Internal structure of the great tumulus of Apollonia as revealed by seismic tomography

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Abstract
We investigate the tumulus of Apollonia using the NSTomo3D seismic tomography software. Results reveal P-wave velocities of >850 m/s at the perimeter and <650 m/s in the middle. High velocities are associated with travertine rocks that were used as building materials. Low velocities correspond to unconsolidated sediments used as filling material. Several structures revealed that are of potential archaeological interest.

Keywords
Apollonia; Macedonia; seismic tomography; tumulus

Introduction

The great tumulus of Apollonia in northern Greece is located ~50 km east of the city of Thessaloniki and ~3 km south of the lake Volvi. It is a part of the northern cemetery of the ancient city that was established ~1 km south of the tumulus. With a diameter of ~100 m and height of ~20 m, it is one the largest tumuli in the greater region of Macedonia. A series of previous geophysical surveys including electrical resistivity tomography and seismic soundings revealed complex internal structure (Tsokas et al. 2011). A recent limited excavation at the perimeter of the tumulus unearthed a looted rectangular Macedonian tomb of dimensions 7 × 4 m, founded on natural travertine rock (Acheilara et al. 2011). However, the possibility of additional burial monuments hidden within the tumulus necessitated further investigation by means of geophysical prospecting utilizing various methods, including a 3-D seismic tomography under the program EKATY.

Seismic methods are among the most popular in geophysical exploration over a wide range of applications including archaeology. Complex 3-D heterogeneity and strong topographic variations as in the case of imaging tumuli, may pose significant problems in 2-D surveys as the seismic wave propagation occurs in out of the plane directions. In such cases 3-D data acquisition and full 3-D inversion is crucial to obtain robust and meaningful images of the subsurface.

In this work we present the results of the 3-D P-wave travel time tomography of the great tumulus of Apollonia. For the tomographic inversion we have used the recently developed software NSTomo3D that allows to account for the topography and finite frequency effects by using finite frequency kernels instead of infinitely thin ray paths. Furthermore, it provides tools to efficiently calculate the full model resolution matrix that can be challenging in large inverse problems as such related to 3-D model inversions.

Data and methods

Data collection

The seismic tomography experiment was designed to provide a dense 3-D data coverage of the tumulus. A total of 24 geophones connected with a Geometrics StrataVisor seismograph were deployed in 13 locations that covered the

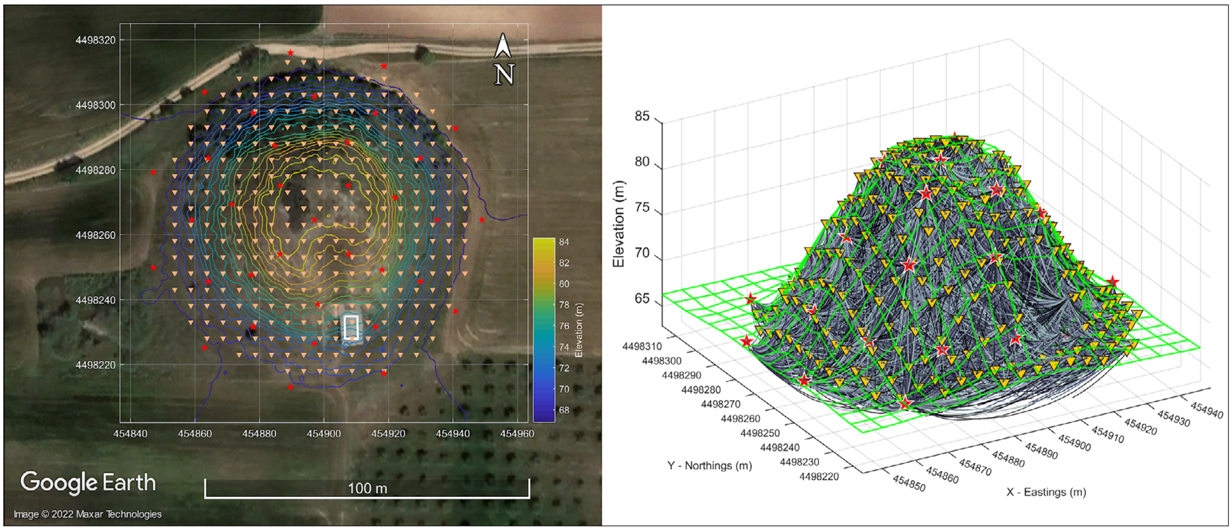

Fig. 1: The great tumulus of Apollonia. Left: satellite image obtained from Google Earth showing the tumulus and the surrounding region overlayed with the topography contours. The excavated area where the unearthed tomb can be seen as a white rectangle at the southern part of the tumulus. Locations of geophones and sources are shown with triangles and stars, respectively. Right: ray paths that correspond to the picked travel times. The map projection is the Hellenic Geodetic Reference System 1987, in m.

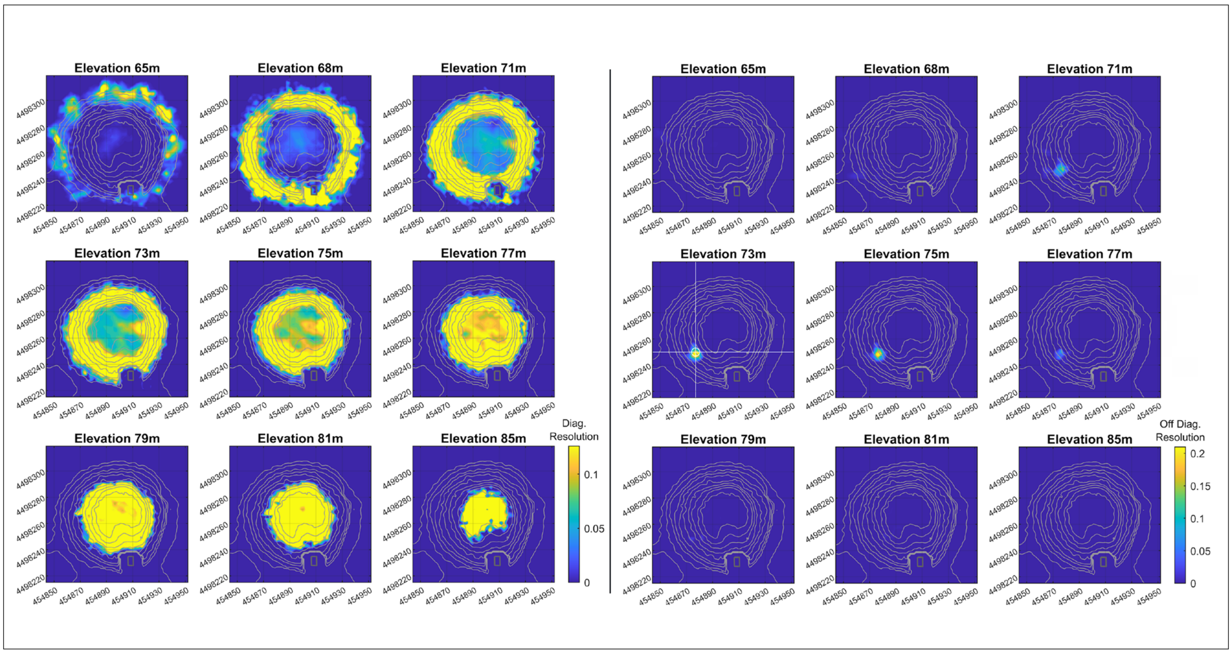

Fig. 2: Resolution analysis. Horizontal depth-slices showing (left) the diagonal elements of the resolution matrix and (right) the off-diagonal resolution corresponding to the point marked with the cross.

surface of the tumulus, forming a regular grid with spacing of 5 m. For each array/geophone a total of 33 P-wave sources uniformly distributed on the surface of the tumulus were established using a sledgehammer (Fig. 1). A total of 8,579 usable P-wave travel times were picked together with their error estimates, corresponding to 267 different geophone locations. Analysis of the frequency spectrum at a window around first P-wave arrival yielded a dominant frequency of $\sim$40 Hz. This frequency was used in the calculation of the sensitivity kernels (Bogiatzis et al. 2022).

Method

For the forward problem a high-quality irregular grid was constructed that included explicitly points delineating the topography. Grid points on the air were fixed during the inversion to the velocity of P-waves in the air (343 m/s). We inverted using damping and smoothing constraints. The optimal weighting of the constraints was derived through a 2-D L-curve analysis (Aster et al. 2013). The starting model was homogeneous medium with velocity of 600 m/s inferred by averaging the apparent velocities of the picked traveltimes ensuring that the errors follow a zero-centered Gaussian distribution. The inversion converged after ~30 iterations achieving reduction of the RMS error of ~43%. In addition to the velocity model, the full model resolution matrix was calculated efficiently using direct sparse methods and the Dulmage Mendelsohn decomposition (Bogiatzis et al. 2019) allowing to evaluate the robustness of the imaged features (Fig. 2 left). The off-diagonal elements of the resolution matrix show the extend of smearing/averaging of a hypothetical spike anomaly in the estimated tomographic model for each one of the model parameters. This allows the estimation of the 3-D resolution length, which in this case is less than ~4 meters (Fig. 2 right).

Results

Large velocities >850 m/s are imaged in the perimeter of the tumulus and relatively low velocities <650 m/s in the central region (Fig. 3). This is consistent with presence of travertine rocks perimetrical, some of which are visible in the area and at the unearthed tomb. At the eastern and southern sides, the high-velocity anomalies are continuous and of high amplitudes. On the western side the high velocities have generally lower amplitudes and appear fragmented but wider as they extend closer to the center. The perimetrical ring of high velocities is interrupted at the northern side, where the velocities are similar to the interior of the mount, corresponding to unconsolidated soil. A general increase of the velocity with depth, can be attributed to pressurization of the sediments due to the overburden. A small high-velocity anomaly at the top of the mount is related with a modern concrete-made structure, used as topographic station.

Discussion and conclusion

Our results suggest that the Apollonia tumulus was founded using hard materials i.e., travertine rock, to form an open dome that subsequently was filled with soil. The western side of the dome which is segmented presents more complexity and interesting pockets of low velocities indicating possible targets of archaeological interest. The excavated tomb appears to lie in the region of high velocities. The interior of the tumulus appears less heterogeneous with no obvious targets. Our results are in good agreement with previous seismic soundings (Tsokas et al. 2011).

Acknowledgments

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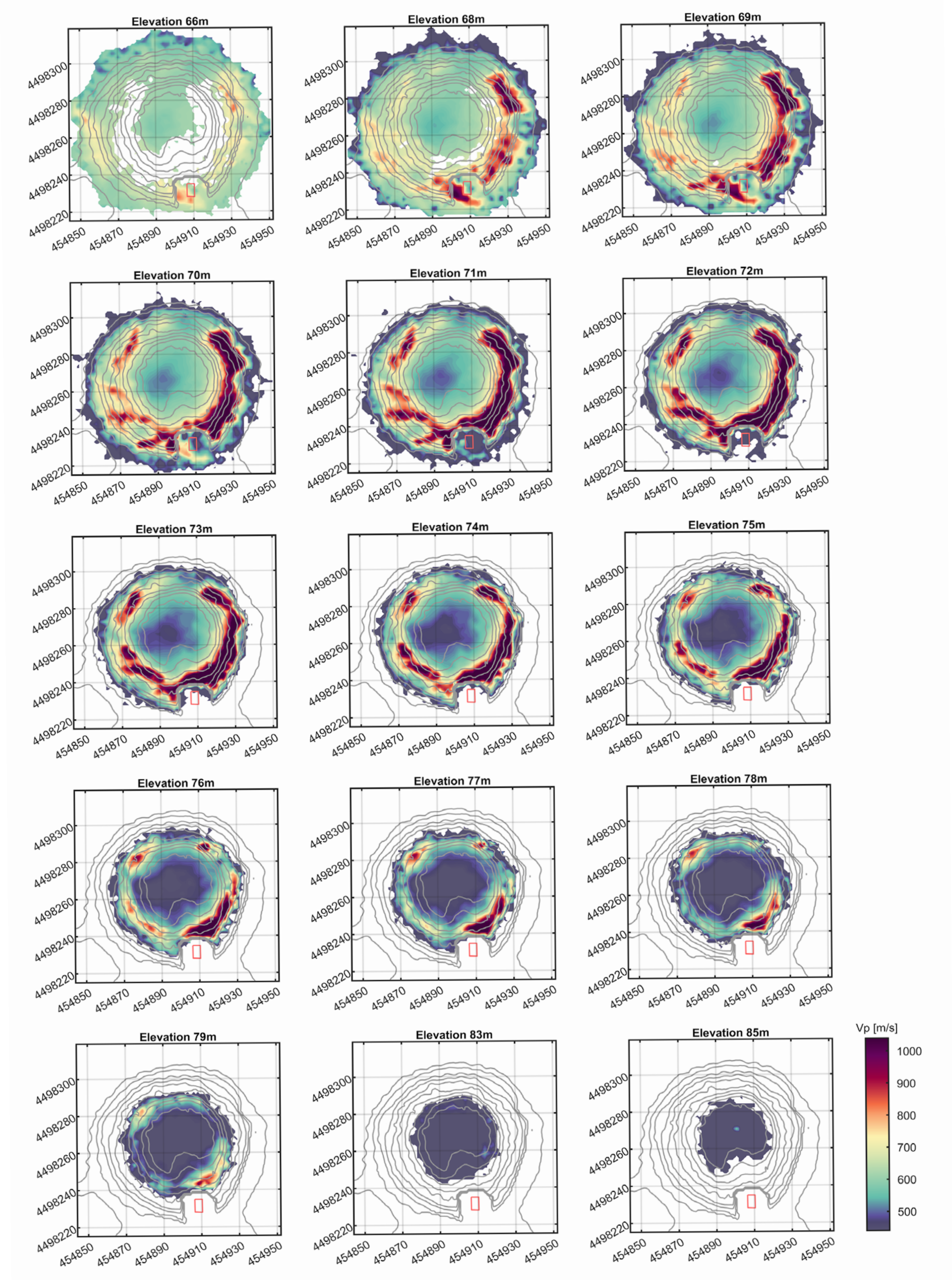

Fig. 3: P-wave velocity model. Horizontal slices at different elevations with the P-wave velocity.