Archaeological Prospection
Archaeol. Prospect. **11**, 145–158 (2004)
Published online 12 May 2004 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/arp.228

Investigation of a Monumental Macedonian Tumulus by Three-dimensional Seismic Tomography

L. POLYMENAKOS[1], S. PAPAMARINOPOULOS[1]* A. LIOSSIS[1] AND CH. KOUKOULI-CHRYSSANTHAKI[2]

[1] *Department of Geology, Laboratory of Geophysics, University of Patra, Rio, Patra, Greece*
[2] *Archaeological Society, Athens, Greece*

ABSTRACT Monumental tumuli are important monuments of past human activity, and may contain burial structures of high cultural and historical value. Seismic tomography is used to investigate the internal structure of a monumental tumulus. Energy sources and recorders are placed on the periphery at the base of the tumulus. Travel time data are analysed and processed with three-dimensional tomographic inversion in order to construct images of the distribution of seismic velocity in the interior of the tumulus. Velocity variations are known to correlate well with the lithological character of the earth materials, thus providing important structural and lithological information of the tumulus. A case history from a Macedonian tumulus in northern Greece is presented. The results are interpreted in terms of evidence for possible man-made buried structures, such as tombs, walls, etc.; three-dimensional modelling is used to assist in the interpretation and evaluation of the significance and reliability of the results.

Key words: seismic tomography; tumuli; archaeology

Introduction

Tumuli are man-made hills erected to cover a tomb, usually of a highly esteemed and important person. Tumuli may cover one or more tombs, that is, burial structures, as well as other structures (Lazaridis *et al.*, 1992; Lazaridis, 1993). They occur in southeastern Europe and the Middle East and were erected continuously from prehistoric up to post-classical time. Both the tumuli and their contents are important monuments of past human activity and need to be preserved. Their investigation needs to be non-destructive apart from excavation at specific levels. According to the literature (Lazaridis, 1993; Tsokas *et al.*, 1995, and references therein) and direct observation (e.g. in Amfipoli and Vergina, northern Greece), tombs are mainly located close to the base (or a few metres lower) of the tumulus and usually not far from the periphery (Figure 1a), or they may be located near or at the centre. Tombs are reached from the periphery with a ramp (or tunnel when located at the centre), which was used during the construction of the tomb and thereafter filled with loose material from the vicinity. When several structures are contained in the tumulus, their location does not follow a specific trend, as depicted in the example in Figure 1b.

There have been various efforts to investigate the internal structure of tumuli with geophysical methods (Tsokas *et al.*, 1995; and extensive references therein). However, all efforts (such as resistivity soundings or imaging, magnetic profiling,

* Correspondence to: S. Papamarinopoulos, Department of Geology, Laboratory of Geophysics, University of Patra, Rio, Patra, Greece. E-mail: papamar7@upatras.gr

Received 11 January 2003
Accepted 10 January 2004

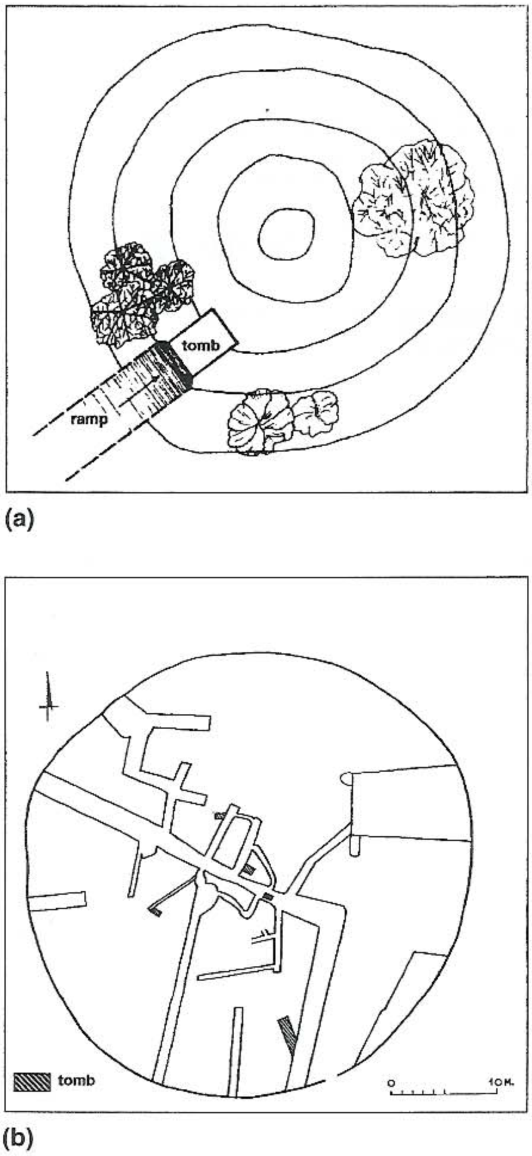


Figure 1. Examples of tumuli and their internal structure in plan view—not to scale. (a) A tumulus containing a typical tomb (after Tsokas *et al.*, 1995). (b) A tumulus containing various cultural and burial structures (after Lazaridis *et al.*, 1992).

seismic reflection, etc.) are based on probing of the interior in one or two dimensions, mainly from locations at the top of the hill, hence having limited penetration depth and limited aperture information. Tsokas *et al.* (1995) exploited the effect of the material associated with the ramp on the arrival times of seismic waves, by exciting a source at the top of the tumulus and recording times around the base of it. Their simple field layout proved to be successful in locating a tomb.

In trying to take the above ideas a step forward, seismic tomography was thought of as an attractive candidate for the investigation of the interior of a tumulus, using a full coverage, non-destructive method in real three dimensions. Seismic tomography is a means of reconstructing the distribution of physical properties in a medium (e.g. earth material), by using measurements of travel time or amplitude of wave energy propagated through it. The fundamental concept in tomography is that of the projection. Seismic measurements constitute a projection of the internal structure of the earth medium. An image of the internal structure of the earth medium is therefore produced by combining information from a set of projections obtained at different viewing angles. Applications include lithological characterization, fracture and void detection, fluid monitoring, stress evaluation, blast assessment and others (Nolet, 1987; Friedel *et al.*, 1992; Jackson and Tweeton, 1994).

In the context of a tumulus, the fill material of the ramp (if existent), possible disturbed earth material and the burial structures themselves are considered as constituting seismic velocity anomalies with their environment and capable of producing a change in the travel times and/or the amplitude of seismic waves. Seismic tomography is used in order to investigate the very existence, detectability and character of such anomalies. If anomalies are present and detectable, then tomographic applications could provide a very efficient way of investigating tumuli in a non-destructive way. The availability of three-dimensional tomographic analysis algorithms allows an extensive and non-labour-intensive coverage of a tumulus with seismic sources and receivers and subsequent rapid processing and interpretation on a PC-level computer. Application of three-dimensional algorithms, especially, allows for a highly efficient investigation without a priori postulating the particular tomb locations, thus greatly simplifying the overall investigation task and improving quality and robustness of interpretation.

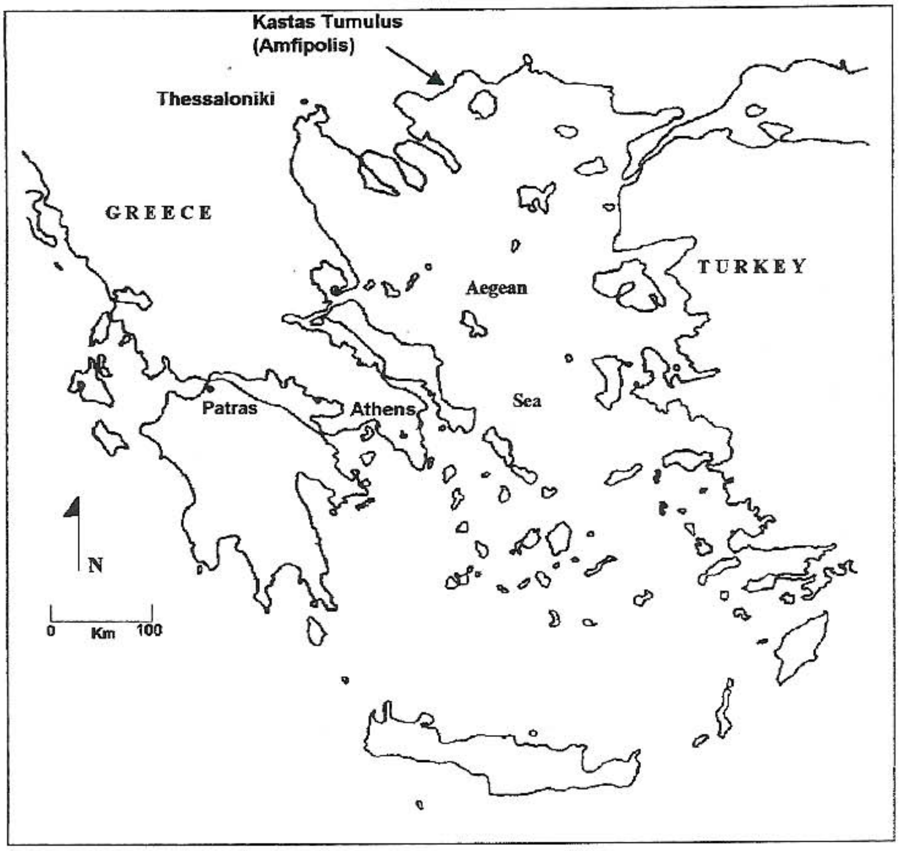


Figure 2. Simplified location map of KastasTumulus, northern Greece.

A tomographic experiment was carried out at the tumulus of Kastas, located in the vicinity of the present village and the ancient city of Amfipolis in northern Greece (Figure 2). Ancient Amfipolis was a significant cultural and commercial centre of the ancient Macedonian kingdom, inhabited from prehistoric times until the fall of the kingdom in the early hellenistic period. A large number of monumental burial structures, among them tumuli containing tombs of the 'macedonian' type, have been discovered and excavated in the surroundings of the fortified ancient city. The tumulus of Kastas is an artificial hill of a normal circular shape, with circumference of about 360 m, an average diameter of 160 m and height of 21 m. It is made of alternating layers of sand, red soil and occasional gravels. From scattered findings in the vicinity and within the material of its structure, the hill was thought to contain an important burial structure (Lazaridis, 1993). After several excavation periods, the local archaeological service decided to investigate the tumulus by non-destructive methods. This resulted in the application of several geophysical methods, such as magnetic, resistivity imaging and seismic tomography.

Experimental procedure

Seismic tomography is carried out by exciting a seismic energy source at several locations on the sides of an investigated medium and using the arriving wave energy at all receivers located on the sides of the medium. Figure 3 presents schematically the tomographic procedure. Measured characteristics of the received wave energy include amplitude and travel time. Amplitude is

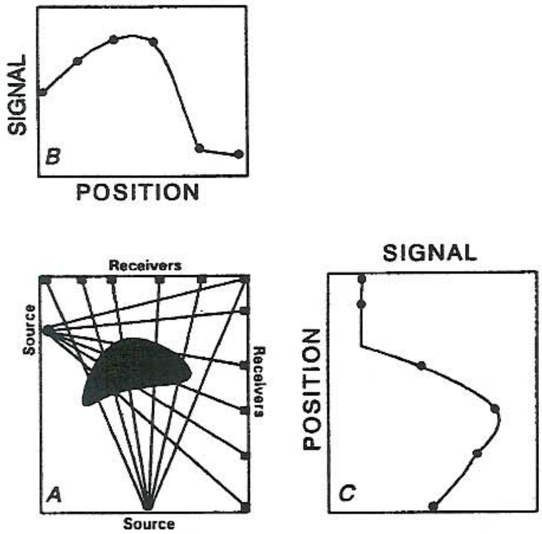


Figure 3. Schematic illustration of anomaly projections. Physical anomaly (A) projects as data anomalies (B and C); tomography involves reconstruction of physical anomalies from their projections.

determined by the distance travelled and by attenuation along the transit path. Travel time depends on raypath length and on velocity along the raypath. Inversion of either type of data results in an image of velocity or attenuation in the earth material, respectively. Of them, travel times/velocity will be considered hereafter, as it is easier to obtain from field records and is related directly to the physical character of the earth material. Inversion can be performed in two or three dimensions, considering data quality and angular coverage as well as time and cost. For details on inversion schemes the reader is referred to Nolet (1987) and Jackson and Tweeton (1994, 1997).

Considering the Kastas tumulus, an initial effort to perform a tomographic experiment was made using a simple layout, by exciting a limited number of seismic sources on one side of the tumulus and recording the time arrivals on the opposite side. Results were interesting but quite limited in information. It was therefore decided to design an experiment with the fullest possible angular coverage under the particular field conditions. In the new experiment, data recorders and sources were located along the periphery at the base of the tumulus, thus providing full angular coverage. Figure 4a presents a plan of the hill and location of sources and receivers. The circular location of sources and receivers and the elevation difference between them along the base (about 12 m in a NE–SW direction), provided for a real three-dimensional tomographic application, aiming mainly at the hypothetical location of tombs near the base of the tumulus. Along the periphery there were 120 geophone locations at average distances of 4.5 m and 16 source locations at average distances of 34.5 m. Figure 4b provides a perspective view of the location of sources and receivers. A total of 2000 records were made, of which 1596 were selected for further processing, after the appropriate quality control. The source was a falling 30 kg weight, yielding a main frequency of about 70 Hz, and vertical geophones with a resonance frequency of 100 Hz were used as receivers. Data were recorded on a 24 channel EG&G Geometrics 2401X seismograph.

The above layout allowed for coverage of the internal structure of the tumulus in a volume containing the base, located at an average elevation of 90.0 m above sea-level, and extending 10 m above and 13 m below the base, having a total vertical length (thickness) of 23 m, between elevations of 77 m and 100 m above sea-level.

Data Analysis and Processing

Data analysis

Only first arrivals were used in the tomographic analysis. Initial quality control and processing of the field records was made by *Tomtime* software (Tweeton, 1999b). The error in time picking is 3 msec on average. A time–distance plot for the first arrivals is presented in Figure 5a, and an average velocity of 0.9 km s^{-1} is calculated assuming straight raypaths, as shown in the relevant velocity histogram in Figure 5b. With respect to the main frequency of 70 Hz, this yields an average wavelength of 12 m and a corresponding resolution of 3–6 m.

From the time–distance plot there appear two major groups of times, one at distances 0–30 m with a sharp increase in time and one at distances 30–140 m with a gently increase in time—these refer to a two-layer structure. Two other

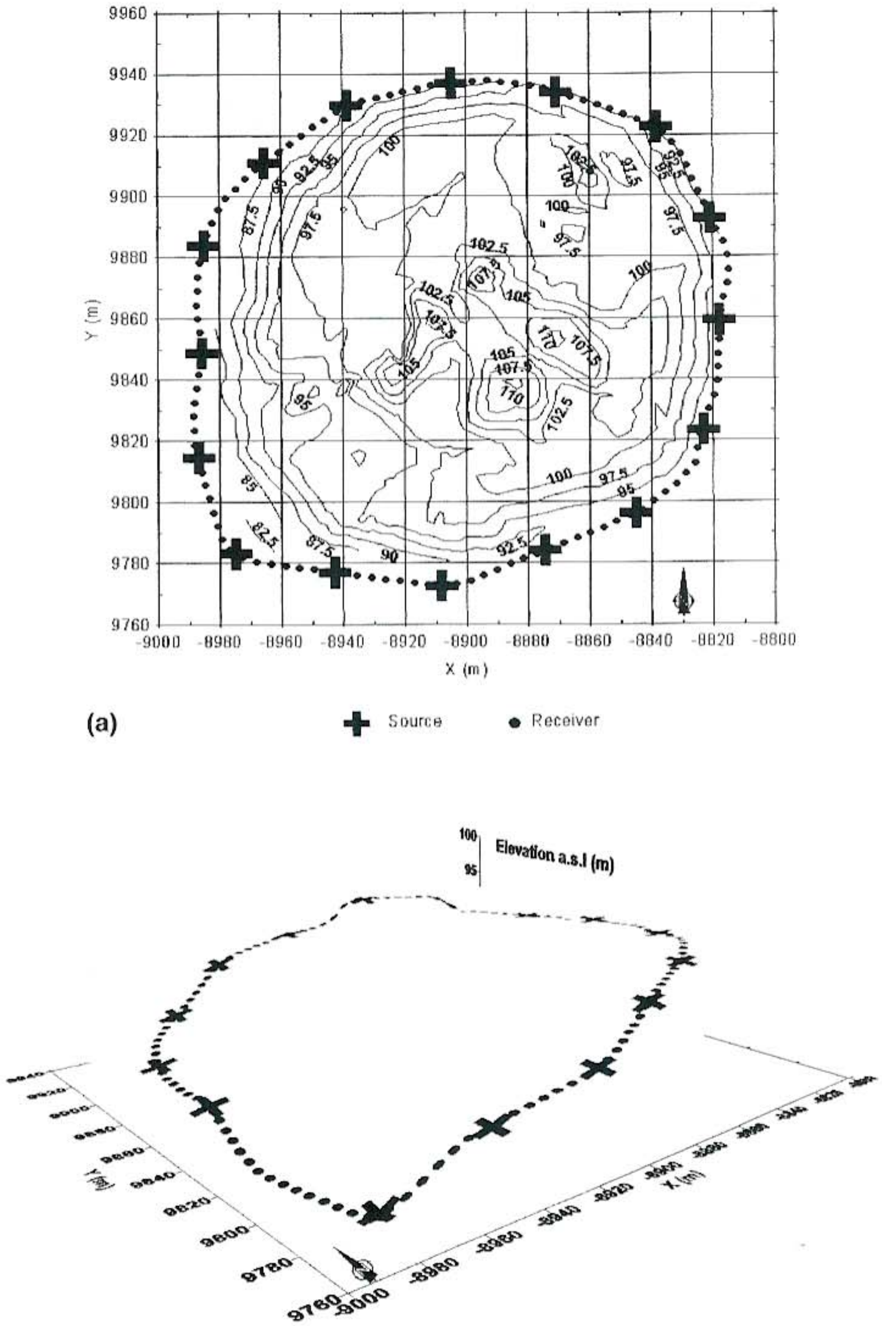


Figure 4. (a) Plan of Kastas tumulus with source and receiver locations of the tomographic experiment. Numbers near the isolines correspond to elevation a.s.l in metres. (b) Three-dimensional perspective plan of the source and receiver locations.

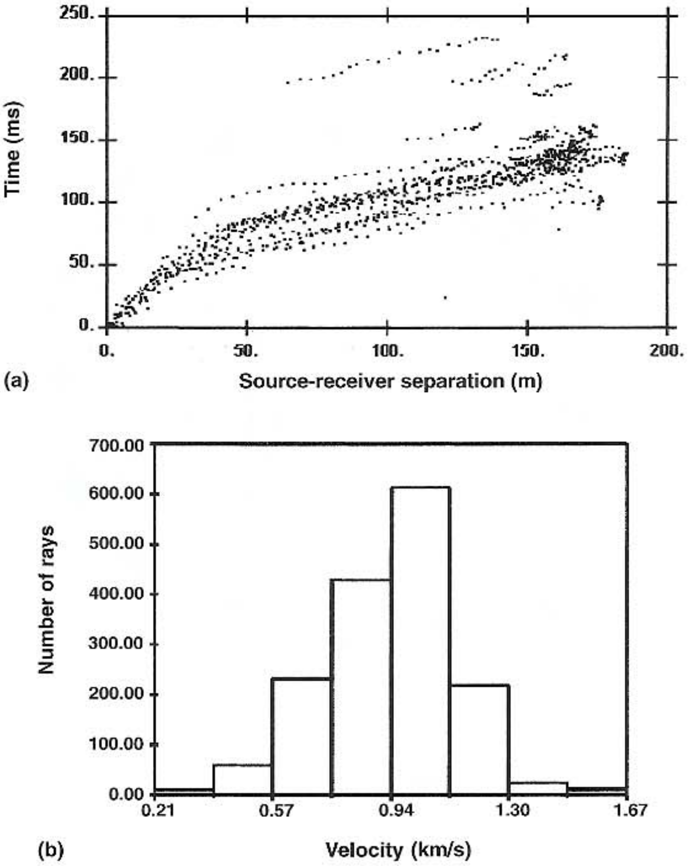


Figure 5. Plots from the tomographic dataset. (a) Time–distance plot. (b) Histogram of seismic velocities calculated assuming straight raypaths.

groups are observed: one shows higher times at distances of 60–150 m, related to a low-velocity layer, and the other shows varying values at distances greater than 150 m, corresponding to varying material characteristics.

Independent information on the seismic velocities of the soil material of the hill and the underlying material was provided by seismic refraction lines shot on top of the hill, at an elevation of 105 m. Also, a number of first arrivals from the tomographic experiment were used for the same purpose. These tests provided a two-layer structure with the upper layer having an average velocity of $0.7\,km\,s^{-1}$ and the lower one an average velocity of $1.2–1.4\,km\,s^{-1}$. The interface was estimated at an elevation of 90 m. Around the base of the tumulus, velocities have a range of $0.4–0.6\,km\,s^{-1}$, which is compatible with the existence of loose material as verified *in situ*.

Inversion

Inversion of the travel-time data was made using a variation of the SIRT algorithm (Lytle *et al.*, 1978; Peterson *et al.*, 1985; Um and Thurber, 1987) with use of the *Geotom* software (Tweeton, 1999a). This involves modification of an arbitrary initial velocity model by repeated cycles of three steps: forward computation of model travel times, calculation of residuals and application of velocity corrections. Forward calculations may be carried out by either straight and/or curved rays, using wavefront migration. Straight rays allow rapid calculation but are less physically realistic compared with curved rays, the latter being more time-consuming, however. The decision upon the use of curved rays is based on the velocity contrasts in the earth material. Velocity contrasts greater than 20% and handling of out-of-plane effects require the use of curved rays. The inversion algorithm allows for the use of constraints on the velocity values, in order to reduce the non-uniqueness problem, which results from limited coverage of the investigated medium owing to the geometry of source and receiver locations and the source character. Refraction of wave energy is modelled by using wavefront migration, based on Huygens' Principle, thereby suppressing the shadow-zone problem, which affects conventional ray-tracing calculations.

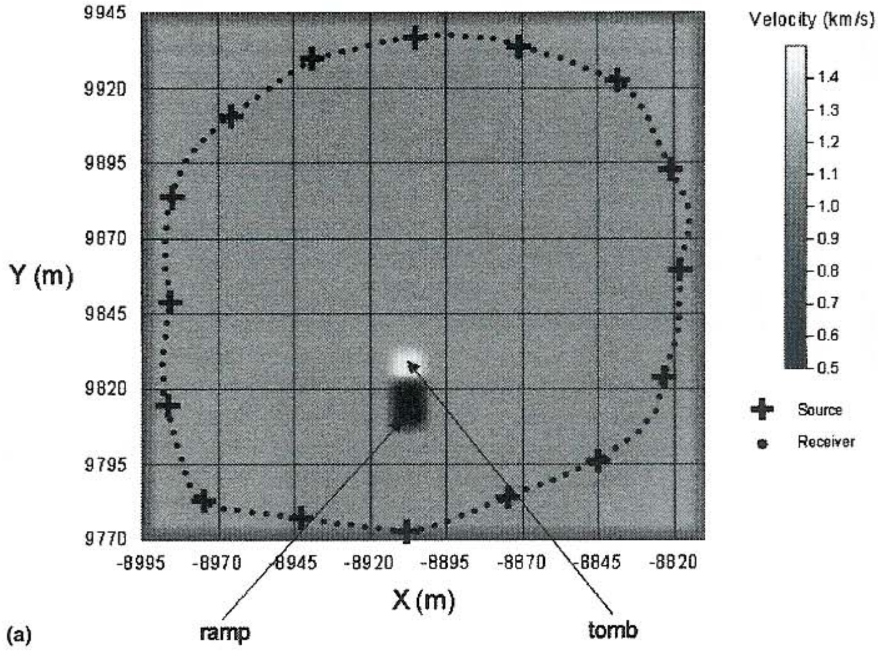
The calculation grid was designed in three-dimensions and matched the source-to-receiver geometry as closely as possible. Considering an average resolution of 4 m and mathematical consistency, the grid has dimensions $X \times Y \times Z = 5 \times 5 \times 2.5$ m. Inversion was performed with both straight and curved rays, to allow for handling of strong velocity contrasts, refraction and out-of-plane effects. The starting velocity model consisted of two layers, the upper assigned a velocity of $0.7\,\mathrm{km\,s^{-1}}$ (at elevation 90–100 m), and the lower assigned a velocity of $1.2\,\mathrm{km\,s^{-1}}$ (at elevation 77–90 m). Minimum and maximum allowable velocities (global constraints) were applied with values of $0.3\,\mathrm{km\,s^{-1}}$ and $2.0\,\mathrm{km\,s^{-1}}$, respectively. Local (node) constraints were defined appropriately as to allow for small modifications of velocities during the inversion process. The inversion process converged after five straight and ten subsequent curved ray iterations, with an RMS error of 10%. Curved ray iterations were necessary as they greatly improved the reconstructed velocity distribution, the coverage of the tomographic volume and also stabilized the inversion process.

Modelling the tomb effect

An attempt was made to simulate the effect of a tomb 'buried' in the soil material of the hill, in order to explore the imaging capability of the actual experimental configuration. The model consists of assigning a velocity of $1.5\,\mathrm{km\,s^{-1}}$ to nodes of the grid 'occupied' by the tomb, and $0.5\,\mathrm{km\,s^{-1}}$ to the ramp filling material. After considering information from the literature and direct observation of some representative excavated tumuli in northern Greece, the dimensions of the tomb and ramp were designed to be 20 m long, 5 m wide and 5 m high. Regarding the dimensions of the calculation grid ($5 \times 5 \times 2.5$ m), the tomb and ramp occupied five nodes along, two nodes across and two nodes in height. Following on-site information, the 'tomb' was placed at various locations within the volume of the tumulus. Figure 6a shows a horizontal tomogram with the tomb at an arbitrary location and elevation. A tomogram is a slice of the tomographic volume in a preferred direction (horizontal, vertical or other) displaying the distribution of a specific quantity. Using the original experimental source/receiver geometry, synthetic travel times were calculated and then were input to the inversion process with a uniform average velocity starting model. The calculation grid had similar dimensions to the original, and the same amount and type of iterations were performed.

The combined result of straight and curved ray iterations for the arbitrary tomb location and elevation of Figure 6a is presented in a horizontal tomogram in Figure 6b. The result of the inversion for a tumulus volume without the tomb is presented for comparison in a horizontal tomogram in Figure 6c.

The original model is satisfactorily reconstructed, taking into consideration that this result comes from synthetic travel-time data, which are limited in frequency and energy information with respect to real seismic data and that the initial velocity model is only an estimate with respect to real stratigraphy. In Figure 6b, the tomb itself is only marginally differentiated from the background velocity distribution. However, characteristic high-velocity 'tails' (artefacts) are observed to expand from the 'tomb' location, and a low-velocity concave lobe is formed as a result of the 'ramp' reconstruction. These features are not observed in the result without the tomb (Figure 6c), thus showing the clear effect of the tomb in the reconstruction. Moreover, the tails act as indirect indicators of the existence of a high-velocity anomaly, located at their onset. The reconstructed velocity distribution is not homogeneous: it is characterized by high velocity 'anomalies' with a NE–SW trend, located mainly in the E–NE sector of the tumulus. This is observed in both data with and without the



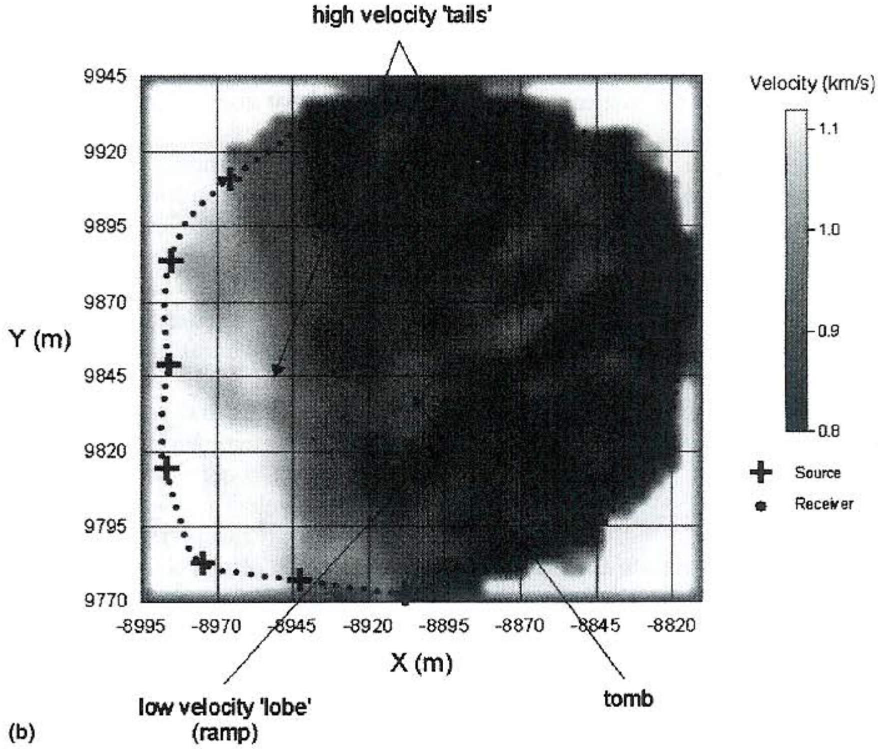


Figure 6. Modelling of the tomb effect. (a) Initial model tomogram showing the 'tomb'. (b) Results from inversion of synthetic data calculated for the 'tomb' model. (c) Results from inversion of synthetic data calculated without the 'tomb' model.

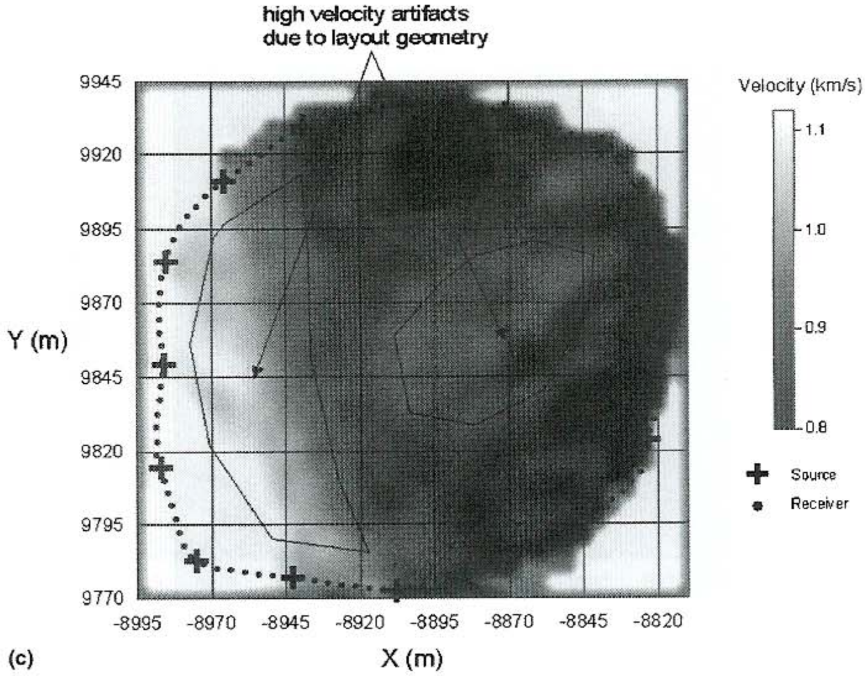


Figure 6. (*Continued*).

tomb, and is an artefact attributed to the effect of the source/receiver geometry on the behaviour of curved rays: the elevation difference between the sources and receivers in the NE–SW and NW–SE direction and the velocity interface at 90 m elevation produce an accumulation (focusing) of seismic rays in the northeast sector, thus resulting in this velocity anomaly.

The above results imply that the detection of even this modest anomaly is possible through an appropriately designed experimental configuration and processing.

Interpretation

Horizontal tomograms of velocity and ray density are presented in Figure 7, at the elevation of 87.5 m, that is below the base of the tumulus which is at an average elevation of 90.0 m. Ray density (rays per unit model cell) is a simple global indicator of the inversion reliability and contributes to the interpretation of the velocity image.

The major features of velocity and ray density tomograms are as follows (see Figure 7a and b).

(i) High-velocity anomalies (velocities greater than 1.2 km s^{-1}) appear in the central (H1), eastern (H2, H3), northern (H4) and southewestern (H5–H7) sectors. Characteristic high-velocity 'tails', are observed to radiate from anomalies H1 and H5, resembling the 'tomb effect', such as those observed in Figure 6b. These anomalies are interpreted as cohesive material and could reflect stone structures.

(ii) Low-velocity anomalies (velocities less than 1.2 km s^{-1}) appear in the south and southwest sectors (L1 and L2) and along the periphery (L3). Anomaly L1 extends between the periphery and anomaly H1, and anomaly L2 is confined between anomalies H5–H7, producing an image of a highly disturbed material. Low-velocity anomalies are interpreted as loose material, which is probably fill of the trenches dug inside and

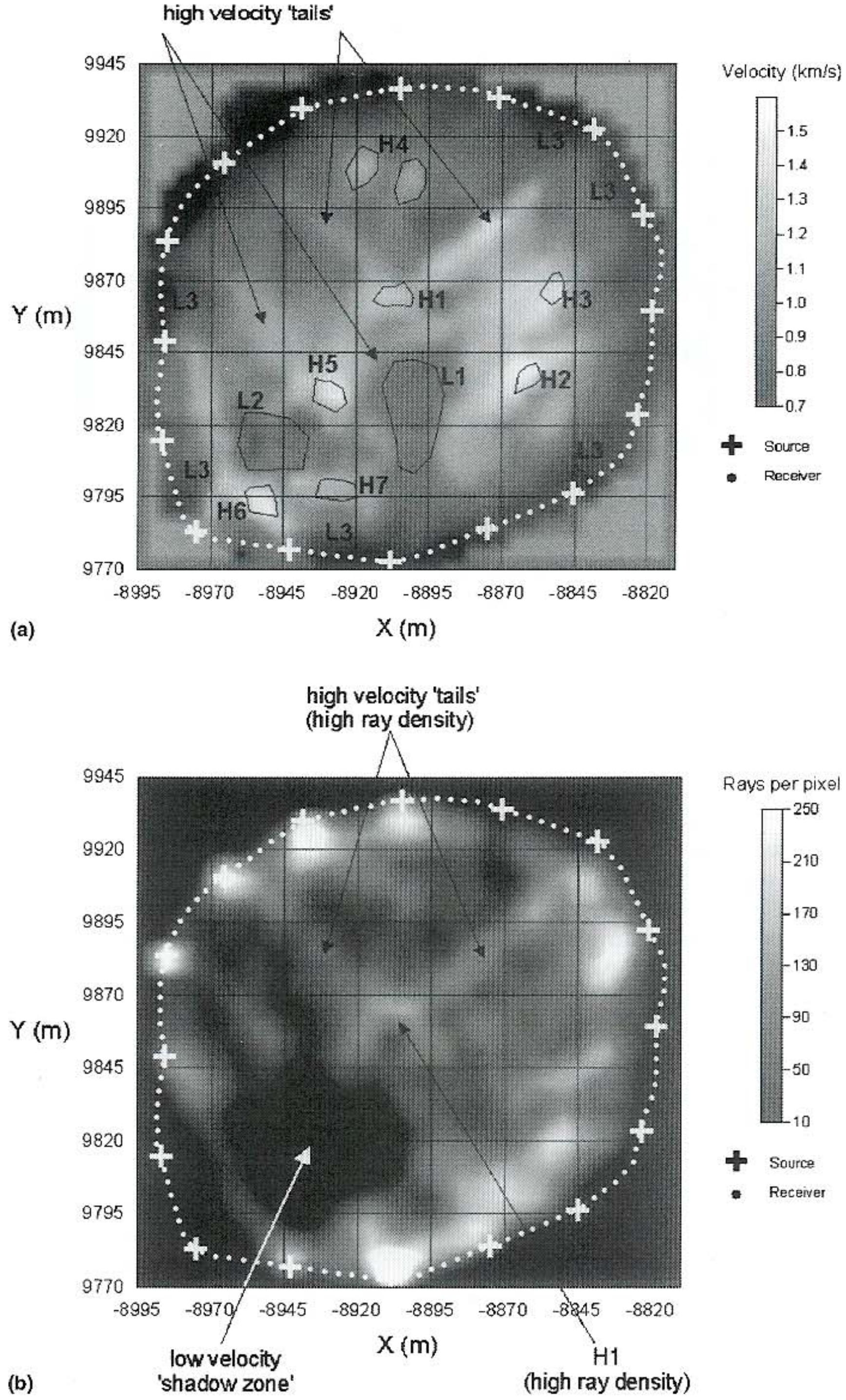


Figure 7. Tomograms of the results from inversion of real experimental data at elevation 87.5 m: (a) velocity and (b) ray density. Results of synthetic data without the tomb model are presented for comparison (c).

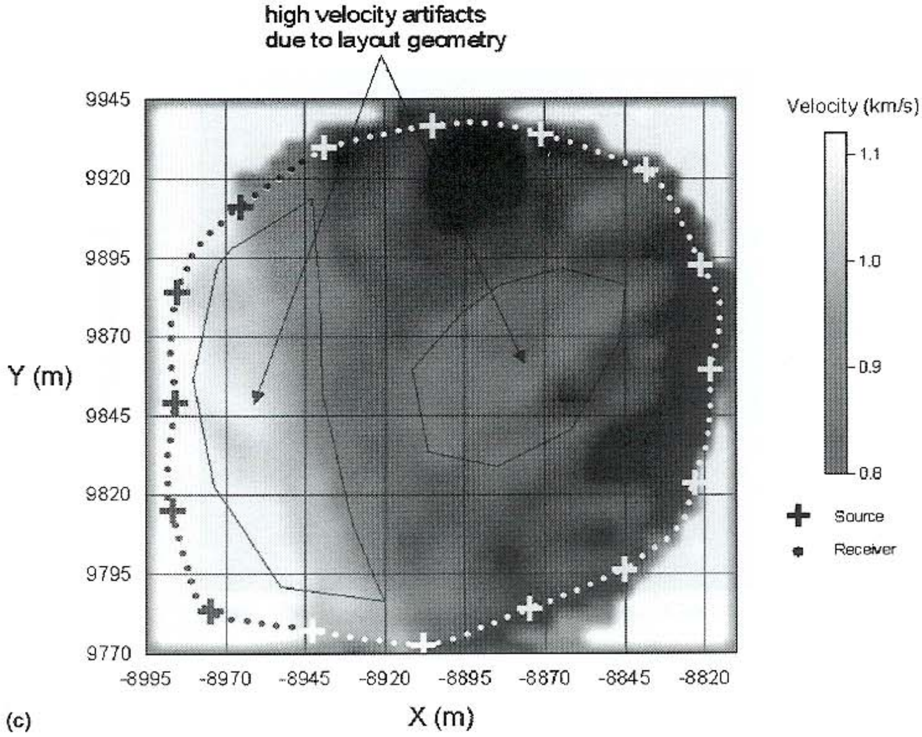


Figure 7. (*Continued*).

around the tumulus. In the ray-density tomogram, a sharp decrease in ray density is observed in the sector containing anomalies L1 and L2, implying the presence of loose material.

(iii) The resulting velocity distribution is considered as generally reliable because most parts of the tomogram locations are sampled by more than 100 rays on average and the model fit error (RMS value) is quite low (about 10%). Local increase/decrease in ray density, such as at the location of anomalies H1, H2, L1 and L2 respectively is due to focusing/defocusing of rays in high/low velocity areas.

By comparing Figure 7b to the image of the synthetic data without the tomb (Figure 7c), it is clear that the above anomalies are real and not a result of layout geometry or errors in the initial data assessment.

In Figure 8(a–d) are shown two other horizontal tomograms at elevation 85.0 and 90.0 m, that is, below and above the tomogram at 87.5 m of Figure 7. Most of the high-velocity anomalies (particularly H1 and H5–7) are present at 85.0 m, whereas only H2, H6 and H7 are still present at 90.0 m. Also, most low-velocity anomalies are present at 85.0 m but they are absent at 90.0 m. The tomogram at 90.0 m is characterized by an extended low-velocity area covering most of its western part.

It is proposed that various stone structures, some of which could be probably tombs, are buried in the tumulus, the overall image resembling that of the example in Figure 1b. Of the anomalies observed, anomaly H1 is the strongest one and, with anomaly L1, have the characteristics to be good candidates for a tomb and a ramp, respectively. The presence of anomaly H1/L1 also at 85.0 m elevation, that is, well below, about 5 m, the base of the artificial hill, strengthens the estimation that it is related to a significant burial structure, in accordance to literature descriptions concerning the location and dimensions of such structures.

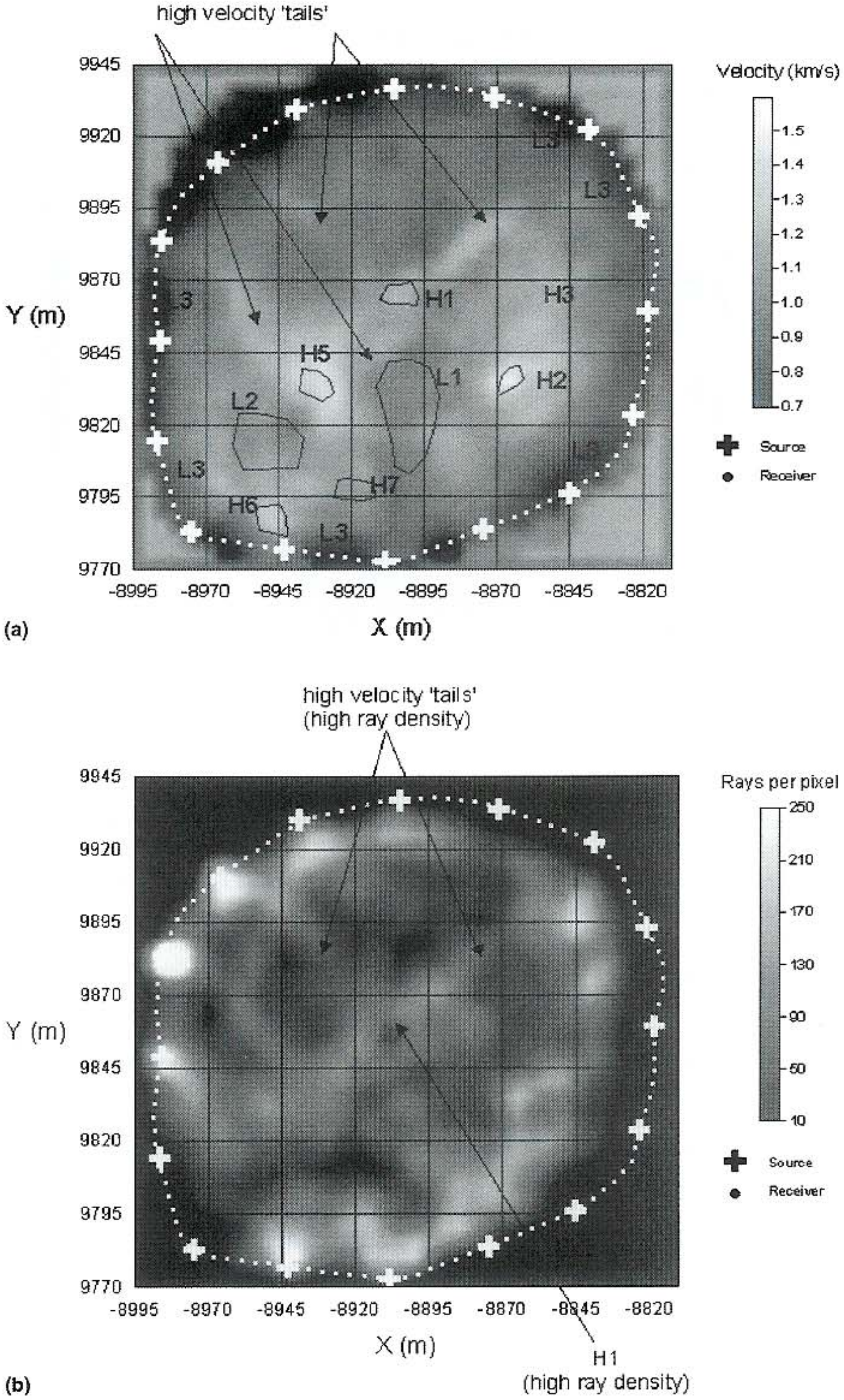
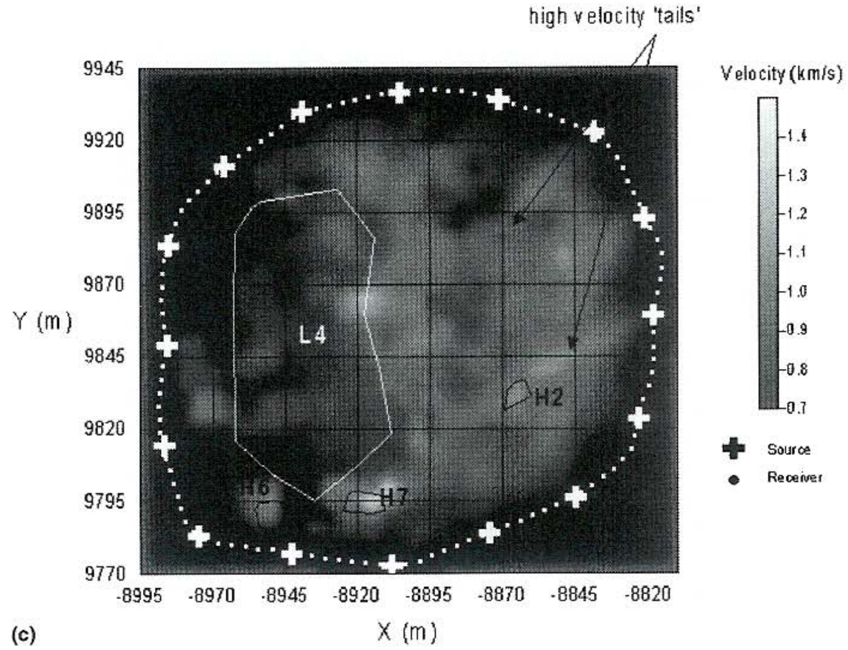
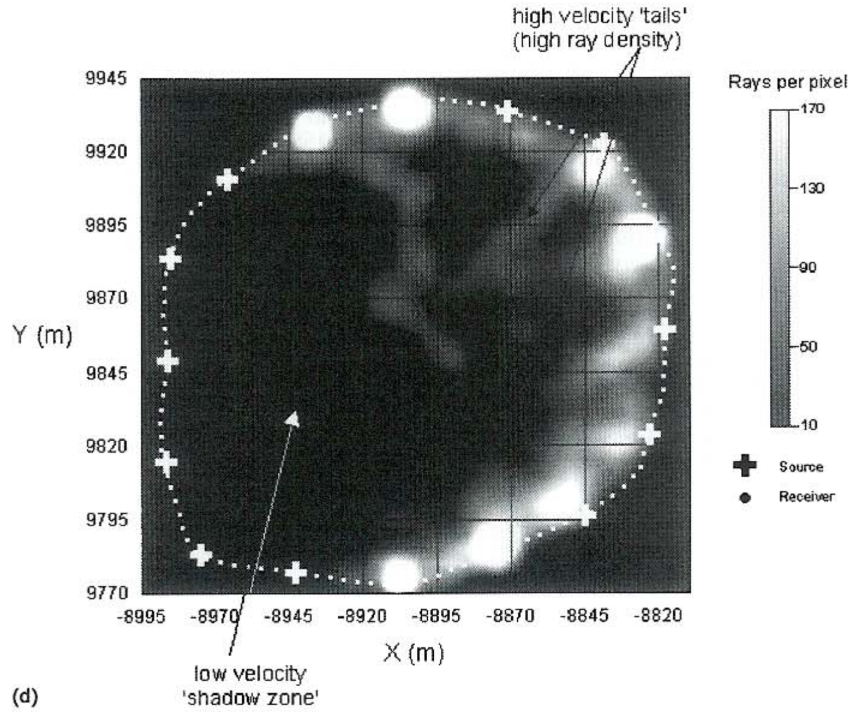


Figure 8. Tomograms of the results from inversion of real experimental data: (a) velocity and (b) ray density at elevation 85.0 m; (c) velocity and (d) ray density at elevation 90.0 m.



(c)



(d)

Figure 8. (*Continued*).

Conclusions

The capability of very good angular coverage along the periphery of the tumulus base with a simple field procedure and three-dimensional inversion, makes seismic tomography an attractive exploration tool for the investigation of monumental tumuli. Synthetic tests provide evidence that anomalies produced by buried structures within the tumulus can be detected reliably. Tomograms from inversion of real data provide interesting images of the internal structure of the tumulus, with features that can be associated with man-made structures. Although these results remain to be ground-proofed, it is clearly shown that seismic tomography has the ability to provide important subsurface information for the exploration of artificial hills, in a non-destructive manner. A main advantage of the method is that it can be adapted to the specific site conditions: more sources and receivers, source characteristics adapted to the site conditions, a better designed layout and sophisticated software will certainly provide even better information in the near future. This is a subject of ongoing research at the Geophysical Laboratory of the University of Patra.

Acknowledgements

We would like to thank Dr Chris De Wispelaere, the Science For Peace NATO programme director and all the members of the steering group of the former Science for Peace programme for financial assistance in the realization of this highly interesting project. Xenophon Bafitis who greatly assisted during the field work and the members of the Archaeological Service of Kavala who participated and assisted in many ways, are greatfully acknowledged.

References

Friedel MJ, Tweeton DR, Jackson MJ, Jessop JA, Cumerlato CL. 1992. Mining applications of seismic tomography. In *62nd Annual Meeting and Exposition of the Society of Exploration Geophysicists*, 25–29 October, 1992, New Orleans; 58–62.

Jackson MJ, Tweeton DR. 1994. *MIGRATOM—Geophysical Tomography Using Wavefront Migration and Fuzzy Constraints*. RI-9497, US Bureau of Mines, Minneapolis, USA.

Jackson MJ, Tweeton DR. 1997. *3DTOM: Three-dimensional Geophysical Tomography*. RI-9617, US Bureau of Mines, Minneapolis, USA.

Lazaridis D. 1993. *Amfipolis, a Guide to the Antiquities*. Ministry of Culture, Archaeological Research and Restoration Fund (TAPA): Athens.

Lazaridis D, Romiopoulou K, Touratsoglou G. 1992. *O tymvos tes Nikissianes (The tumulus of Nikissiani)*. Ellenomnemon, Library of the Archaeological Society of Athens; 121. (In Greek with English abstract.)

Lytle RJ, Dines KA, Laine EF, Lager PL. 1978. *Electromagnetic Cross-borehole Survey of a Site Proposed for an Urban Transit Station*. UCLR-52484, Lawrence Livermore Laboratory, University of California.

Nolet G (ed.). 1987. *Seismic Tomography, with Applications in Global Seismology and Exploration Geophysics*. Reidel: Boston.

Peterson JE, Paulson BNP, McEvilly TV. 1985. Applications of algebraic reconstruction techniques to crosshole seismic data. *Geophysics* **50**(5): 1566–1580.

Tsokas GN, Papazachos CB, Vafidis A, Loukoyiannakis MZ, Vargemezis G, Tzimeas K. 1995. The detection of monumental tombs buried in tumuli by seismic refraction. *Geophysics* **60**(6): 1735–1742.

Tweeton DR. 1999(a). *Geotomcg, Three Dimensional Geophysical Tomography*. Geotom LLC: Minneapolis.

Tweeton DR. 1999(b). *Tomtime, Seismic Data Analysis and Processing*. Geotom LLC: Minneapolis.

Um J, Thurber C. 1987. A fast algorithm for two-point ray tracing. *Bulletin of the Seismological Society of America* **77**: 972–986.

