reduce area increases; this increases the transverse resisting stress, via the coefficient of friction. However, as the increased stress acts over a reduced area, the net result is not beneficial.

5.9 If one combines this effect, with the additional damage caused to the contact material, as a result of the increased contact stresses, it could be concluded that (i) weathering has a significantly deleterious effect in frictional capacity; (ii) the phenomenon of friction across a rough, weathering, surface becomes impossible to model.

5.10 Up to now, we have only considered the contact surface between two blocks, one above the other, and the action of gravity alone. If a horizontal force acts on the upper block (say, wind action, earthquake action, movement of adjacent blocks), then this horizontal force combines vectorially with the vertical force to give an inclined resultant. An inclined resultant, acting on a horizontal surface, will induce a sliding force at the interface, which needs to be contained by the frictional resistance. If the inclined resultant acts on an inclined surface, the component of force, parallel to the interfacial surface, increases, at least in the situations illustrated below; this leads, once again, to higher demands on the frictional resistance at the interface.

5.11 Furthermore, the successful transmission of what is now an inclined force through a lower block, to the ground, depends on whether the inclined force can still pass through the interface between the lower block and the ground, or not. If the inclined force does pass through such lower contact surface, the conditions of equilibrium are as described for the interface above – that is, whether horizontal sliding above the ground, or vertical displacements into the ground can be resisted, or not. If the inclined force does not pass through such lower contact surface, the block becomes liable to rotation about one of its edges, as illustrated.

5.12 If the upper block is in contact with more than one block, underneath, or with adjacent blocks, the displacement of the block, or otherwise, will depend on the vectorial interaction of all the forces at the contact surfaces, whether normal or transverse to the respective contact surfaces, and the relationship of the resultant of all these forces, either to the line of action of the vertical gravity of the block in question, or to an inclined line of action, if there are also horizontal actions in addition to gravity.

5.13 In all cases, the magnitude of the resisting forces, in three orthogonal directions, must be equal and opposite to the relative component of the resultant action, in the same three orthogonal directions. And the actions and the respective reactions must also be collinear, so that no disturbing couples could be set up. In a structure composed primarily of blocks resting on top of each other, the complex relationship described above, between two blocks, is repeated for every pair of blocks, and indeed for all blocks in contact. Any rotations/displacements occurring in one contact area will, therefore, have an effect on many other contact surfaces. Each little change in one area can therefore significantly affect the state of equilibrium in another area. The effect of weathering, that is the modification of the contact areas over time, can therefore be very significant. It is also very difficult, if not impossible, to model unless one has full and correct detail of, not only the blocks themselves, but also the detail of all contact surfaces between all blocks.

5.14 If the geometry of the blocks were simple and regular, and known, then the calculation of the position of the centre of gravity of each block would be easy, as would the forces required at the points of contact between blocks. The verification of equilibrium of each block would be a relatively simple, although tedious, calculation. This verification would have to be carried out for every block. In addition, the forces at each point of contact would not be immediately known, unless there were only one contact between each pair of blocks. The magnitude of contact reaction forces, in an assembly of masonry blocks, would require the solution of systems of simultaneous equations describing equilibrium at each contact point. As the number of contact points increases, this solution would require computing assistance.

5.15 In addition, the criterion of equilibrium, by itself, is not sufficient to describe the degree of safety of a masonry structure. A simple column formed by equal cubes of masonry is in equilibrium if the strength of each block allows the transmission of (gravity) force from the top block, in sequence, to the bottom block, and then to the ground. It can be appreciated, however, that if the horizontal cross-section of the column of blocks became smaller and smaller, as the column became higher and higher, there would come a time when the column of blocks would fail, not because the strength of the masonry is not sufficient to react against the weight of each block, but because of the phenomenon of elastic instability, or buckling. A simple column of blocks is susceptible to buckling, as it gets thinner, because any lateral disturbing force could, eventually, bring the “castle” down.

5.16 There is a further issue that needs to be explained, relating to the nature of equilibrium. When actions are static, equilibrium refers to the fact that all actions, as they are transmitted through the main interfaces of the block system, are completely balanced by frictional forces and compressive strength. Another definition of equilibrium can be applied when actions are not static, that is, dynamic, as in the case of wind forces, or the “jerks” produced by seismic action, or even as in the small displacements that occur as a result of modifications of the contact areas. If the disturbed system, originally in equilibrium, returns to its original positions, when the disturbance is removed, we can refer to “stable” equilibrium. If a horizontal force is applied to a block resting on a flat surface, such that the inclined line of action (with the interaction with vertical gravity forces) causes a slight rotation of the same block, and if, when the horizontal force is removed, gravity can bring the block back to its original position, then the structure is not only in equilibrium, but also in a state of stable equilibrium. In this case, minor disturbances cause displacements and rotations, but when the disturbances are removed, then the system reverts back to its original state.

5.17 If the system does not revert to its original state when the disturbance is removed, but the structure remains in equilibrium in its new configuration, without any further displacement, one could refer to a state of neutral equilibrium.

5.18 On the other hand, if the structure in the disturbed state is not capable of either reverting to its original configuration, or, at least, retain its current configuration, then the system will continue to displace, even when the disturbance is removed, until it collapses. If this state is reached, even after a very small disturbance, the original configuration could be referred to as in a state of unstable equilibrium.

5.19 This long discourse has been considered as necessary in order to explain the significance of the task at hand. That the current assembly of masonry blocks, or the current configuration of unsupported megaliths, is in equilibrium is not in doubt. The state of equilibrium is proven by the fact that the assembly of megaliths *exists.* If the current configuration (and this is understood to include all the complex system of contact surfaces, transmitting gravity, and, up to now, wind actions, down to the ground) is in place at all, this means that all actions within this configuration are in equilibrium.

5.20 If the state of contact surfaces did not change with time, (that is, did not weather), this state of equilibrium would last forever.

5.21 If the current configuration included active supports, (such as props), then it is likely that these supports are contributing to the current state of equilibrium of the current configuration; this implies that if the existing props are removed, something has to change in the current configuration, so as to re-establish a system in equilibrium without the external supports – unless there is currently no contact between the supports and the supported (which can certainly be observed to be the case, in some locations). This change in configuration is in effect a disturbance. The structure could displace into another configuration, but remain in equilibrium, or it could remain in its new configuration without displacement – or it could even displace catastrophically into collapse, depending on whether the currently propped structure is in a state of stable, neutral or unstable equilibrium.

5.22 Ii is practically impossible to determine this without removing the props, that is, without actually causing the disturbance to the system unless the configuration of the relative blocks, and the various contact surfaces between them were known exactly, so as to allow some kind of predictive modelling. Nevertheless, knowing the type of equilibrium at one moment in time is not sufficient to guarantee the same type of equilibrium in the long-term, unless the process of alteration of the contact surfaces were completely frozen in time. Or, alternatively, some system could be put in place that could react to the slight displacements by generating “reactions” to recover stable equilibrium. This is similar to the action of the brain, which senses slight movements of the body, and makes immediate small changes to muscle tension, or body position, to regain equilibrium. Even if such system were technically possible, its installation would, it should follow, require some kind of device at every interface – and this would inevitably have a major visual impact on the monument.

5.23 The response to the problem of weathering therefore cannot be much more than one whereby weathering – that is, alterations of the contact surfaces – were reduced to a minimum, so as to preserve the current state of affairs. The problem would then change to one whereby the term "structural stability" would not be used to describe the current state of affairs – since the monument is currently obviously stable – but to define the degree of "disturbance" that the structure could absorb without changing its current state of equilibrium into instability. Once again, this could only be done if one knew exactly the geometry and characteristics of each block, and each contact surface, and if one produced some mathematical model whereby the effect of "disturbances" could be simulated.

6.0 Numerical Modelling

6.1 As has been pointed out before, masonry is formed by discrete units, separated by joints, which may be dry, or empty, or filled with mortar or other materials. This configuration makes structural analysis complex. Mathematical tools to assess "discontinuous" structures, such as masonry structures, are available in the form of Discrete Element Analysis (or Distinct Element, or Discrete-Finite Element, or Rigid Body, or Boundary Element analysis) (Lemos, 2007). These are different formulations intended to allow an assessment of the overall structure as an assembly of distinct bodies, interacting along their boundaries, in the ways described hitherto. Phenomena of joint sliding, joint separation, large relative movement of units, and change of geometry and connectivity, as described before, are considered as strongly non-linear problems.

6.2 Discrete Element modelling requires exact knowledge of the solid geometry of each block. Most programmes then assume that such blocks behave as rigid bodies. The rigid body assumption is quite valid, when the dominant mode of failure is a mechanism failure – as has often been observed. However, it is also possible to include block deformability to address the elastic contact situation. The next problem is knowledge of the contact characteristics between blocks. Normally point contacts are assumed – which is a reasonable assumption in the case of the rough masonry blocks. An alternative contact formulation is edge-to-edge. Knowledge of the number and location of point contacts is not easy to acquire, particularly for the depth of the walls in question. The constitutive nature of the contacts is a further complication – is the contact hard, or is it soft, or deformable?

6.3 The deformation and strength characteristics of the solid masonry block can be determined in a laboratory. The information could be based on results from geologically-similar material, with some allowance for the effects of weathering. The characteristics of the joint are even more difficult to determine. In dry joints (as contrasted to mortared joints) the rough and irregular contact surfaces induce stress concentrations, and local deformations around the block surface. Nonetheless, some idea of the typical nature of contact surfaces is required, and this is very difficult to obtain.

6.4 Assuming that it were possible to obtain a complete 3D description of the temple megaliths, it would be possible to model using proprietary software, which is appropriate for discontinuous structures, for example based on boundary element mathematics or discrete element algorithms. Discrete Element Modelling has been used to assess masonry structures over the last forty years. Initially these techniques were used to study fissured rocks, which are also characterized by discontinuities, (Goodman, 1968). The fundamental concept of DEM models is the ability to represent masonry “as an assembly of component blocks in mechanical interaction”. The use of discrete or distinct element modelling of masonry structures is reported in literature, for example, (Cundall, 1971), (Cundall, 1988). Applications of these techniques are, however, normally found in research literature, and for relatively simple buildings, using ashlar masonry blocks (regular parallelepipeds) with plane contact surfaces, (Gilbert, 1995), (Briccoli Bati, 1995), (Lemos, 2001), (Psycharis, 2003), (Mayorca, 2003). Some examples involving 2D models of irregular dry-stone masonry walls, (Powrie, 2002) (Roberti, 2001), have also been found; however, no examples have been encountered in the literature of masonry 3D-modelling of structures, that are composed with elements that are as irregular as the megaliths in Ggantija. Many of these models have difficulty with the representation of fracture of the blocks, as contrasted to rigid body displacement; this would require the use of deformable block models with elasto-plastic characteristics (which are, in any case, currently not known). The literature reports one DE formulation which uses fracture mechanics criteria to represent fracture, (Munjiza, 1995). A further formulation is to use particle DE models, (Lemos, 2006). The problems remain with Input data – although it is possible that particle models can help in this regard.

6.5 The problems of proper joint modelling lie in the difficulty of modelling the contact behaviour. Most Distinct Element models assume point-to-point, or edge-to-edge contacts, even if some codes allow vertex-to-face interaction. The modelling of multiple point contacts, over a contact surface, remains difficult. Most Distinct Element models allow opening of joints, and re-configuration of contact zones.

6.6 There is an alternative approach which converts the discontinuous structure into a continuous structure, with, however, properties equivalent to the discontinuous structure. This could only be done, however, if sufficient information existed for the constitutive properties of the discontinuous system (that is, basic relationship between actions and the response to the actions). In the case of the megalithic structures, with non-regular blocks, such constitutive properties are exactly what one is seeking to discover; therefore, the use of equivalent continuous structural analysis techniques is not useful in this case.

6.7 Validation of results from numerical models, with experimental data remains, however, very difficult. It is obviously meaningless to validate models in general terms; it is necessary for the validation to be very specific. In other words, it is known that with the right input data, it is theoretically possible to get reasonably accurate models of behaviour. But which right input data is required? And how accurate does it have to be, once that it is not possible to validate by physical experimentation?

6.8 When the methodology for the structural analysis of this monument was being formulated, it had been indicated that a 3D model of the Ggantija Temples, obtained using laser scanning technology, was available. It was expected that this model would be very accurate, at least as far as concerns the megaliths on the external faces of the walls. The model cannot, however, give any information on the interfacial contact surfaces, because these surfaces are, by definition, hidden from the laser scan. It was presumed that some field measurements and tests would have to be carried out in order to characterize such contact surfaces.

6.9 However, although the 3D model, prepared by General Engineering of A.B.C s.a.s. of Florence, Italy, is available, it has turned out that it is very difficult to create a complete, solid 3D, model, to be used for distinct element analysis. The data available consists of the geo-referenced laser scan point data, of surface contour drawings derived from this data, and versions of such drawings merged with photographs, ortho-photo maps, dxf-format files, mdl-format files, and records of the photographs and scans from the survey. The data made available also includes a 3D movie clip of the whole model. Not least, the dxl-format files are very difficult to handle using ubiquitous Autocad drawing software, and the mdl-format files can only be read using proprietary software which is not easy to use.

6.10 In addition, not only the data available does not give information on the nature of the contact surfaces, (information that is vital for a realistic assessment of the interaction between adjacent blocks), but one could argue that *it may be intrinsically impossible* to obtain definitive data of the nature of the contact surfaces, because such nature changes with time – because of weathering, and because of even small movements of one block relative to another.

6.11 The key issue, in all of these approaches, is the ability to model the real structure as closely as possible. The incomplete nature of the temple ruins precludes any simple model. In a complex situation, the structural integrity may depend on a parameter which is not modelled correctly.

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7.0 Monitoring

7.1 The approved Methodology also envisaged that a system of movement sensors would be installed at the critical locations of the structure. It was originally envisaged that the movement monitoring would be useful so as to, first of all, to be able to understand the nature and scale of movements of critical elements in the temple structure, but also to be able to calibrate the eventual computer modeling. The difficulty with this is that unless there is some sort of preliminary structural modeling of the whole structure, it is difficult to anticipate where such sensors should be located, and what data should be collected.

7.2 It was therefore decided that the movement sensors would **not be installed** for this purpose, and therefore not at this stage, but **after** any interventions, so as to act as a network of early warning, at the locations of the interventions, which, together with the data obtained from the weather collection system on the site, particularly temperature, humidity and wind conditions, could sound the alarm as a result of movements occurring at these critical locations. The problem would still remain that of identifying the level of movement that would be considered as critical enough to trigger a warning. However, with real-time measurement technologies, it might be possible to avoid a decision on such trigger until after a period of monitoring would give a reasonable understanding of what order of magnitude of movement, or vibration, is of concern and what is not.

7.3 Different systems of monitoring are possible. Nevertheless, the nature of the monument to be monitored informs the selection process. Ideally, sensors would be wireless, to avoid the installation of wires all over the place, capable of secure installation (therefore, probably out of easy reach), and with long power capability. In general, it is possible to monitor movement, or vibrations, of a body, by means of an accelerometer. An accelerometer can record movement or vibration in one direction or in bi-axial or tri-axial directions. Typical accelerometers would be cylindrical, typically 20-30mm diameter, and 30 – 50mm high. It is obviously important that the connection to the base, whose movements or vibrations are to be measured, be as rigid as possible. This implies the use of either mechanical connections, or surface adhesives. It is also possible to monitor changes in angle by tiltmeters, or digital clinometers. These can normally measure tilt uni-axially or bi-axially, depending also on the way they are mounted. Once again, a rigid mechanical connection to the base is required. Typical vibrating wire tiltmeters are approximately 250mm long, by 30-35mm wide. Wireless inclinometers are available that measure ca 40mm x 40mm, and that, attached to a surface, can measure the pitch, roll and yaw of that surface. Other sensors are available that can measure opening or closing of discontinuities, (joints or cracks), but, in this particular context, it is difficult to see how such monitoring – that is applied to a specific discontinuity, which may not participate in a displacement event – can be of useful significance.

7.4 The sensors are normally accompanied by wireless data aggregators, or collectors, and a central wireless base station. The base station can be used to communicate automatically with a computer, via various modes, including mobile communications technology and internet. In other words, data could be collected off-site.

7.5 Various makes have been identified, including Techkor Instrumentation, Geokon Inc., and Microstrain. It is proposed that the monitoring system be designed after a decision is taken on the type of intervention envisaged, if any. A definitive decision has to be taken, however, on the fixing systems that would be approved – since a direct connection between any instrumentation and the base to be monitored is vital for meaningful readings.

7.6 Non-contact monitoring systems are less easily available. Some progress has been made with the use of periodic photogrammetric surveying, or laser scanning, to monitor movement. Small reflectors are attached to various critical locations of the monument and identified in a photogrammetric survey or laser scan. Successive surveys or scans can be compared, also automatically, in order to give a picture of any movement. However, the use of this technique as an on-going monitoring system is difficult to see.

8.0 Some Alternative Approaches to Structural Stability Issues

8.1 The fundamental objective of this study was to assess the current structural stability of the megalithic structure, and in particular to assess whether the current structural props could be removed, or, if this were not possible, re-designed to be more attractive and less intrusive on the monument. The methodology originally envisaged was that a reliable three-dimensional virtual model could be used to predict the behaviour of the monument, when the props would be removed, and, further, when other dynamic events, such as storms or earthquakes, occurred. The difficulty of accurate interface modelling, and the dynamic nature of the weathering processes that affect such interfaces, combine to render the possibility of accurate virtual behaviour models virtually impossible. An alternative approach to the issue of structural stability therefore needs to be explored.

8.2 The biggest unknown, in ruins of this nature, is not whether the extant megaliths are in equilibrium – because clearly, those still standing *must* be in equilibrium – but for how long would such megaliths, whose contact history was changing as a result of weathering mechanisms, would remain in equilibrium. The best type of intervention, therefore, would be one where the agents of weathering are, as much as possible, removed from the scene, for example by installing protective shelters, as has been done elsewhere.

8.3 Another option would be to counteract the effects of weathering at the contact surfaces by somehow filling in the gaps that have hitherto been formed at the contact surfaces, to reinstate contact where it has been lost, and hence to improve the bearing and sliding resistance of assembly. This is more difficult than it sounds, since it introduces a whole new range of problems, including that of joint infill changing the structural load paths inside the monument to something which may be deleterious, and that of joint filling material selection, and joint filling reversibility.

8.4 A variant of this option would be to install an extensive system of displacement and rotational sensors, all over the monument, so that, when any displacement (above what has to be an arbitrarily defined trigger level) is identified in a particular group of blocks, action could be taken on the contact surfaces related to such group – such as the insertion of wedges, or similar “improvements” in contact geometry. In theory this would require a sensor per block, or else a difficult identification, or “guestimation”, of the more critical blocks – which would clearly be very intrusive. Alternatively, one could adopt a system of non-intrusive, but high resolution, monitoring, such as high-speed laser scanning, or photogrammetry, which could allow the rapid comparison of the sequence of images so as to identify any differences. This is a technique which is still being explored.

8.5 Another option is to embark on a “Jenga-like” process of removal of the props which appear to be in contact with the monument, (those props which are not in contact could be removed without further ado). The words “appear to be in contact” are used carefully, since mere contact does not necessarily imply that there is any transmission of forces across the contact interface. The process of removal of the props requires detailed and real-time monitoring, so that any consequences could be immediately identified. Ideally, the process of removal of the props would have been simulated, but this requires detailed knowledge of the block geometry, and of the joint surfaces, just as would be required for a full structural analysis – and, as indicated previously, this detailed knowledge is not available. If all props were to be removed in this way, this would indicate that the assemblage of stone blocks is stable – but the challenge would remain to stop all parts of the contact areas from “changing”, or weathering, so as to maintain the equilibrium without props, previously achieved.

8.6 A further alternative is to accept the props in contact with the megaliths as a necessary, permanent, “evil”, and, in this case, to replace the current, visually intrusive, propping structure with one which is visually more respectful of the monument. A number of alternatives come to mind, using materials such as pre-tensioned glass struts, possibly in tensegrity assemblies, (that is glass tubes in compression stabilised by steel cables). The process of dismantling of the existing props and replacing them with a new propping structure includes the same sort of risks as outlines in 8.5

above, with the benefit, however, that once the replacement propping structure is in place, the problems of long-term weathering are less important. However, the problems of anchoring the propping structures, as elegant and lightweight as they may be, to the ground – something which is vitally necessary for a propping structure to work – cannot be under-estimated. Stability of propping structures can only be guaranteed by direct anchoring into the ground (i.e. by drilling into the ground and anchoring the propping structure), by a very heavy base for the propping structure (i.e. by heavy concrete blocks, or sand-bags – which would re-introduce the problem of visual impact), or by a very deep propping structure, (i.e. deep at the contact with the ground, possibly tapering upwards). None of these options seem easy.

8.7 A final alternative is one which carries risk, and also involves direct interventions on the monument. It is one which, however, is more likely to give long-term peace of mind with minimum visual impact. This alternative is that of dismantling the megalith assemblies, where the propping structures have been deemed necessary, and re-constructing. The process would start from the very top, with the propping structure still in place, and would proceed, carefully downwards, with the sequential removal of a row of props and the disassembly of another row of megaliths, until all the props have been removed. This process would, first of all, allow access to some critical megaliths at the bottom of the assemblages. In the South Facade, for example, there are some megaliths with very significant cavities which would need, in any intervention, to be repaired, by infilling. Dismantling the blocks above would make this operation so much easier, and would give it so much greater chance of success. The dismantling of the individual blocks would also allow the complete, and detailed, characterisation of the surface geometry and texture, which would then allow the creation of a more realistic simulation model, than is currently possible. This would allow the simulation of the reconstruction process itself, as well as allow a virtual assessment of, say, response to dynamic disturbance.

8.8 The reconstruction process could also introduce the possibility of adopting “cushion” elements between blocks, so as to enhance long-term resistance at the contact surfaces of the re-assembled structure. It is acknowledged, of course, that this is archaeologically a difficult issue, since is introduces “alien” elements, which would be difficult to disguise or hide. Nevertheless, it is a possibility that only dismantling and reconstruction could offer.

8.9 The proposal to dismantle and reconstruct is probably an extreme one. It is, however, not unheard of. There are two circumstances where reconstruction has been adopted. In a scenario with which Malta is familiar, reconstruction has been adopted, in Mnajdra, Hagar Qim, Ggantija and Tarxien, *after unforeseen, and unplanned, circumstances.* The biggest issue, in these cases, was the availability of detailed documentation which could guide the forced reconstruction. In alternative scenarios, as has been used in other important monuments abroad, such as the

Parthenon in Greece, monuments have been dismantled and re-assembled, either to correct previous incorrect reconstructions or to improve the condition of the monument. The key consideration is the information available to carry out such reconstruction – and the laser survey carried out recently should give this information. Nevertheless, the difficulties of such an option are not under-estimated.

8.10 In all of the alternative scenarios addressed above, the importance of reducing the potential for alteration of the contact surfaces remains undiminished. Hence, some sort of overall protection to the monument is likely to be required in all scenarios.

9.0 Data Collection: Photographic Survey

9.1 The study has obviously included a detailed photographic survey, over 2010, which is used to highlight the situation, and to identify potential areas of concern. The photographic survey is summarized in Appendix A.

9.2 For the sake of completeness, archival photographic material, as has been obtained, has also been collated in Appendix B. Archival material is useful for comparison with current situations. Indeed, one impression that such archival material makes, when comparing with current status is that the rate of surface deterioration of most of the stone units – with some notable exceptions – is much less severe than imagined. More important seem to be the collapses that result from loss of equilibrium.

10.0 Conclusions

10.1 In the light of the above, the following observations are made, with reference to the original task list.

10.1.1 All available geometrical and topographical data, has been collated.

10.1.2 A detailed survey of the propping structures is available from the 3D models collated – however, this information may not be very relevant to the problem at hand. Eventually, a decision has to be taken on its removal or otherwise, irrespective of its current configuration. The main question is whether such proppisng structures are actively supporting the monument or not. Mere contact is not sufficient to indicate this. However, in some areas, where there were pieces of wood between the metal structure and the stone surfaces, there is some evidence, via the indentation of the wood, that some active transmission of force did occur, or is still occurring.

10.1.3 Typical contact surfaces have only been studied by visual inspection; no latex casts have been taken, in view of the conservator concerns – but especially because, as has been shown above, modelling analyses, in which such contact surface characteristics would have been useful, have been found to be intrinsically not useful – because the problem of weathering, and therefore the alteration of such surface characteristics remains, and nullifies the usefulness of any such "measurements".

10.1.4 The procurement of movement sensors has been delayed, because, as explained above, it is proposed that movement sensors be employed not as a means of obtaining data before carrying out a structural analysis, but as a early warning system that some displacements are taking place.

10.1.5 The issues underlying the difficulty of modelling have been addressed above.

10.1.6 The identification and monitoring of dynamic events was intended to calibrate the modelling referred to above; if such modelling is not carried out, the simulation of dynamic events is an unnecessarily risky operation that does not yield useful results.

10.1.7 As per 10.1.5 above

10.1.8 As per 10.1.5 above

10.2.1 The first report, outlining the organisation and methodology to be adopted throughout the study, including the identification of the necessary assessment programs, to enable the structural analysis of the megalithic structure and 'modern' supporting elements, has been delivered.

10.2.2 The current report represents the "Data Analysis and Interpretation Report". It includes an evaluation of the proposed data gathering and modelling campaigns, overall identification of the areas that require particular attention, an evaluation of the condition of different structural elements, and the conditions which determine existing and potential structural failures, and recommendations for corrective interventions, particularly as regards the existing "visually intrusive" scaffolding/propping structures.

10.2.3 The final Structural Assessment Report will be based on the response to section 8, above. This response is expected to include consultations with all stakeholders.

11.0 Recommendations

11.1 The author is convinced that it is possible to adopt the scenario described in paragraphs 8.7 to 8.10 above. Even if the author is equally convinced that many parts of the propping structure are not, actually, actively supporting the stones of the monument, the situation where the propping is located, particularly the South Facade and in the interfaces between apses 6 and 7 and 5 and 7, the state of stability remains highly precarious and indeterminate. It is, as has been explained before, in a state of unstable equilibrium, and the situation is highly susceptible to the effects of weathering, which can alter the current situation at the interfaces, to a situation where the unstable equilibrium would be lost, without warning.

11.2 In other words, simply removing the propping structures is not sufficient, even if it could be shown that the structures are not, at this moment in time, active. In order to change the state of equilibrium, to neutral if not to stable, other interventions are required, following, or preceeding, the removal of the propping structures. In the view of the author, the most effective would be the option of dismantling the critical areas, and re-assembling. The process should include the scanning of each individual block, and then, some form of discrete element analysis – for the dismantled portion – to enable a check on the stability of the re-assembled section, even following dynamic events. It is re-iterated, however, that, as with any other solution, the long-term protection of the monument, to reduce the incidence of interface weathering, and hence alteration, remains a requirement.

11.3 The dismantling process requires a small team of skilled labourers, with a crane, under careful supervision. The re-assembly process will require further study, as described above, but will be helped by the extensive 3D laser scanning already carried out. It will also require decisions on the insertion of new interface material, or otherwise; or possibly the insertion of hidden structural support, within the fabric.

Alex Torpiano

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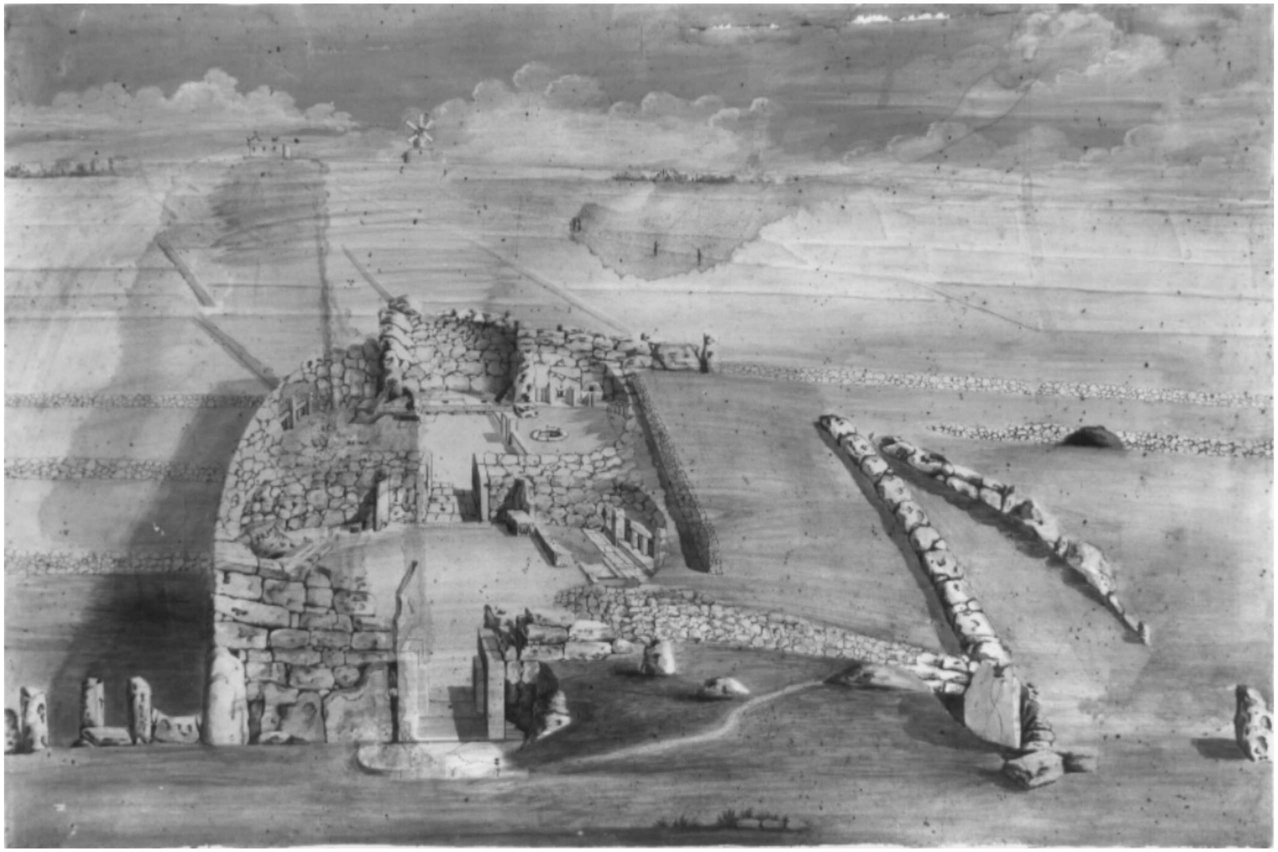

STRUCTURAL SURVEY AT GGANTIJA TEMPLES, GOZO

APPENDIX A

CONTRACT CT2115/2009

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12.0 Photographic Survey

1. North-west Elevation – composite

2. South-west Elevation – composite

Notes:

1. The North-west elevation is characterised by a lower ring of upright megaliths separating “flat” large megaliths, topped by up to four horizontal layers of smaller megaliths. The lower “flat” megaliths are further characterised by diagonal cracks at one or both lower corners. The upright megaliths have been studied by Tampone, and are reported to have a tapering width, from top to bottom, as well as a wedge-shaped horizontal section. These are features are attributed (Tampone, 1994), (Torpiano, 2011), to the classical construction process for the external wall for the temple complexes. The stability of this outer wall depends on the locking in of this lower ring of megaliths, in a form of ring compression. The outer wall rests on, or contains, the inner walls, is of prime importance in giving overall stability to the whole complex. The upper rings are probably also slightly wedge-shaped in plan (on the basis of evidence from Mnajdra), so as to form a convex structure, which leans slightly inwards, and therefore locks in the interior structures. The stability of this system is fairly secure in the direction in the plane of the wall. It is less secure in a direction normal to the plane of the wall, either when the internal walls no longer provide the structural continuity/support to the external wall, or when, as is indicated on the right of this image, weathering leads to changes in the contact surfaces to the extent that the lower megalith is pushed outwards. This perceived movement seems to have induced the insertion of the three steel props that are observed on the right. It is not clear whether these propos were (i) ever useful to maintain the stability of the wall, (ii) useful at the moment. At least one of the props was, for a long time in recent years, not even in contact with the megalith it was meant to support.

2. The South-west elevation is characterised by a central area which is likely to have been the site of a previous collapse of the system described above. Part of this area was also the site of a collapse in 2003 (see. Photos 73-75).

3. The South-east elevation is composed of the main “South” façade of the South Temple, against which a propping structure was erected, (and which is one of the concerns of the current investigation), and the main façade of the North Temple. The interface between the two concave facades is the site of an old collapse.

4. The North-east elevation shows the beginning of the characteristic construction system of the exterior wall, as referred to before. The horizontal courses of megaliths that are extant, are barely in contact with one another, and are particularly susceptible to displacement under actions normal to the plane of the façade.

3. South-east Elevation - composite

4. North-east Elevation - composite

5. North-west external wall - detail

6. North-west external wall - detail

7. West external wall - detail

8. Props against west external wall – detail

9. Props against south-west facade – detail

10. South-west elevation – previous collapse

11, 12 Detail of stone-work

Notes:

5. Detail of eastern end of the north-west external wall. Top megaliths are often not in contact with any adjacent megaliths, and contact with lower surfaces generally tenuous. This means that these megaliths are susceptible to actions normal to the plane of the wall.
6. Continuation of north-west elevation detail. Same comments.
7. Continuation of north-west elevation detail. Close-up of the external props. If the external displacement of the propped megalith is continuing, and if the props are actually supporting the top part of the wall, it is possible for the megalith to fail in flexural tension along a horizontal line – the horizontal cracks which are visible could actually have been caused by this situation. On the other hand, there is no current sign of continuing distress.
8. Detail of propped area shows significant outwards inclination of propped megalith. Nevertheless, there is no evidence of continuing outward displacement. May need long-term monitoring.
9. Detail of corner with South facade, and propping structure for this facade.
10. Area of south-west elevation where there was a previous collapse and reconstruction using small-sized stones, and a further recurrence of the collapse in 2003, and subsequent reconstruction.
11. Condition of stone-work illustrates haphazard nature of interface contacts, exacerbated by weathering, and subsequent small rotations, and hence crushing of small stones. Process in on-going, and impossible to predict. It is, nevertheless, certain that it is a site where, at some stage, additional collapses will occur, as stone weathering leads to loss of stones.
12. ditto

13. Propped south-east facade – detail

14. Previous collapse between temples – south-east facade detail

15. Propped south-east facade – close-up

16. Propped south-east facade – close-up

17. Propped south-east facade – close-up

18. Propped south-east facade – close-up

19. Propped south-east facade – close-up of contact between scaffolding and stones

20. Erosion, cavitation and precarious equilibrium in south-east facade – close-up

Notes:

13. South facade of south temple, with propping structure. This is one of the major problems of the site, Detailed close-ups of this facade are shown in photos 15 to 18. Image 19 shows a composite set of photographs highlighting the contact between elements of the supporting structure and the individual stones. Image 20 shows another composite set of photographs characterising the condition of typical stones in the facade, and of the contact between them. These situations are all problematic.
14. View of the other side of the south facade of the south temple, where the interface with the north temple has collapsed completely.
15. Top part of problematic south facade, showing top megaliths with limited contact surfaces at vertical joints, and tenuous contact at lower horizontal surfaces. Some of these stones are probably only in place because of contact with propping structure. Horizontal contact surfaces in lower courses also demonstrate large gaps – and hence a limited area of contact, which tends to become less as weathering continues. The state of equilibrium is very precarious. It is impossible to model without exact information on the nature and configuration of the contact situation. In addition, this contact situation is susceptible to continuous change as a result of on-going weathering.
16. Precarious state of equilibrium more dramatically obvious in this view, particularly at the top right-hand stones. The effect of reduced contact at horizontal surfaces, that is the concentration of stress, is shown by the cracking of the megalith below.
17. The situation continues in the lower levels, with large gaps at the horizontal interfaces. In addition, many of the lower megaliths have large cavities, presumably formed as a result of centuries of water flow (when the site was buried?). These cavities further complicate the state of equilibrium of the facade, in the sense that the megaliths are weakened, and become more susceptible to stress concentrations at the contact surfaces. The situation is impossible to model unless full details of both contact surfaces and cavities are known.
18. Ditto
19. The first set of images highlights lower megaliths that exhibit extensive cavitation, and, in some instances, cracks have formed across the weakened section of the megaliths. The contact between the metal elements of the propping structure and the megaliths was originally mediated via timber pieces. In some instances, the contact is so minimal that the timber pieces have fallen. In other places, the metal pipes seem to have formed an indentation into the timber pieces, indicating a moment of active displacement of the megaliths in the direction of the propping structure. In other instances still, contact still seems full, but there is no evidence of indentation. This means that it is impossible to determine whether the propping structure is currently, (or has been in the past), effectively providing support to the South facade. Even where there are signs of indentation, the relative megalith might now have a stability which does not require the propping structures. The whole assembly is, however, in a state of critical equilibrium. Any changes in the current situation, as a result of even minor changes in the contact surfaces, caused by weathering, may lead to dramatic changes – or possibly nothing.
20. These are all examples of precarious equilibrium, where changes in the contact situation may lead to displacements.

21. Apse 2 - composite

22. Apse 3 - composite

23. Apse 5

24. Apse 6 – composite

25. 26. Detail of stonework

27. View towards entrance

Notes:

21. The internal stonework of the apses is characterised by smaller, generally unworked, stones, assembled in typical dry wall construction, stabilised by smaller stones in the joints, and possibly by a final covering layer. The quality of the individual stones is generally sound, as is the overall stability of the interior wall – except perhaps for the upper courses. The concave geometry of the apse assists in achieving this stability. Problems of stability arise for the individual free-standing megaliths, that occur within the apse, and at the ends of the apse.
22. ditto
23. ditto
24. ditto

25. Images show close-ups of the typical stone held by other smaller stones wedged in the joints between the larger stones. Stability depends on the integrity of this wedging, which can be lost if weathering of the contact surfaces occurs.
26. Ditto
27. The vertical uprights flanking the main axis of the temple are not supported at the top, and have undergone minor displacements inwards. This is a natural consequence of the geometry of the temple structure. The stability of the uprights is uncertain. When the inclination increases to the extent that the vertical line passing through the centroid of the block passes outside of the base, the megaliths can overturn. The quality of the contact surface at the bottom of the megalith obviously contributes to this situation.

28 , 29. Detail of scaffolding – junction between apse 6 and 7 – discontinuity in masonry assembly

30 , 31. Detail of scaffolding – junction between apse 6 and 7 – discontinuity in masonry assembly

32 , 33. Detail of scaffolding – junction between apse 6 and 7 – discontinuity in masonry assembly

Notes:

28. In 2005, following a further assessment of the condition of the monument, a significant vertical discontinuity, at the corner of the wall between Apse 6 and Apse 7, was considered to be of sufficient concern to warrant an additional preventive intervention, in the form of a propping structure. The vertical discontinuity is expressed as a widening of a sequence of vertical joints, which are not vertically aligned with each other, but displaced as is typical of masonry. The discontinuity appears on the corner of the wall in Apse 6, and slightly smaller, in the corresponding corner of the wall in Apse 7. It is presumed that these two discontinuities are in fact the edges of a planar discontinuity that separates the corner of the two apses from the rest of the structure. There is no evidence that the corner has in fact displaced, since the propping structure was erected, such that it is pushing against the same propping structure. It is impossible to model the stability of the corner without exact information of the horizontal and vertical contact surfaces, including those in the body of the construction.
29. ditto
30. ditto
31. ditto
32. ditto
33. ditto

34. Apse 6 - composite

35. Apse 9 - composite

36. Apse 10 - composite

37. Apse 10 – composite

38. North-east external wall - detail

39. North-east external wall - detail

40. North-east external wall - detail

41. North-east external wall - detail

42. North-east external wall - detail

43. Free-standing megaliths – detail

44. Propped external wall – detail

45. Apse 10 – composite

46. Apse 10 – composite

47. Apse 9 – composite

48. Apse 13 – composite

49. Apse 12 – composite

50. Apse 12 – composite

51. Apse 14 – composite

Notes:

1. The internal stonework of the apses is once again characterised by smaller, generally unworked, stones, assembled in typical dry wall construction, stabilised by smaller stones in the joints, and possibly by a final covering layer. The quality of the individual stones is generally sound, except for a limited number of stones, which appear to be deteriorating at a faster rate than the others. The overall stability of the interior wall appears sound – except perhaps for the upper courses, as for the other apses. The concave geometry of the apse assists in achieving this stability. Problems of stability arise for the individual free-standing megaliths, that occur within the apse, and at the ends of the apse.
2. ditto
3. ditto
4. ditto

5. Comments about the external wall have been made in Note 1.
6. The situation of the top row of horizontal megaliths is highlighted in this image.
7. ditto
8. ditto
9. ditto
10. Some free-standing megaliths at the edges of the monument are susceptible to horizontal actions normal to the plane of the stones.
11. Further detail of the propped megaliths on the north-west elevation.

12. The internal stonework of the apses is once again characterised by smaller, generally unworked, stones, assembled in typical dry wall construction, stabilised by smaller stones in the joints, and possibly by a final covering layer. The quality of the individual stones is generally sound, except for a limited number of stones, which appear to be deteriorating at a faster rate than the others. The overall stability of the interior wall appears sound – except perhaps for the upper courses, as for the other apses. The concave geometry of the apse assists in achieving this stability. Problems of stability arise for the individual free-standing megaliths, that occur within the apse, and at the ends of the apse.
13. ditto
14. ditto
15. ditto
16. ditto
17. ditto

18. The stability of the stones forming the shallow end apse of the north temple is based on the contact surfaces of the haphazard assemblage of stones, which has clearly lost megaliths in previous collapses.

The contact surfaces between megaliths are certainly non-uniform, but also very difficult to characterise. In addition, weathering of the contact surfaces, also exacerbated as a result higher stresses present, produces an ever-changing situation of equilibrium. The same high stresses also result in damage (cracking) of the stones, especially the smaller stones wedged in between the larger ones, in order to lock them in place. This damage becomes more likely as the stones are exposed to weathering mechanisms, which affect the intrinsic cementation of the stone. When small pieces of stone are lost, the state of equilibrium changes, leading possibly to a new situation of contact stresses, or to a subsequent loss of other stones, or to a catastrophic collapse of the whole assemblage. It is impossible to model these mechanisms without detailed and accurate information about the stones, the contact surfaces, as well as the rate and type of weathering.

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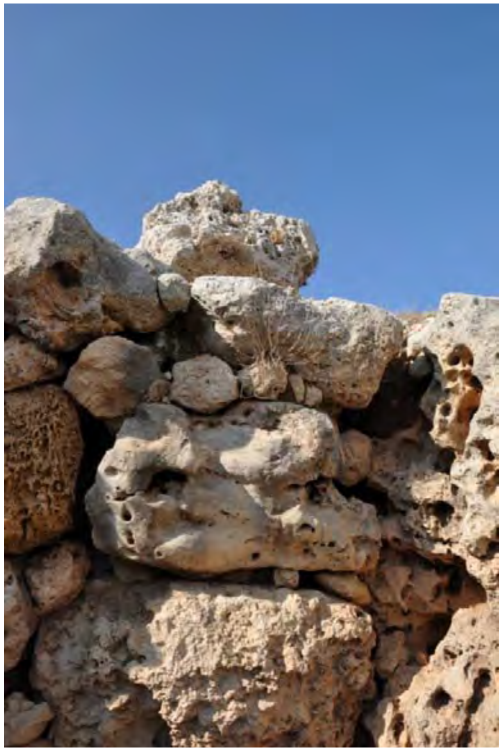

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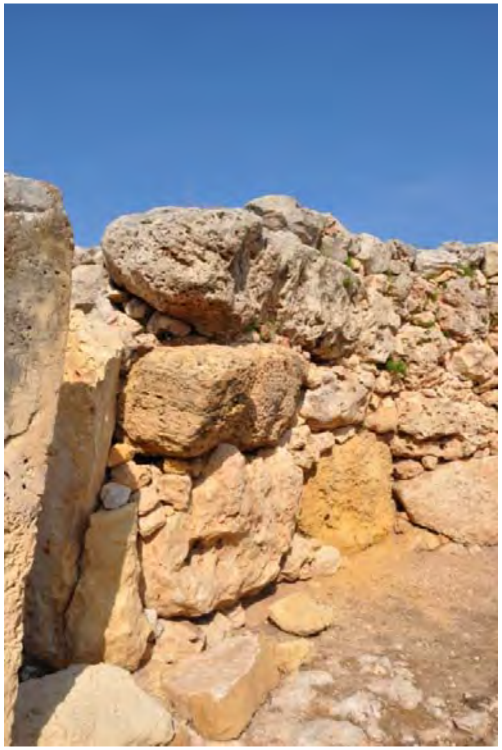

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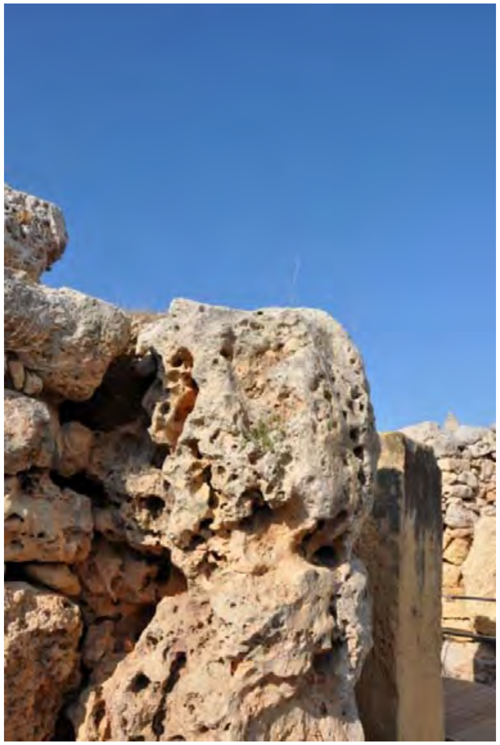

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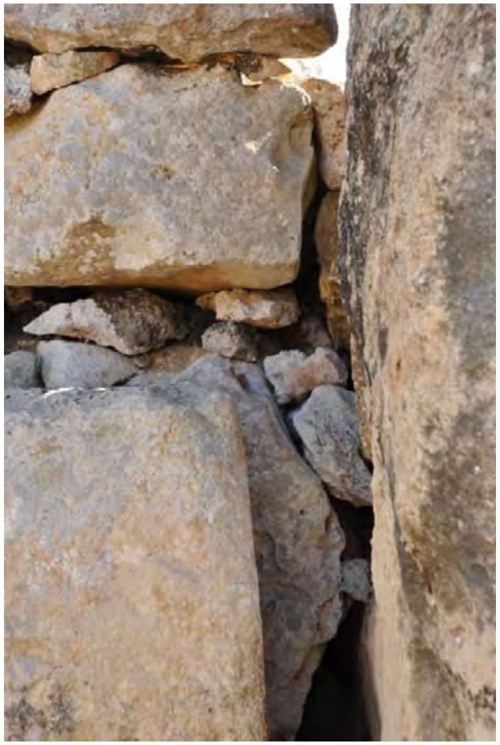

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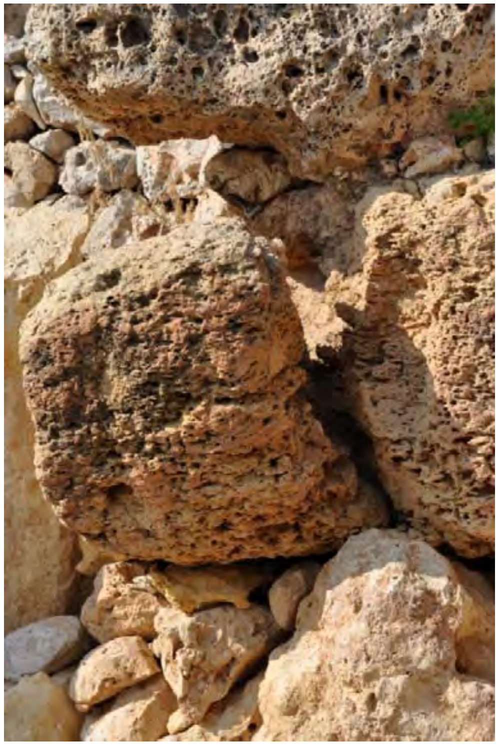

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72.

73. View of 2003 collapse in south-west elevation – composite

74. Detail of 2003 collapse

75. Detail of 2003 collapse

76. 2005 view of South Temple – rear view of South Facade

77. 2005 view of South Temple – propping at Apse 7

77. 2005 view of North Temple – Apse 13

78. 2005 view of North Temple

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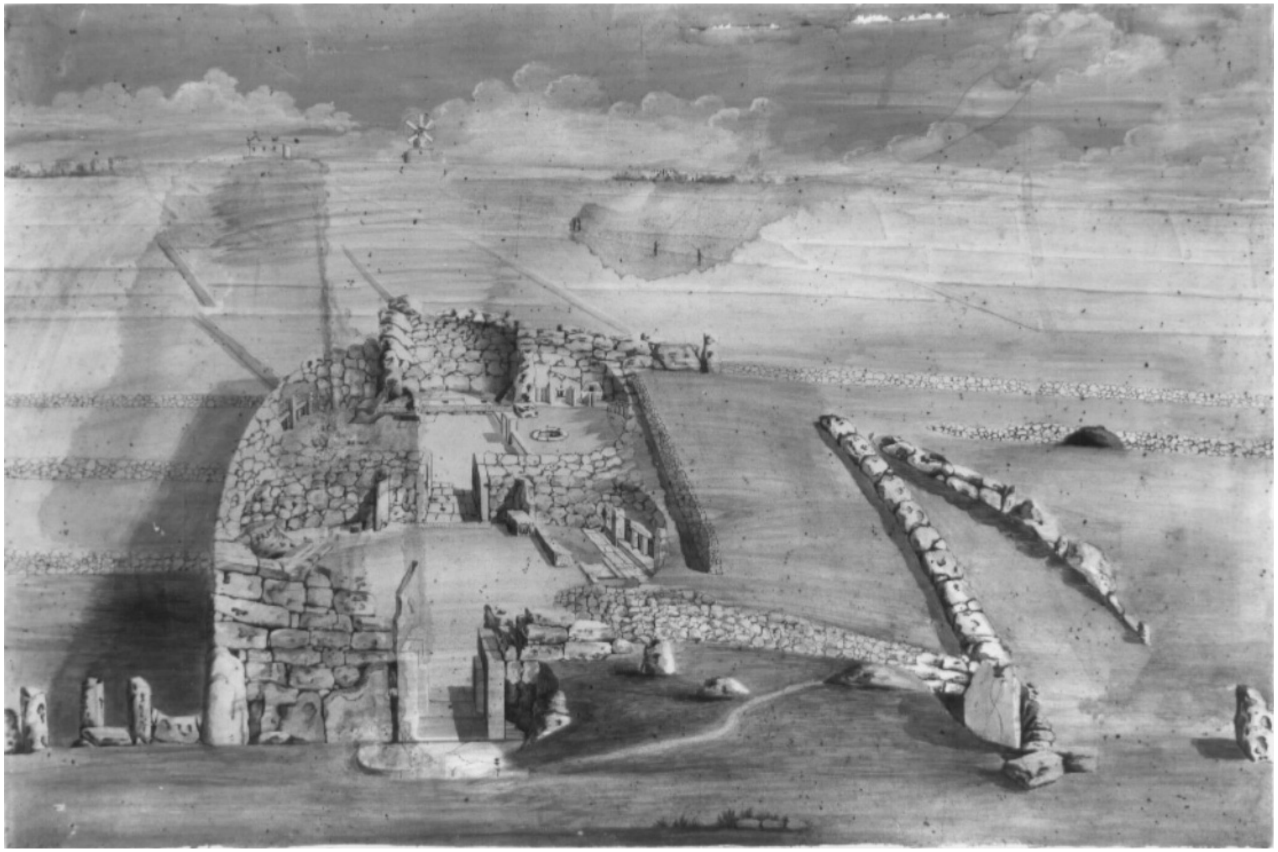

STRUCTURAL SURVEY AT GGANTIJA TEMPLES, GOZO

APPENDIX B

CONTRACT CT2115/2009

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13.0 Appendix: Historical Images – A Review of Archival Visual Information

1. Historic Aerial Photo – Archives Heritage Malta

2. Historic Aerial Photo 1937 – Archives Heritage Malta

3. Historic Aerial Photo 1937 – Archives Heritage Malta

4. Historic Aerial Photo 1937 – Archives Heritage Malta

5. Historic Aerial Photo 1937 – Archives Heritage Malta

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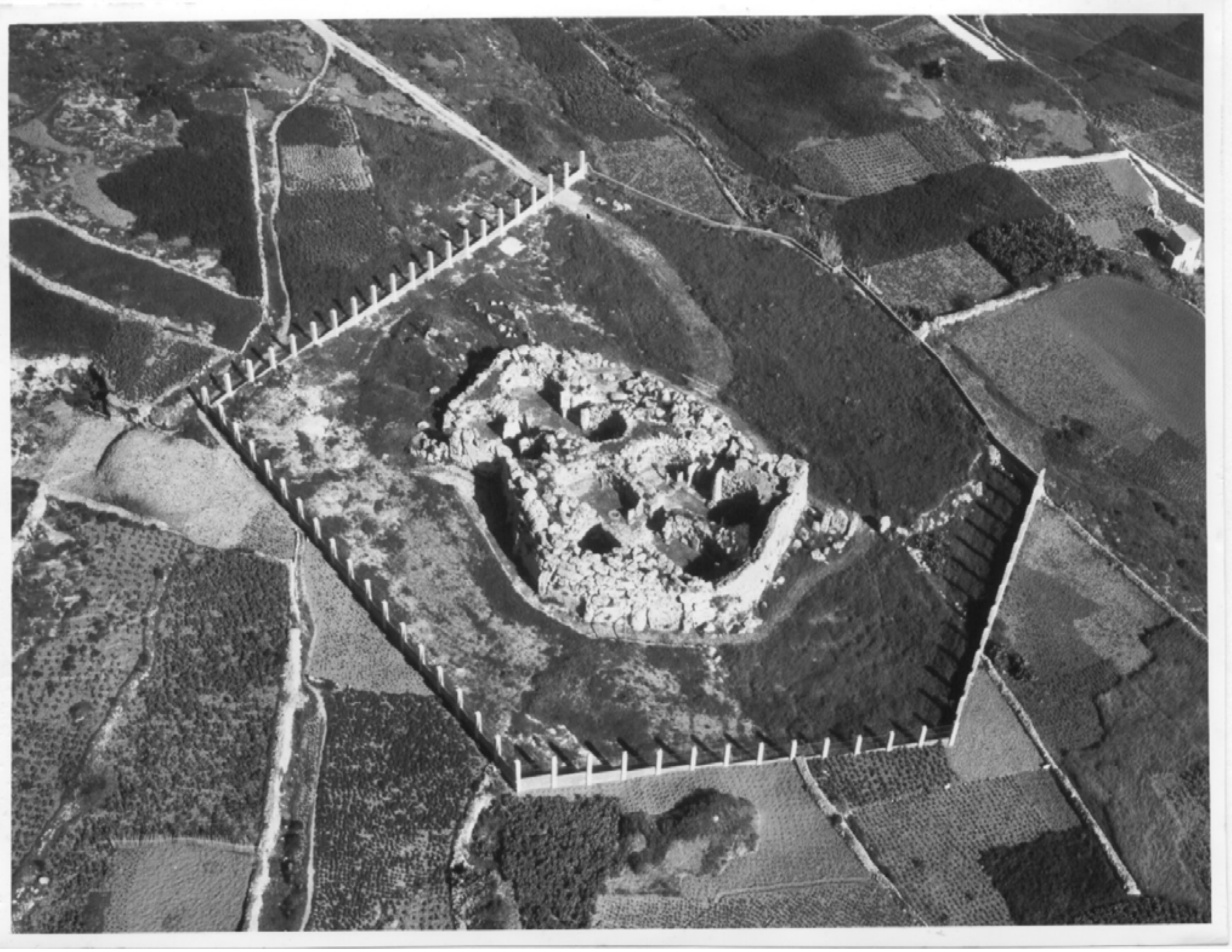
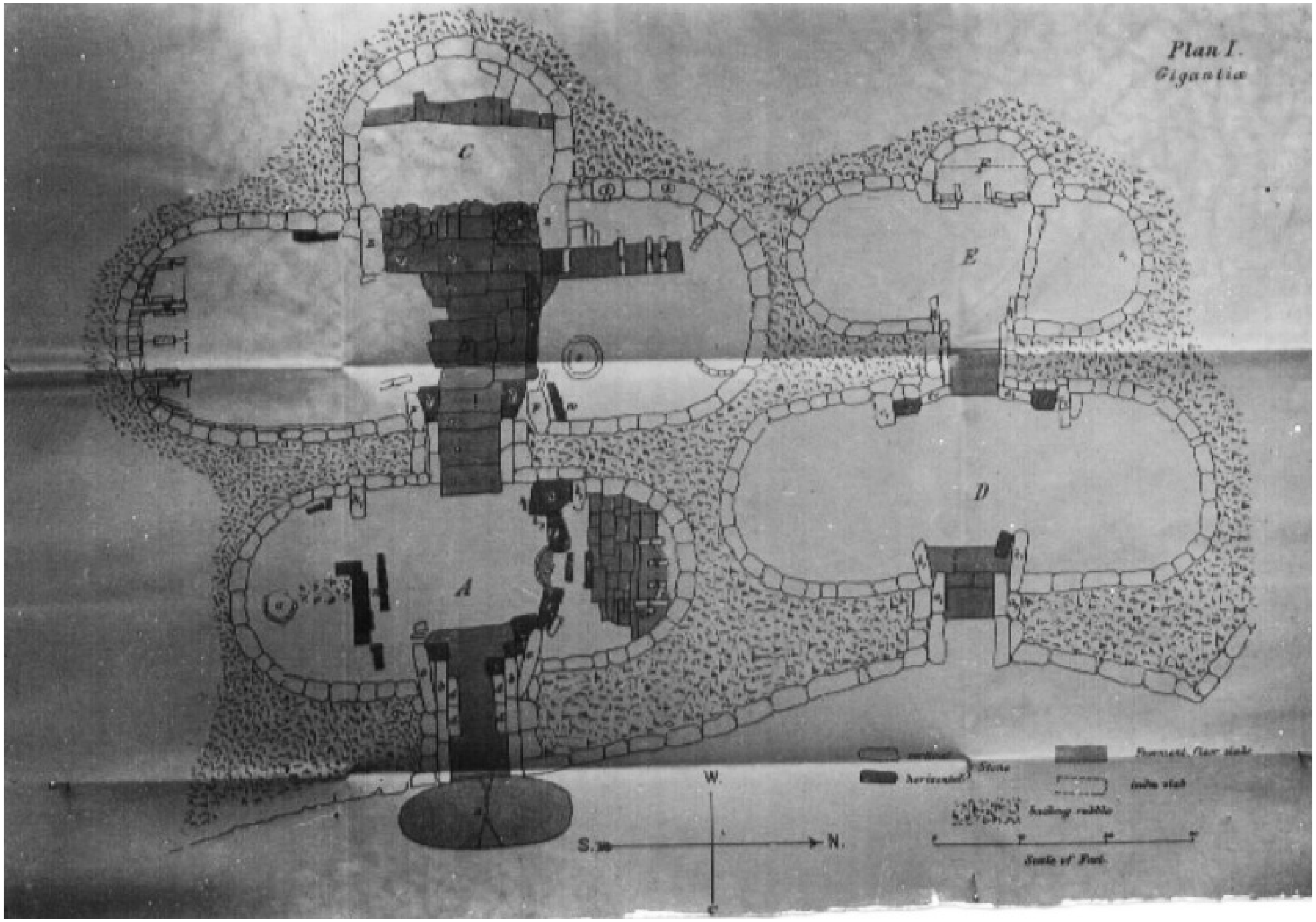
6. Historic Aerial Photo 1960 – Archives Heritage Malta

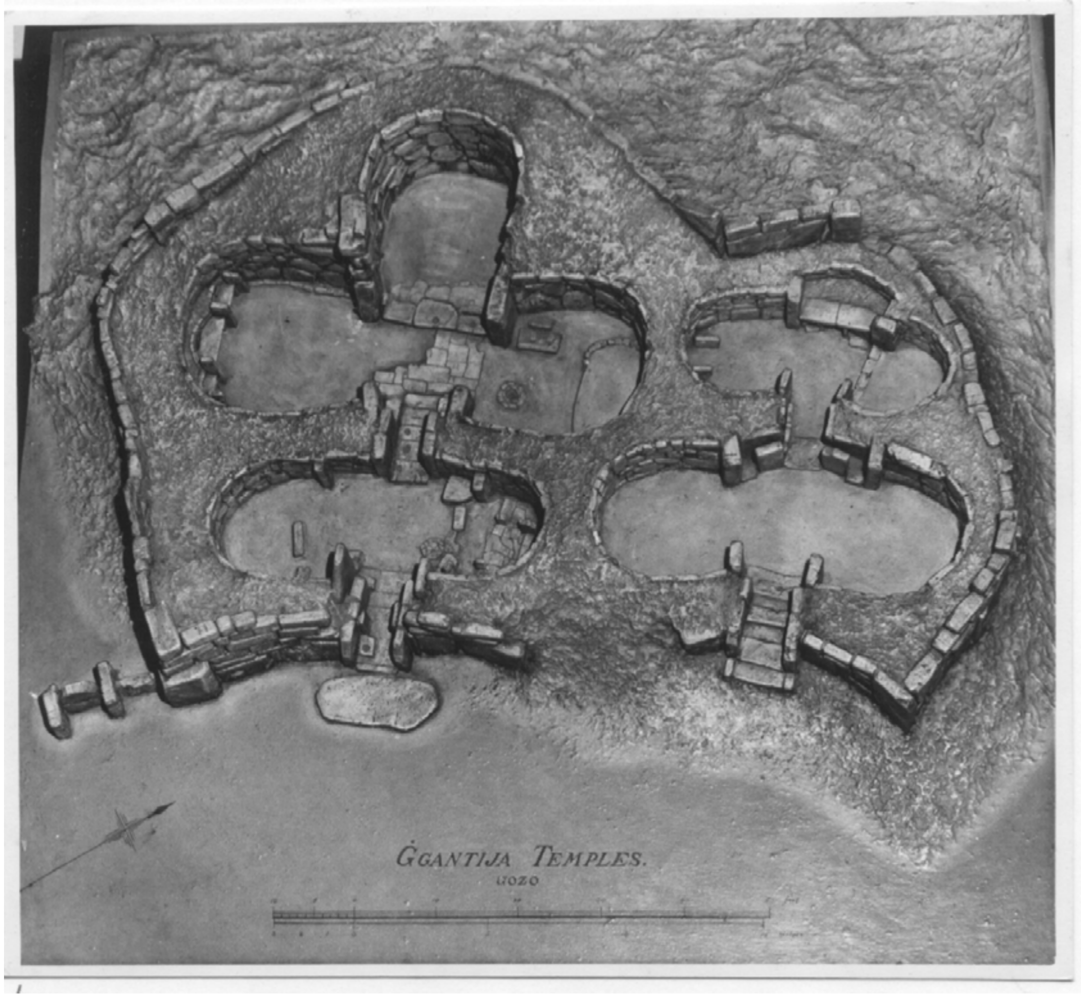


7. **Historic Aerial Photo 1960 – Archives Heritage Malta**

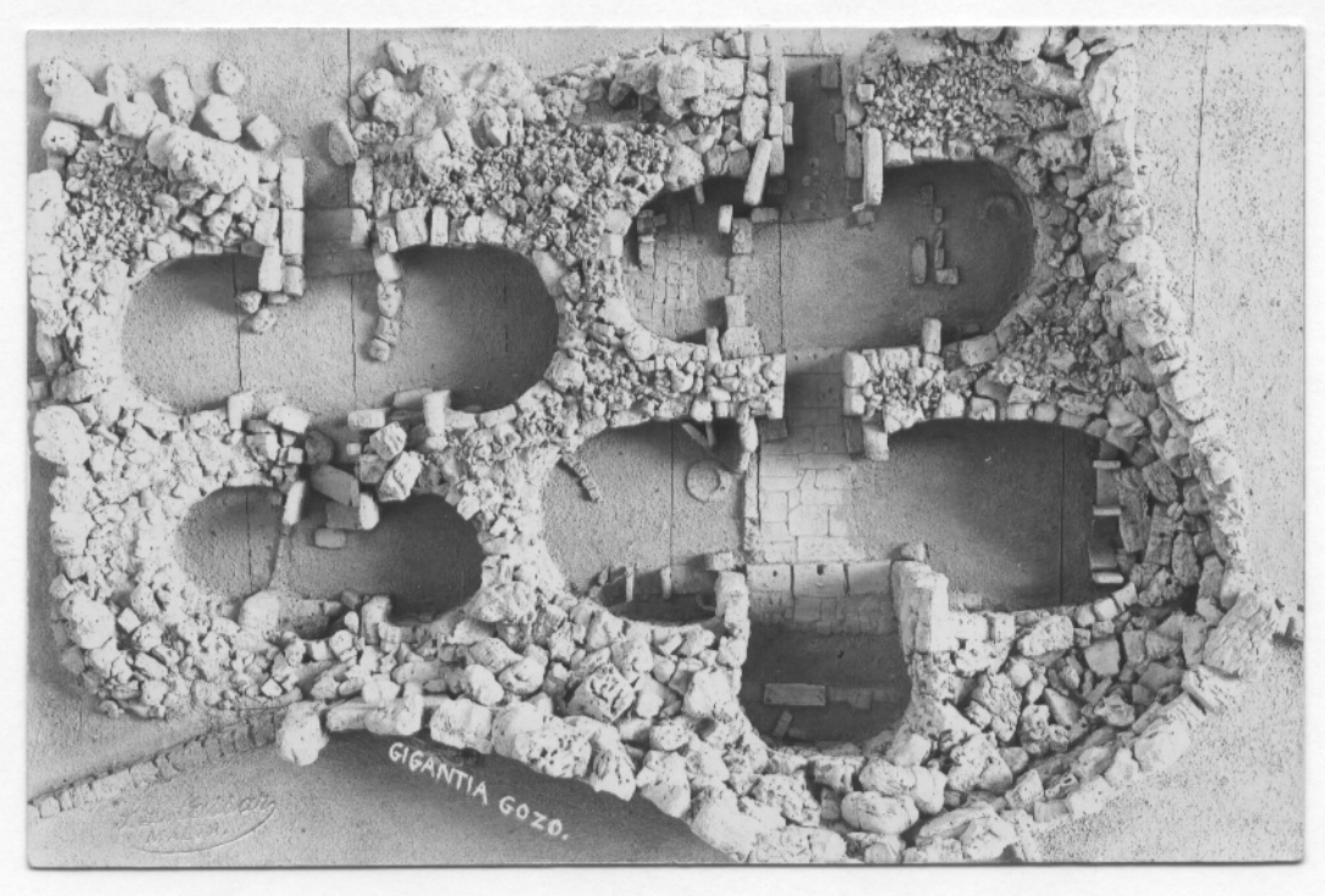
8. Historic Aerial Photo 1960 – Archives Heritage Malta



9. Historic Plan – Archives Heritage Malta



10. Historic Model – Archives Heritage Malta



11. Historic Model – Archives Heritage Malta

12. Historic Views 1953 (?) – Archives Heritage Malta

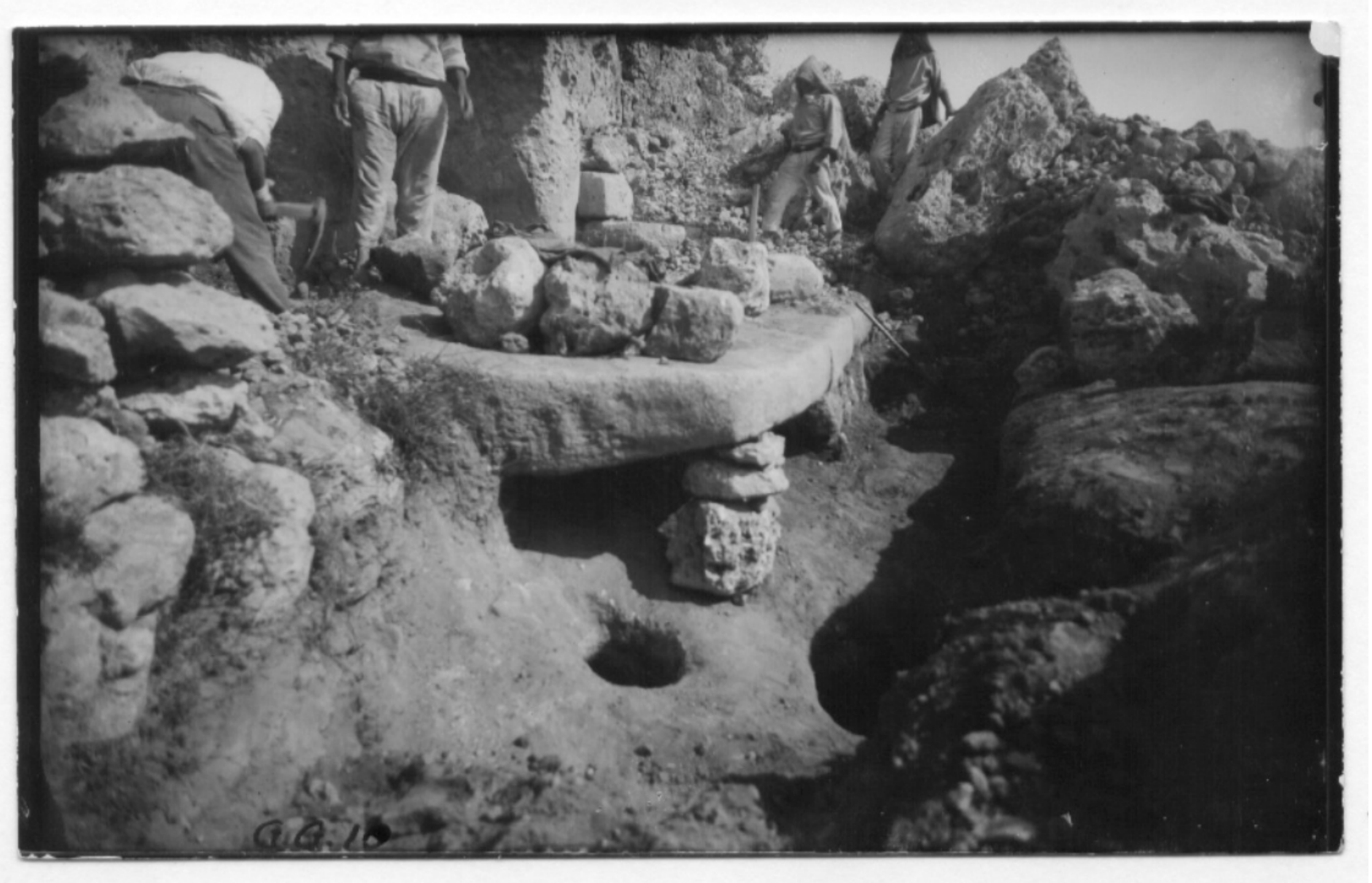
13. Historic Views (1929?) – Entrance South Temple – Archives Heritage Malta

14. Historic Views 1933 – Entrance South Temple – Archives Heritage Malta

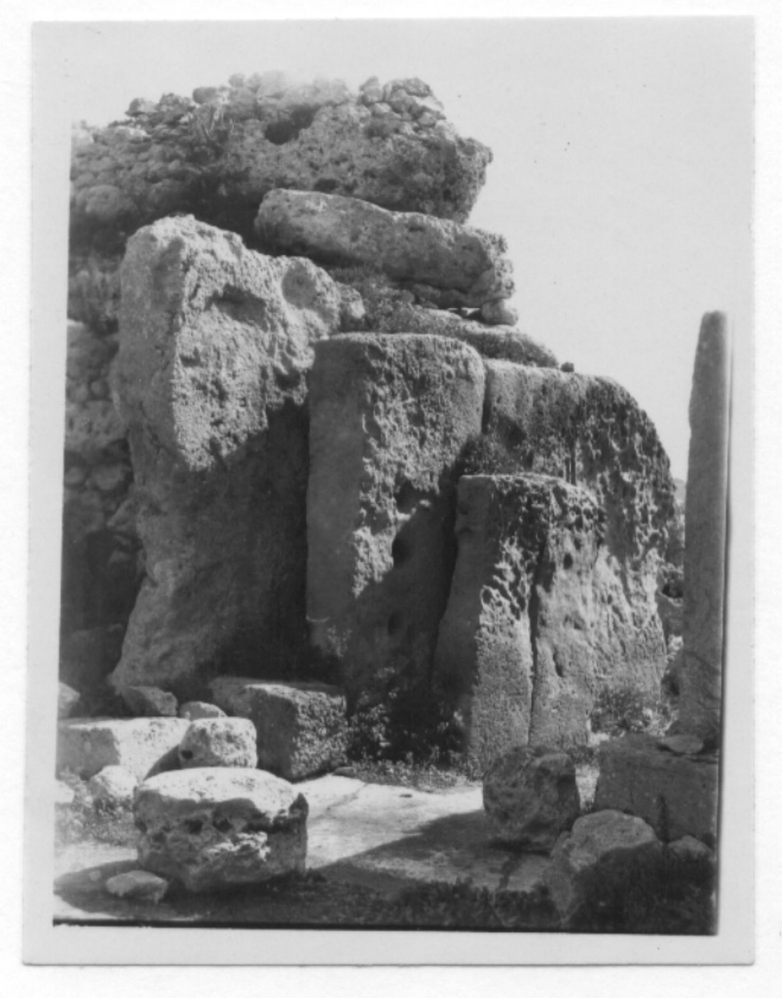
15. Historic Views 1933 – Entrance South Temple – Archives Heritage Malta

16. Historic Views 1933 – Entrance South Temple – Archives Heritage Malta

17. Historic Views 1933 – Entrance South Temple – Archives Heritage Malta

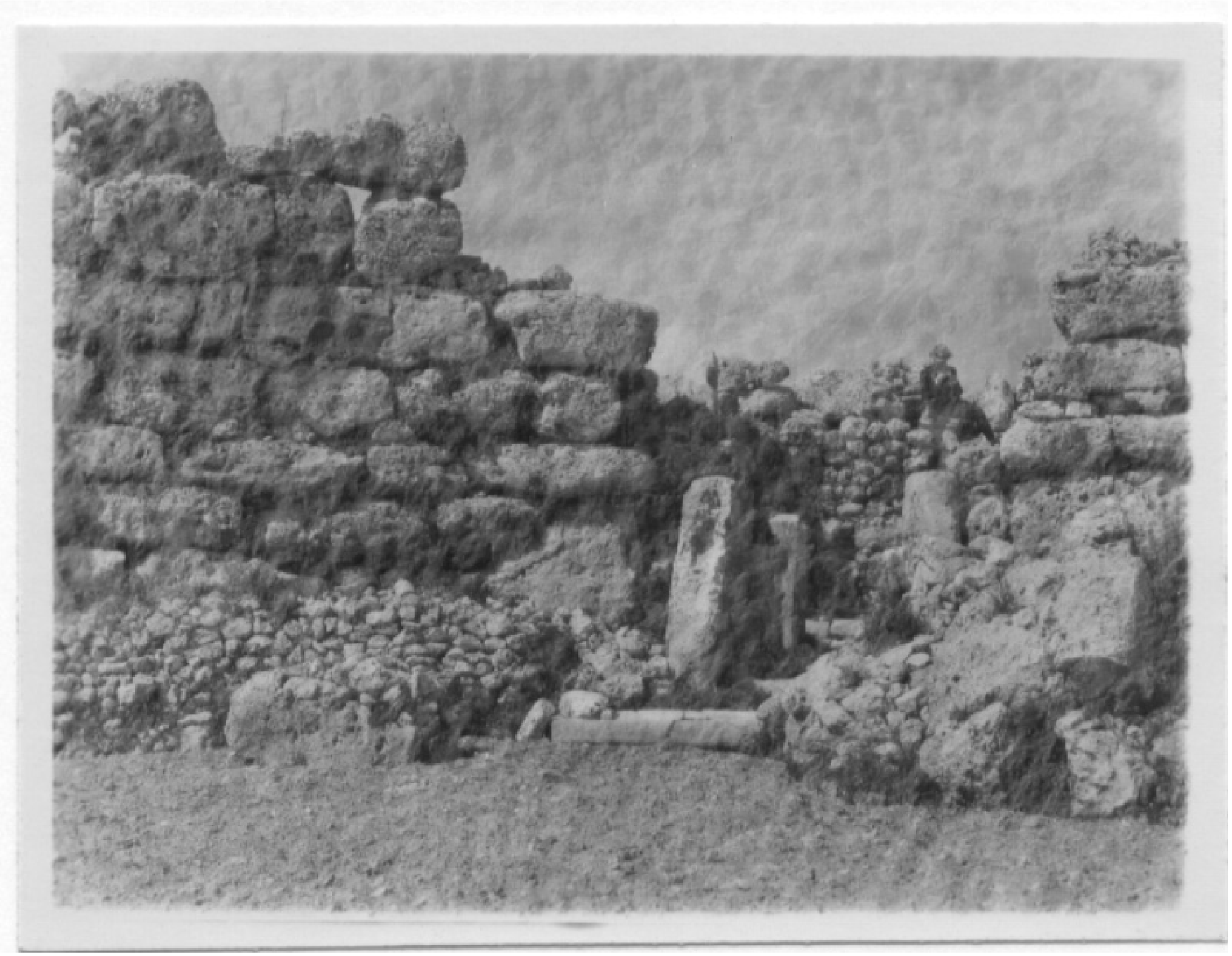


18. Historic Views 1933 – Entrance South Temple – Archives Heritage Malta



19. **Historic Views – Entrance South Temple – Archives Heritage Malta**

20. Historic Views (1933?) – Facade South Temple – Archives Heritage Malta



21. Historic Views – Facade South Temple – Archives Heritage Malta

22. Historic Views – Facade South Temple – Archives Heritage Malta

23. Historic Views – Facade South Temple (West Corner) – Archives Heritage Malta

24. Historic Views 1936 – Facade South Temple – Archives Heritage Malta

25. Historic Views – Facade South Temple (East End) – Archives Heritage Malta

26. Historic Views – Facade South Temple – Archives Heritage Malta

27. Historic Views – Facade South Temple – Archives Heritage Malta

28. Historic Views – South View South Temple – Archives Heritage Malta

29. Historic Views (1960?) – South View South Temple – Archives Heritage Malta

30. Historic Views (1933?) – South View – Archives Heritage Malta

31. Historic Views (1933?) – South View – Archives Heritage Malta