GEOPHYSICS, VOL. 60, NO. 6 (NOVEMBER-DECEMBER 1995); P. 17351742, 12 FIGS.

The detection of monumental tombs buried in tumuli by seismic refraction

Gregory N. Tsokas*, C. B. Papazachos*, Antonis Vafidis‡, M. Z. Loukoyiannakis**, G. Vargemezis*, and K. Tzimeas*

ABSTRACT

A tumulus is a construction erected to cover a tomb. Some tumuli are impressively massive and may conceal architectural masterpieces. Seismic refraction is employed to locate the tomb and to allow selective excavation without destroying the tumulus. The detectors are spread along a circular profile on the periphery of the tumulus, and acoustic waves are generated on its top. Time delays observed in the arrivals of the headwaves reveal the position of the monument. The delays are not caused by the monument itself, but are an effect caused by the presence of a ramp that was dug in the undisturbed soil to help in the construction of the tomb.

Three case histories in Northern Greece establish the efficiency of the technique. In the first example, an experiment was conducted at a previously excavated tumulus, and time delays attributed to the revealed ramp are observed. The second case study led to the discovery of an impressive monument; 3-D modeling by finite difference verifies the interpretation. A third study is also reported; where, for the most promising portion of the data, 3-D modeling has been performed.

INTRODUCTION

Several geophysical methods have been successfully applied to the detection and mapping of concealed natural and anthropogenic subsurface cavities (e.g., Owen, 1983; Tsokas and Rocca, 1986; McCann et al., 1987). These methods include resistivity profiling (Habberjam, 1969; Militzer et al., 1979), gravity methods (Fajklewicz et al., 1982), crosshole seismic surveys (McCann et al., 1986), and seismic resonance techniques (Arrowsmith and Rankilor, 1981).

In archaeological geophysics, the most common subterranean man-made cavities are the tombs. Tombs comprise significant exploration goals, for if they are not looted, they usually contain important findings. Several successful case studies of detection by geophysical methods have been reported (Orlando et al., 1987; Tsokas et al., 1994) which demonstrate the potential of the methods used. However, the reported detections refer to structures buried at small depths in comparison to their dimensions. Furthermore, the successful case studies often refer to terrain that is relatively flat and in some cases gently sloping.

The detection of tombs inside a tumulus is a particular problem. Tumuli are the artificially erected small hills that covered the monumental tombs. They commonly occur in South and Eastern Europe, Asia Minor, and the Middle East. They conceal structures that deserve to be preserved. Indeed, the tumuli are by themselves monuments of past human activity, and obviously they should not be destroyed or even disturbed. Therefore, much effort has been devoted to finding ways to remotely locate the tombs beneath the tumuli and to excavate selectively.

Katevski (1986) and Petkov et al. (1989) have reported the successful location of tombs within tumuli in Bulgaria; they employed the resistivity profiling method and conducted circumferential profiles following the topographic contours of the tumuli. A study in a tumulus in Southeast Asia Minor has been reported in Utecht (1988) and Utecht et al. (1993); the objectives were to map the stratigraphy in the construction of the tumulus and to possibly locate a monument under the artificial cover. Seismic, electromagnetic (EM), and ground penetrating radar (GPR) methods were employed for the investigation by Utecht; however, the monument was not detected.

Tsokas and Rocca (1987) employed vertical electrical soundings arranged on a rectangular grid at a tumulus in northern Greece. The current lines expanded along topographic contours and coherency criteria were used to match

Manuscript received by the Editor March 3, 1994; revised manuscript received March 2, 1995.
*Geophysical Lab., Aristotelian University of Thessaloniki, Thessaloniki 540 06, Greece.
‡Dept. of Mineral Wealth, Technical University of Crete, 73100 Hania, Greece.
**DEP-EKY, Kifissias 199 24 Maroussi, Greece.

the soundings. Although the tomb was not located, the technique allowed the pinpointing of the edge of the ancient pit.

Three case studies are presented here to demonstrate the successful use of seismic refraction methods for the investigation of tumuli. The efficiency of the method is clarified by 3-D simulation studies.

STATEMENT OF THE PROBLEM

Tumuli were constructed in stages. First, a pit was dug and a ramp constructed (dromos) at one edge of the pit (Figure 1). The ramp was used to lower masonry into the pit that was used to build the tomb. Usually the tomb was a monumental construction made of hewn stones. In Greece, these tombs were small but of excellent construction, representative of the best buildings of the era. After the funeral rituals, the tomb was usually sealed, and the tumulus was erected to cover everything.

As illustrated in Figure 1, the loose material comprising the tumulus fill and cover is likely to have different geophysical properties than the undisturbed environment. This condition favors the location of the monumental structure. However, the top of the tomb is usually at a depth a few times larger than its dimension. Also, the material of the tumulus is highly heterogeneous, generally with high clay content that can limit the penetration of electrical and electromagnetic techniques. Magnetic surveys could be used (Morariu et al., 1989) if the tomb is buried at shallow depth and contains large quantities of ferrous objects, or if its masonry is magnetic (e.g., bricks). High-resolution seismic reflection surveys seem appropriate for the application, but they require a lot of effort to cover the whole area of the tumulus to the desired resolution.

In 90% of the known cases, the tombs are located close to the periphery of the tumulus. This is reasonable because the

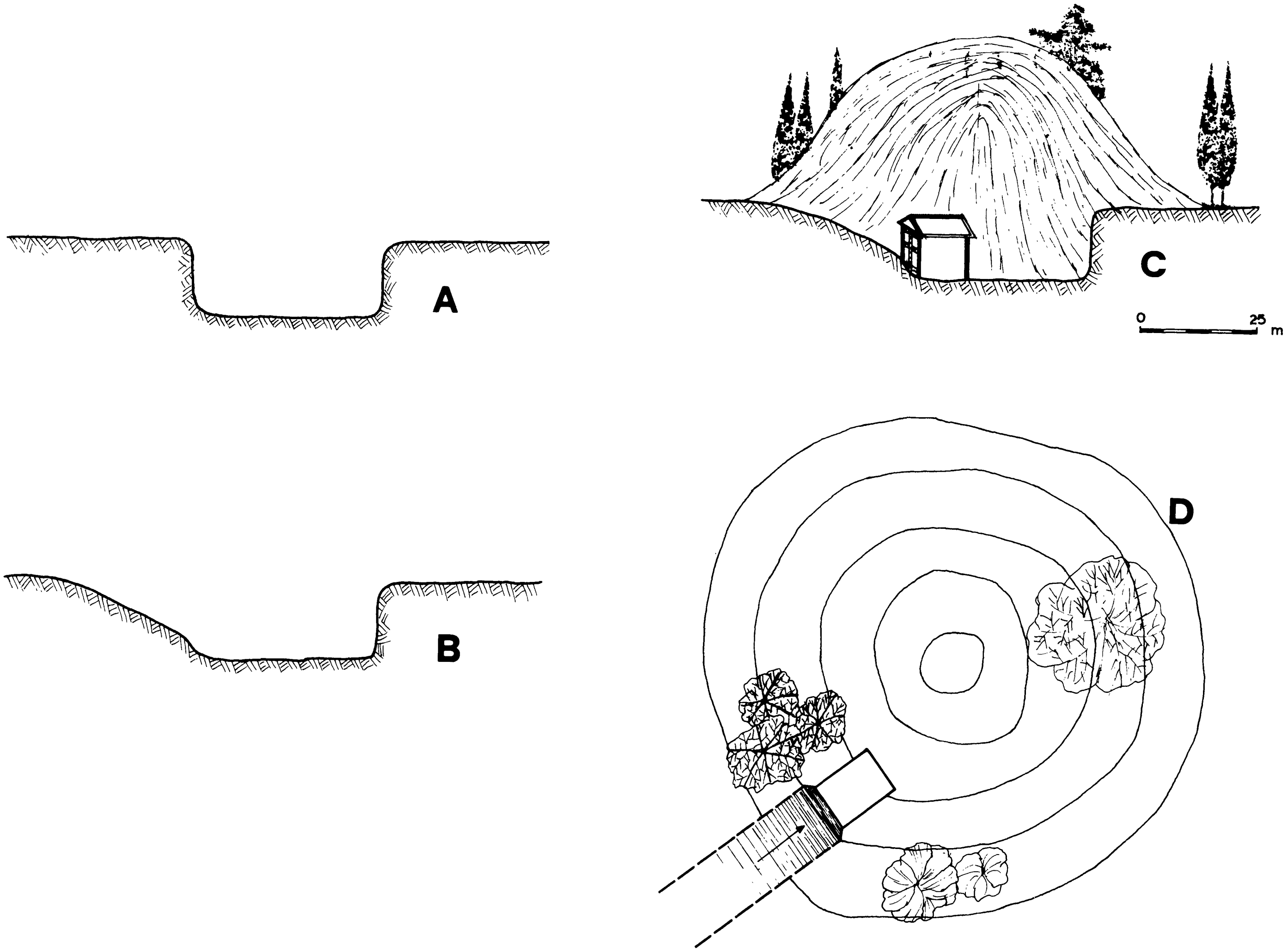

FIG. 1. A tumulus and the monument that it hosts were constructed in stages. A pit was dug first (a) and a ramp was made (b) to facilitate the transport of masonry. Finally the monumental tomb was built, and after the funeral rituals, the tumulus was erected (c). The tumulus and the concealed monument are shown in the lower left part of the figure (d) in plan view. In most cases, layering is observed in the construction.

possibility of finding any other point inside the tumulus is greater by using a tunnel. For security reasons, the worst selection would have been the center; in that case any tunnel having radial direction could reach the tomb.

These facts lead to the consideration that the ancient ramp may be detected much easier than the tomb itself, which in turn can be located indirectly. The fill of the ramp is loose compared to the surrounding undisturbed soil (see Figure I). Therefore, if a shot is fired near the center of the tumulus and the geophones are laid along circular profiles in the periphery, delayed arrivals caused by the loose material of the ramp should be detected. Although Rayleigh waves could be employed (Owen, 1983), refracted compressional waves offer the simplest technique and this case is presented here.

3-D SIMULATION METHOD

The advantages of 3-D forward seismic modeling are many. Some of the advantages include more dependable interpretation, better understanding of amplitude variations, more accurate velocity analysis, and determination of data acquisition parameters. There are also some drawbacks; even on supercomputers, because such models require an enormous amount of CPU time and a huge memory for data manipulation.

In the last decades. several techniques have been developed for simulating propagation of seismic wavefields in the earth. Because of the large amount of data and the complex theoretical format, the conventional modeling schemes produced limited results in many cases. However, recent advances in computing based on the vector compilation and the subdivision of the computational sequence into parallel components allow the development and implementation of more accurate and cost effective methods.

A large volume of work related to the solution of 2-D and 3-D acoustic wave problems can be found in the literature (Reshef et al., 1988; Jonson, 1988; Mora, 1988; Mufti, 1989; Myczkowski et al., 1991; Vafidis et al., 1992). Vefidis et al. (1994) presented a fast, parallelized algorithm for modeling acoustic wave propagation in a 3-D heterogeneous medium, and the simulations presented in this paper are based on their algorithm.

In this algorithm, the acoustic wave equation is reduced to a first-order hyperbolic system and solved with a particle velocity-stress finite difference method and the dimensional splitting technique. This method is a version of the MacCormack scheme (Vafidis et al., 1992) that is second-order accurate in time and fourth-order accurate in space. The algorithm is highly vectorized following the semantic vectorization approach, which involves fundamental structuring of the algorithm to suit the architecture of the computer, and also, using the matrix times vector by diagonal technique. It is implemented on vector and parallel supercomputers with results that are exceptional both in execution time and in handling large models. A hyperbolic system formulated for one-way wave propagation in heterogeneous 3-D media is used in implementing absorbing boundaries.

CASE STUDIES

In-situ feasibility study

Figure 2 illustrates the location of the explored tumuli in the northern Greek territory (region of Macedonia). The tumulus near the village of Toumpa was the first one studied. The monument was revealed by excavations long before the geophysical experiment and is shown in Figure 3. Thus, we had the opportunity to study the feasibility of the method in situ. Two short seismic lines with detectors spaced 1.5 m apart were laid radially outward from the source location as depicted in Figure 4A. Line Ml was laid along the radial

FIG. 2. Map showing the sites in which the tumuli referred to in the present study are located. They are close to the villages Toumpa, Messiano, and Agios Athanassios in northern Greece.

FIG. 3. The tumulus of the photograph located near the village Toumpa in northern Greece. It covers a monumental tomb that slightly exceeds the ground surface.

direction that crosses the axis of the monument, and the second line M2 was laid in a direction that presumably crossed no structures. The source point was placed at the highest point of the tumulus and a sledgehammer striking a steel plate was used to generate the seismic waves.

This simple experiment resulted in the traveltime curves shown in Figure 4B. It is clear, that the ramp delays the waves arriving at the geophones of line Ml, and this delay is more severe for larger distances. The time differences between the corresponding geophones, i.e., geophones having the same radial distance, is in the range 9-16 ms, which represents a change of more than 20%.

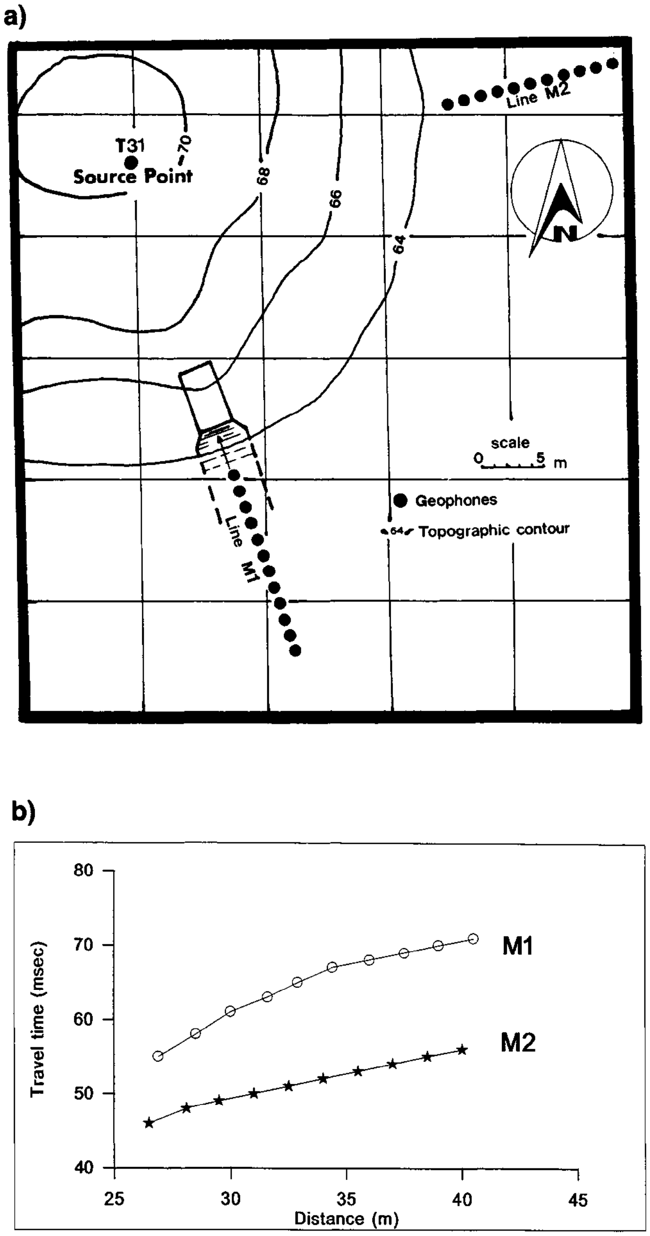

FIG. 4. The layout of the survey with respect to the tumulus and the monumental tomb shown in Figure 3 is shown in (a). The contours are in meters. The traveltime curves for lines Ml and M2 when shot from the point T31 are shown (b).

Short refraction lines conducted in the vicinity of the tumulus helped to determine the velocity structure of the undisturbed earth and design our experiment. A three-layer structure was found, with velocities of approximately 400 m/s, 600 m/s, and 1300 m/s. The thicknesses of the upper two layers were found to be 3.3 m and 10.3 m, respectively, while the thickness of the third layer was not determined. We can assume that the tumulus infill has more or less the velocity of the upper layer. This is a reasonable approximation, because the upper layer consists of drift that is heavily weathered, and the tumulus was constructed of that material. This is confirmed by the velocities of the first layer derived from Figure 4b for lines Ml and M2 of about 410 and 430 m/s, respectively. Also, such a hypothesis fits the forward modeling scheme used.

The preceding considerations suggest that most of the arrivals seen in Figure 4b represent refracted waves. Furthermore, the radial distance of a circular array of detectors can be adjusted such that the refracted waves are arriving first.

The discovery of a monumental tomb in the tumulus of the village Messiano

The topographic relief and the geophone locations around a tumulus near the village of Messiano are shown in Figure 5. The source point is also marked on the top of the tumulus. The first arrivals plotted versus the geophone positions are shown in Figure 6. These positions refer to an arbitrary origin and clockwise numbering. More than 25% delays are observed about geophone positions 80 and 200. Because of the limited spatial extent of the anomaly observed around position 80, in comparison to that around position 200, it was attributed to the ancient ramp. The seismic results were used to plan an exploration excavation. The excavation revealed the monument shown in Figure 7.

In Figure 8, a model of the tomb along the ramp is shown in plane and sectional view. The velocities corresponding to the shallowest layer and the underlying ones were obtained after shooting refraction lines in the fields around the periphery. The dimensions of the various components of the model were measured after the excavation. The tumulus had a height of 13 m and a diameter of 95 m. It was a huge construction covering a monumental tomb measuring 10 x 5 x 5.5 m and a large ramp (dromos) as shown in the figure. Numerical 3-D seismic wave simulations were carried out for the model shown in Figure 8, employing a P-wave source whose excitation function is Gaussian-shaped with a dominant frequency of 30 Hz in accordance with the real experiment. The first arrivals, which correspond to head waves, were picked from the synthetic seismogram. The computed arrival times for geophone locations 22 through 84 are shown in Figure 9 along with the measured values. The two sets of arrival times show good agreement, confirming the proposed model.

The excavations revealed that the large anomaly centered at geophone location 200 was a result of a pit whose material. was used to erect the tumulus. The large but shallow pit was refilled through the centuries.

Case study of the tumulus of Agios Athanassios

The plan view of the tumulus at Agios Athanassios is depicted in Figure 10 along with the circular profile of the geophones. The numbering of the geophones is in anticlockwise order from an arbitrary origin. The arrival times of the waves that were generated at the point marked on the top of the tumulus are shown in Figure lla. The geophone spacing was set to 1 m, and a sledgehammer generated the seismic waves. The pattern of the delays appear to show a remarkable resemblance with the case of the tumulus of Messiano. It seems that two anomalies could be attributed to ensembles of tombs and ramps. They occur at azimuthal locations 35 and 245. Also, a large anomaly is present starting at location 90 through 160, which is probably caused by a pit.

Again, 3-D simulation of the arrival times was attempted at the most promising location. The "most promising location" was defined as the one that seems to be most promising to the archaeologists and simultaneously to present a geophysical anomaly. A model comprising one ramp at that particular location was employed. A portion of the calculated and measured arrival times is shown in Figure llb, while the model used is shown in Figure 12. The variation in radial distance to the geophones has been taken into consideration in the 3-D wave modeling.

CONCLUSIONS

Seismic refraction surveys, employing the particular survey lay out demonstrated in this study, can be used to detect monuments covered by tumuli. The case histories presented emphasize the simplicity of the field procedures and interpretation. Clear anomalies were observed. Finite-difference computer simulation of these experiments give compatible results and verified the interpretations of the field data.

The 3-D computer simulations were valuable to verify our assumptions and procedures but are not necessary, in general, for future investigations. The simulation scheme is time consuming, expensive, and requires too much geometric data that can be obtained only after excavation.

The benefit of such an exploration is that selective excavation can be carried out, leaving the rest of the tumulus undisturbed. This is important because the tumuli are by themselves important historical monuments.

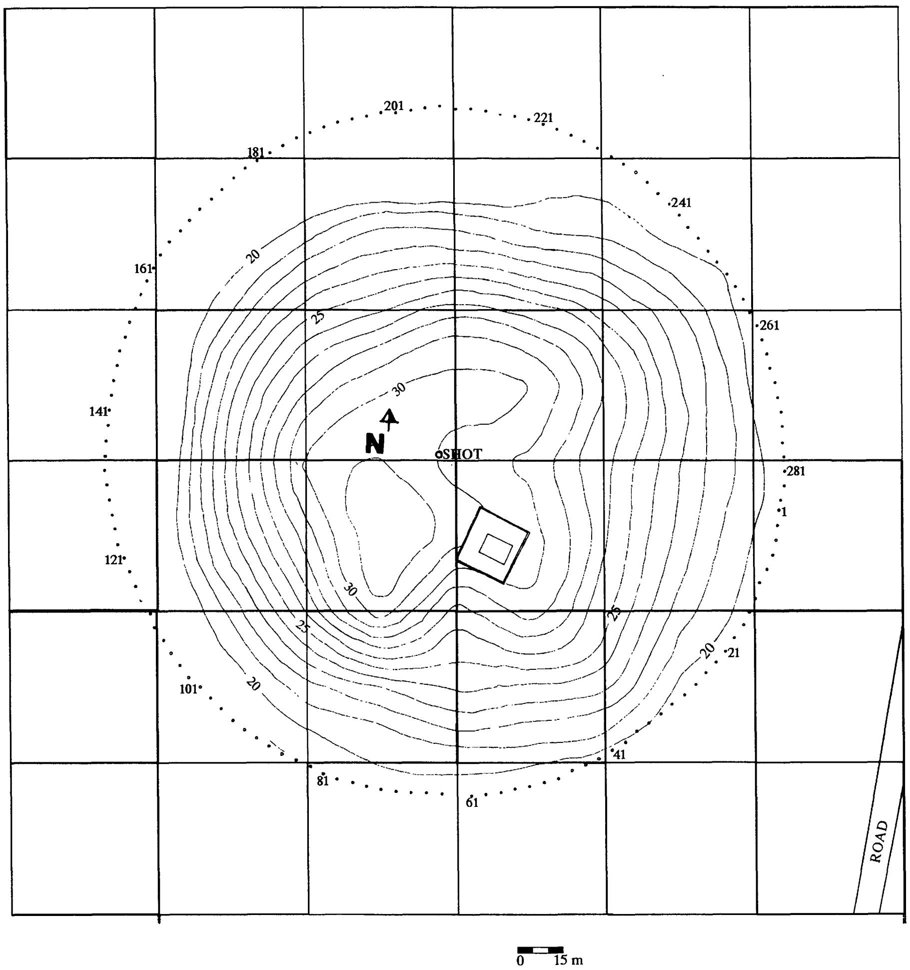

FIG. 5. Contour map of the tumulus in the village of Messiano in northern Greece and the positions of the geophones (solid dots) around its periphery. The geophones were placed at intervals of 1 m. The shot point was not located at the highest point of the tumulus but at the center of the circular geophone array. The plan view of a modern hut is also shown at the top of the tumulus. The contours are in meters.

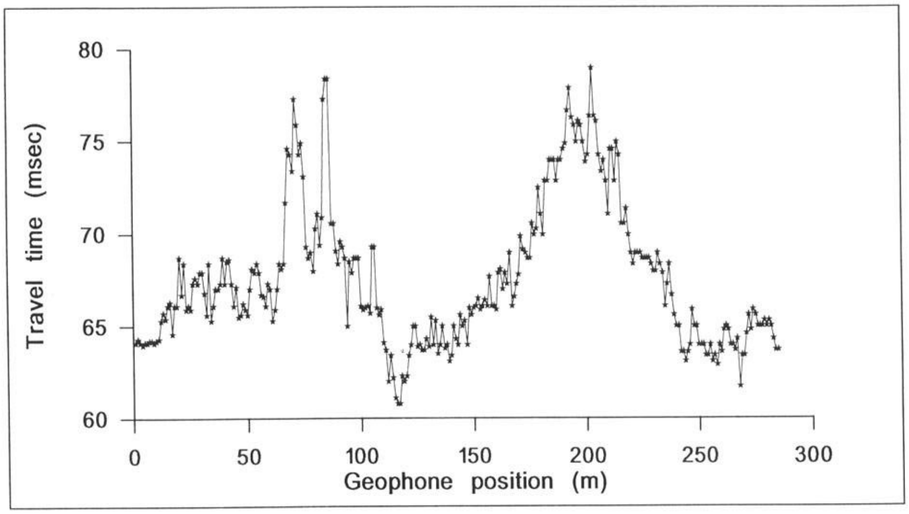

FIG. 6. The arrival times to the positions of the geophones around the periphery of the tumulus in Messiano

FIG. 7. Photograph of the monumental tomb revealed after the geophysical exploration of the tumulus at Messiano.

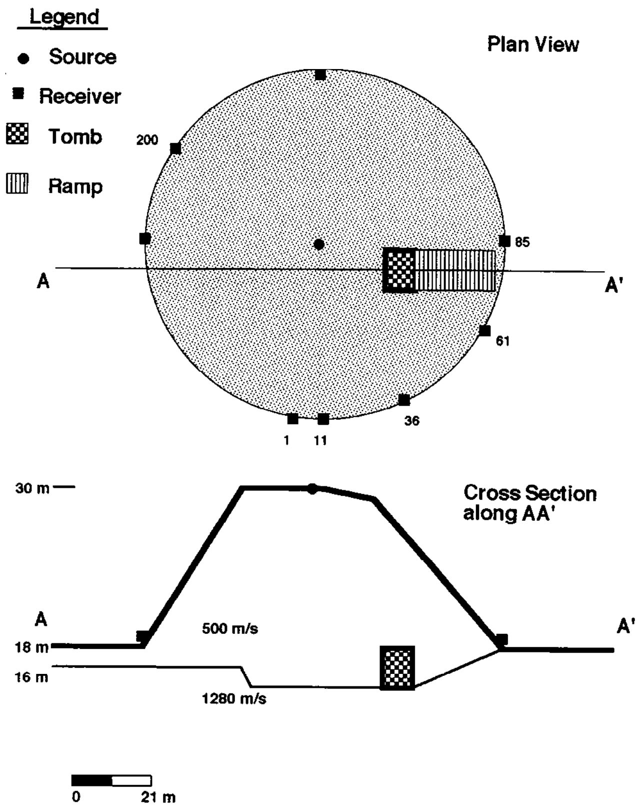

FIG. 8. Plan and sectional view of the model used to simulate the conditions revealed by excavation in the tumulus of Messiano. All dimensions were measured after the excavation and the discovery of the monumental tomb. The assigned head wave velocities were obtained by shooting refraction lines in the periphery.

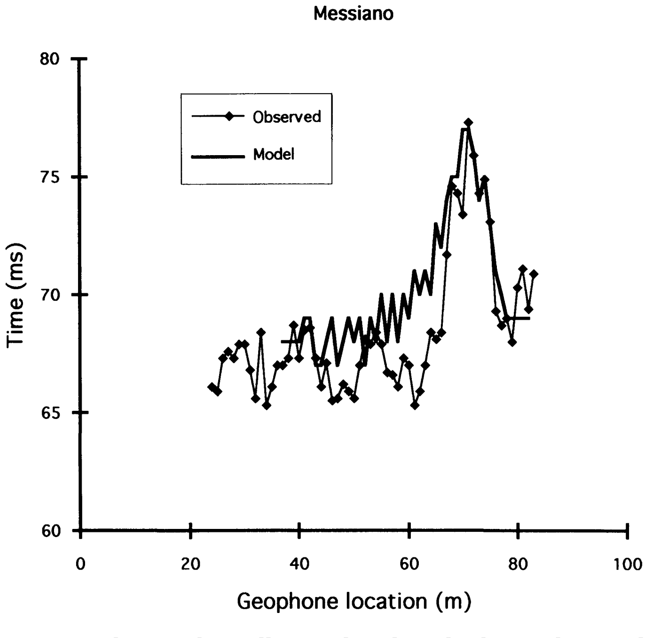

FIG. 9. The synthetically produced and observed arrival times for the experiment at the tumulus near the village of Messiano for geophones at locations 22 to 84.

ACKNOWLEDGMENT

This work was partly financed by the Greek Secretariat of Research and Technology.

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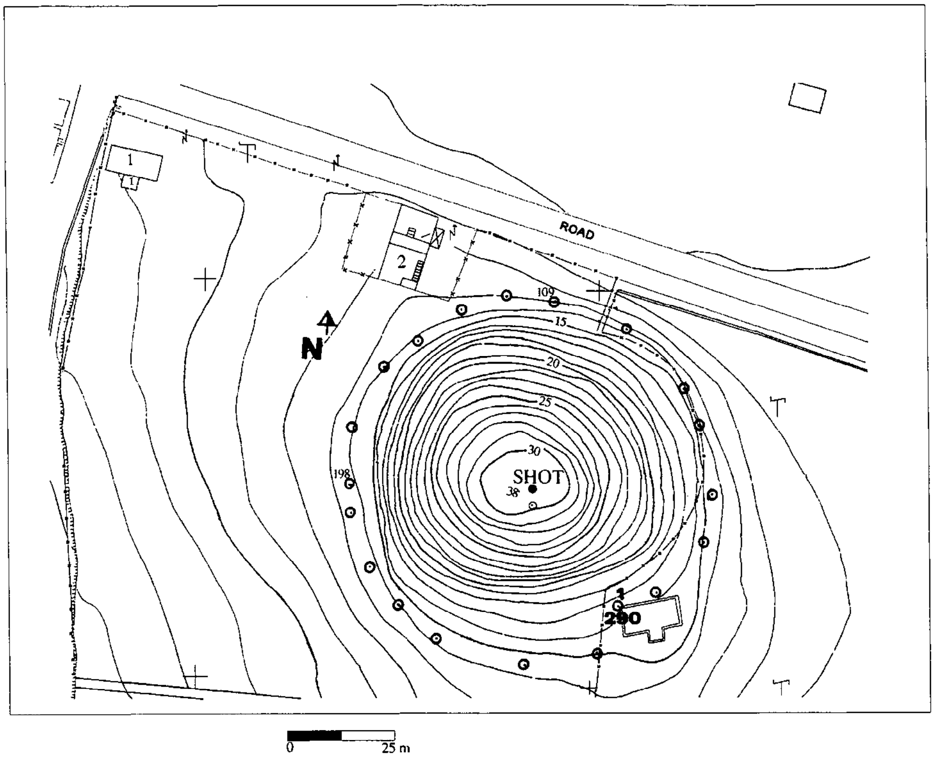

Fig. 10. Plan view of the tumulus in Agios Athanasios along the peripheral line of the detectors (open circles). The times observed in a few detectors about the arbitrary origin were corrected because these receivers were placed closer to the center than the rest. The plan view of a modern building is also shown in contact with the tumulus. The contours are in meters.

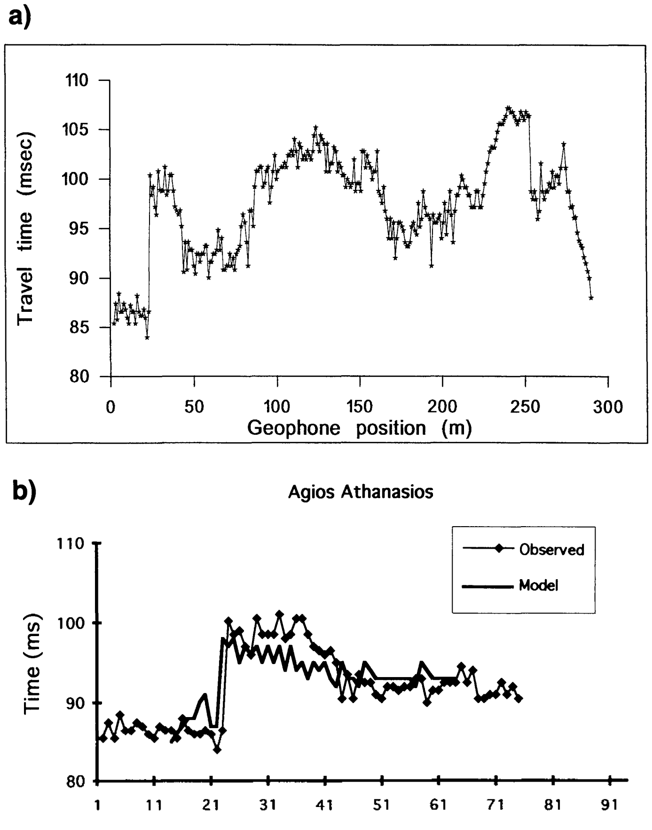

Fig. 11. The arrival times observed at the exploration of the tumulus of Agios Athanassios are in (a), while a portion of the real and synthetic data is in (b).

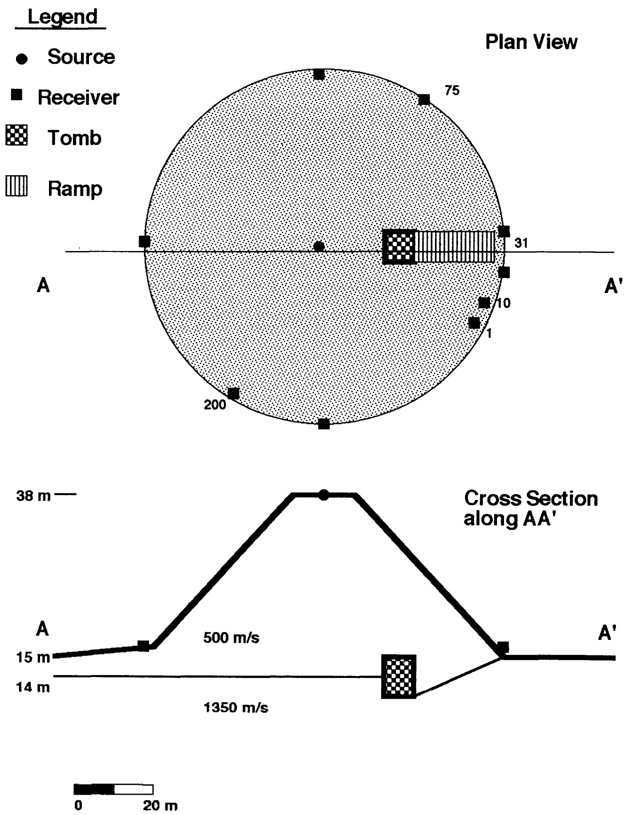

Fig. 12. Plan and sectional view of the model used to compute the arrival times shown in Figure 11**B**.