The Yığıma Tepe of Pergamon: stratigraphic construction of a monumental tumulus from seismic refraction measurements

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Abstract
The monumental tumulus Yığıma Tepe is an important part of the cityscape of the ancient city of Pergamon. The tumulus construction is estimated in the Hellenistic period, the internal structure and exact purpose have been unknown so far. Its height of 32 m and diameter of 158 m make the deep interior of the tumulus practically inaccessible for excavations. Therefore, we applied a combination of geophysical measurements and archaeological sondages to explore the structure of the Yığıma Tepe. The investigations centre on P-wave refraction soundings. They were carried out to clarify the stratigraphic structure and soil composition as a prerequisite for a better understanding of construction techniques, building history and soil deposition. Interactive seismic raytracing, traveltime tomography and visco-elastic forward modelling were applied to derive a three-dimensional seismic velocity model, which was validated by excavations and soil analysis, historical records and additional geoelectric measurements. Our results reveal that the tumulus is composed of three layers, each about 10 m thick, separated by first-order seismic discontinuities which were locally verified. These layers form a stack of conical disks, the interfaces of which define two internal plateaus. The analysis of soil samples showed that the seismic velocity increase at the interfaces is likely to be caused by anthropogenic compaction applied to soils showing increased fractions of silt and clay. By combining topographic data with results from seismic and geoelectric sounding on the tumulus, the surrounding trench and the unaltered surrounding area, we show that the tumulus was built almost completely from the surrounding soils and that 17% of its original volume was displaced by destruction and erosion. Based on this mass balance the strongly destroyed and eroded original surface of the tumulus and its surrounding trench is reconstructed.

KEYWORDS
3D-interpretation, ground-truthing, modelling, refraction seismic, tumulus
1 INTRODUCTION

Tumuli (burial mounds) are artificial mounds typically built above one or several burials, which may be simple sarcophagi or multiple grave chambers. They often consist of multiple layers of gravel and sand, usually taken from the surrounding area. Uncovering the internal tombs is of great archaeological interest. However, in the case of monumental tumuli of up to 30 m height and more, archaeological excavations often cannot do more than only pierce the mounds' surface in reasonable time and effort. In contrast, geophysical prospection is capable to explore tumuli from the near surface down to depths of some tens of metres at resolutions sufficient for solving at least some of the major questions.

Geophysical measurements enable a non-destructive investigation of an entire tumulus. Depending on the size of the tumulus, ground-penetrating radar (GPR), electrical resistivity tomography (ERT) and seismic methods can be used to investigate the structure of the tumulus as well as the position of possible grave structures. For example, geoelectric sounding can resolve burial structures in tumuli by three-dimensional (3D)-inversion of densely spaced two-dimensional (2D)-ERT-profiles (Tsourlos, Papadopoulos, Yi, Kim, & Tsokas, 2014). Chen, Tian, Zhao, Wang, and Yang (2018) used a 2D-ERT approach on star-shaped profiles crossing the crest of a small tumulus to uncover its structure and burial locations. On small burial mounds and in their surrounding magnetic surveys proved to be successful in uncovering near-surface anthropogenic structures (e.g., Parzinger, Gass, & Fassbinder, 2016; McKinnon, King, Buikstra, Thornton, & Herrmann, 2016). Also, GPR reflection surveys can uncover the location of burials in small tumuli (e.g., Conyers, St Pierre, Sutton, & Walker, 2018).

Whereas the main aim of tumuli exploration is the localization of graves, investigations in recent years also focused on the tumulus as a construction itself, either for secure and efficient excavation planning (Polymenakos & Tweeton, 2017) or for getting insight into the building history of a tumulus (Kassabaum, Henry, Steponaitis, & O’Hear, 2014). In prospecting burials or tombs, geophysical methods are often used to detect disturbances of the surrounding soil layers or the remains of access tunnels, the so-called ‘dromoi’. Seismic sounding can be used to distinguish the loose filling of access ramps from the surrounding material (e.g., Polymenakos & Tweeton, 2015) or detect construction related debris around the burial itself by local seismic velocity variations (Forte & Pipan, 2008).

The Yırgıa Tepe, subject of the present article, is the largest tumulus of the ancient city of Pergamon, modern Bergama in Turkey. With its height of 32 m and diameter of 158 m, the Yırgıa Tepe formed an important component of the cityscape of ancient Pergamon. It is of the same size as the famous tumulus of Amphipolis (Kastas, Greece) and belongs to the largest tumuli in the eastern Mediterranean region. The ensemble of Pergamenian tumuli, of which the Yırgıa Tepe is the largest, belongs to the UNESCO World Cultural Heritage.

Despite its interregional importance, only little is known about this tumulus. The open archaeological questions include, amongst others, the date of the construction, which is only vaguely dated to the Hellenistic period (Kelp, 2014; Pirson, 2017). Also, the internal construction as such, the building history and the existence and location of possible burials are unknown. Due to the sheer size of the Yırgıa Tepe these questions cannot be answered solely by archaeological excavations. Therefore, with a focus on the Yırgıa Tepe, a joint geophysical–archaeological research project was initiated in 2014 by scientists of Kiel University and the Pergamon-Excavation of the German Archaeological Institute, forming a part of a comprehensive collaborative project on the funerary landscape and customs in Pergamon and other ancient cities of the Aeolis (Meinecke, 2019a; Pirson, 2016; Pirson, 2017).

The present article focuses on unravelling the major internal constructional phases of the Yırgıa Tepe based mainly on seismic refraction measurements with use of compressional waves (P-waves). Besides solving archaeological questions we intend to demonstrate exemplarily the interpretational advantage that can be gained from combining classical seismic refraction interpretation with travel-time tomography and numerical waveform modelling. P-wave sounding was chosen for this application as a result of test measurements, which had shown that P-waves of sufficient depth penetration, range and resolution could be generated reliably with simple means, such as a sledgehammer, even under difficult terrain conditions such as those at the slippery flanks of the tumulus.

The archaeological objectives of our investigations are:

1. Clarification of the overall stratigraphic structure providing insight into the construction process of the Yırgıa Tepe. The stratigraphy was determined by seismic refraction analysis of linear P-wave profiles crossing the entire tumulus at different azimuths.
2. Reconstruction of the original shape of the Yırgıa Tepe as the monument was affected significantly by prior excavations, grave robbery attempts, erosion and redeposition of soil. The reconstruction is based on topographic and seismic refraction and geoelectric data.
3. Volume analysis and balancing of the different stratigraphic layers relative to item (2). This analysis serves to get information about erosion and deposition patterns.
4. Besides the geometric shape of the strata, the seismic survey provides also the P-wave velocities as a layer attribute, which allows conclusions on soil compaction and on the stability of internal layer interfaces.

The seismic results are compared to archaeological findings from the early twentieth century and from recent test sondages. The resulting archaeologically verified seismic model of the tumulus serves as a background model for the investigation of smaller-scale targets at the different stratigraphic levels, which will be presented in a follow-up article.

The article is organized as follows. After a brief description of the archaeological and geological background (Section 2) we explain first the general prospection concept (Section 3.1) and then the details of data acquisition and interpretation methods applied (Sections 3.2-
3.4). The results and discussion sections each comprise two subsections on the stratigraphy (Sections 4.1 and 5.1) and soil volume balancing and shape reconstruction of the tumulus (Sections 4.2 and 5.2).

### 2 | ARCHAEOLOGICAL AND GEOLOGICAL SETTING

The Yığma Tepe is the largest tumulus in the vicinity of the ancient city hill of Pergamon. The base of the tumulus has a circular form with a diameter of 158 m (Pirson, 2016) and a maximum height of 32 m over the ancient terrain surface. It is surrounded by a trench of a width of 62 m and a depth of approximately 12 m (Figure 1). At the base level, located at ~41.5 m ASL (above sea level), a partly preserved wall 3 m wide and 2 m high surrounds the tumulus (Figure 2). This ring wall is built of massive ashlar masonry of tuff stones. Traces of various attempts of grave robbery can be seen at the tumulus surface. The most prominent of the attempted robberies is a deep ditch that was dug radially from the top into the north-western flank, damaging the cone shape of the tumulus.

The only previous archaeological information about the tumulus traces back to the German archaeologist Wilhelm Dörpfeld (Dörpfeld, 1907a, 1910), who made extensive excavations at the Yığma Tepe between 1905 and 1909. Based on the historical context and the appearance of the ring wall the tumulus was tentatively dated to the Hellenistic period. Dörpfeld excavated the ring wall completely in search of an entrance or Dromos that would lead into a grave chamber. As this attempt turned out to be unsuccessful, his team dug a radial open trench and a tunnel into the centre of the tumulus at or little below the base level using an existing indentation in its north-western flank as a starting point.

At the geometrical centre of the tumulus, two wooden posts were found thought to represent the compass point for the layout of the ring wall and tumulus (Meinecke, 2019b). In the centre Dörpfeld’s team dug and drilled a system of crossing tunnels and wells in search of the burial (Figure 2). This search ended without success in 1909, the wooden beams of the tunnel encasing were removed, and the outer section of the tunnel was filled up. After the old excavation accounts had been revisited by U. Kelp from 2011 to 2013 (Kelp, 2014), the new research project started with geophysical prospections from 2014 to 2017 (Mecking, Rabbel, & Erkul, 2015, 2016, 2018) and small-scale archaeological excavations in 2015 and 2017 (Meinecke, 2019a; Pirson, 2016).

Despite the large radial ditch dug on the north-western flank of the tumulus, it is generally assumed that the interior grave structures, if there are any, are still undisturbed (Radt, 2016). This is due to Dörpfeld’s observations of the undisturbed tumulus fill below this ditch, the sheer size of the tumulus and no indications of a robbed grave complex.

![Aerial photograph of the Yığma Tepe, view from the north](photography by B. Ludwig, DAI Istanbul, September, 2015) [Colour figure can be viewed at wileyonlinelibrary.com]
The geological subsurface, as well as the tumulus itself, consists of alluvial sediments. The valley of Bergama has been shaped by the river Bakır Çayı (ancient: Kaïkos). Its river bed lies now 3 km south of the Yiğma Tepe on the southern periphery of this valley due to the Bergama Çayı (ancient: Selinus), which comes from the northwest and built up an impressive alluvial fan and flows 1.3 km to the north of the tumulus (Philippson, 1912). The thick fluvial deposits lie on top of a weathered bedrock with an unknown, probably varying topography. They consist of more or less poorly graded layers of sand and gravel mixed with blocks up to 0.5 m size. Finer material (fine sand, silt and clay) rarely occurs (< 10%), whereas gravel (50–74%) with a peak in its medium size and sand (24–49%) are the main components (Appendix C, Table CT1, natural base layers, So-03/17, Säu-01/17). On top of these sediments a 1 m thick sandy topsoil developed. Below the tumulus the ancient topsoil is well preserved (Meinecke, 2019a; Pirson, 2016). It is very compact and showed twice as much finer material (18%) and especially clay as all the other natural and artificial layers, but still a high quantity of gravel and sand (Table CT1, natural base layers, So-03/17).

As Dörpfeld (1907a, 1910) already pointed out, the Yiğma Tepe was completely built of this alluvial material, which was excavated out of the surrounding trench. Dörpfeld’s results suggest that the loamy topsoil was used for the construction of a first small core mound of 22 to 24 m diameter, of which he found evidence in the main tunnel in the form of larger soil stiffness compared to the rest of the embankment, which consisted of loose gravel and sand. Except from a distinctive layering of the backfill of the ring wall, with an alternance of construction debris layers and gravel, he described the rest of the fill as homogeneous sandy gravel. Nevertheless, he divided it into three layers 5 to 10 m thick (Figure 2), however without further explanation.

### 3 | DATA ACQUISITION AND INTERPRETATION METHODS

#### 3.1 | Prospection concept

For determining the major stratigraphic layers of the Yiğma Tepe we applied P-wave refraction profiling along a set of lines crossing the tumulus (Figure 3). Seismic was chosen as the principal exploration method because GPR and ERT, which are more common in archaeological prospecting, were not applicable: GPR because of limited penetration depth (a few metres only) (Forte & Pipan, 2008) and ERT because of its low resolution at depth (Szalai, Novák, & Szarka, 2009). But also seismic measurements turned out to be difficult as the hardly walkable slopes and loose topsoil of the mound enabled only a sparse shot point coverage of the flanks, to which the interpretation method had to adapt. Seismic refraction tomography could be applied only in a reduced extent because it requires a sufficiently high and uniform source coverage. Instead we chose to interpret the seismic refraction data by a classical analysis of travel time branches and interactive raytracing and further tested with use of tomographic processing. The resulting seismic velocity models of the subsurface were then evaluated by computing synthetic seismograms with a finite-difference solver of the wave equation.

To obtain independent information on the near-surface stratigraphy, we applied ERT across the tumulus in addition to seismic profiling (Mecking et al., 2015, 2016, 2018). For reconstructing the original shape of the mound, the eroded soil masses had to be estimated. This is based on sample measurements inside and outside the surrounding trench where seismic profiling was conducted. The present topography was determined by drone-borne photogrammetry provided by the University of Cologne.
Details of data acquisition and interpretation methods are explained in the following subsections.

### 3.2 | Seismic data acquisition and interpretation

#### 3.2.1 | Seismic field data

Four of the seismic refraction profiles span the entire diameter of the tumulus, two of which also reach into the surrounding trench. Additional shorter seismic profiles (GRB2P, GRB4P, AGP1, AGP2, AGP3) were measured to get the undisturbed stratigraphy as well as the thickness of the deposited sediments that were eroded from the tumulus. The seismic profile locations are shown in Figure 3.

The difficult field conditions influenced the placement of the profiles on the tumulus and caused irregularities in shot spacing. Shot points are more widely spaced in the slope regions and more densely spaced in the flat region at the top of the tumulus. An ELVIS mini vibration source was used on the first profile P1 due to initial concerns that a hammer blow might not be able to penetrate through the entire tumulus and for saving manpower. However, as the vibro source is mounted underneath a wheelbarrow and has a weight of 120 kg, it was not possible to use it in the slopes at all. Tests with hammer blows then showed that the whole range of the tumulus' width and height could be penetrated with 4 to 16 stacked shots, depending on ambient noise and source coupling conditions. Therefore, a sledgehammer source was used for the later transects.

By using chains of up to 240 seismographs with 10 24-channel-GEODE-seismographs the seismic signals could be recorded synchronously along lines up to 240 m long. Geophone spacing of 1 or 2 m was chosen for enabling a high resolution of near-surface strata. For the acquisition parameters of the seismic profiles see Table AT1 in Appendix A.

#### 3.2.2 | Seismic traveltime interpretation

First breaks were manually picked (with an estimated picking error < 1 ms), and an initial laterally variable P-wave velocity ($V_p$) model set up for each profile based on the identification of traveltime branches and analytical interpretation formulae (generalized intercept times, etc.).

This initial 2D seismic velocity model was then refined by interactively fitting forward-modelled first arrival times to the observed times. We calculated the synthetic first arrivals by solving the eikonal equation using the ReflexW-Software (Sandmeier, 1997; Sandmeier & Liebhardt, 1997). This implementation is based on a finite difference (FD) approximation of the eikonal equation (Vidale, 1988). For the FD traveltime computations the velocity models were gridded with 20 cm grid spacing. This value was chosen because it ensures 1 ms accuracy in the numerical calculation of the traveltimes (Appendix A, Figure AF1(a)).

As the four transects intersect each other at the top of the tumulus they have to tie to each other at the intersection points. To accomplish this, we started modelling on the models with the highest shot coverage. The results were then used to constrain the models of the profiles with less shot coverage at the intersection points.
Traveltime root mean square (RMS) residuals of the final interactively adjusted models in the interior and exterior of the trench are shown in Appendix A, Table AT2.

For profile P2 shot density was high enough for applying refraction tomography for further model refinement. For this purpose, we used the tomography code included in the ReflexW-Software (Sandmeier, 2019). This implementation uses again an FD eikonal equation solver for the 'forward' traveltime computation and the SIRT-algorithm (Simultaneous Iterative Reconstruction Technique) (Kak & Slaney, 1987) for the tomographic inversion. A grid spacing of 50 cm was chosen as a compromise between accuracy of computed traveltimes on the one hand and ray-coverage per grid cell on the other hand. Despite spatial smoothing, too dense gridding may lead to 'streaks' in the tomographic model caused by varying ray density. These streaks get less pronounced with increasing grid size. For the chosen grid size, the accuracy of the computed traveltimes is still about 1 ms (Appendix A, Figure AF1(b)). The inversion converged within 20 iterations with RMS residuals < 4 ms (Table AT2). For detailed parameters of the tomographic computations see Appendix A, Table AT3. To determine the spatial resolution of the first arrival traveltime tomograms we performed a checkerboard test (Zelt, 1998) with cell size varying between 5 and 20 m (Appendix A, Figure AF2). It turned out that the structure with a diameter > 15 m could be recovered. This value is about the size of the radius of a refracting interface. For small critical angles it can be approximated by $R_{FH} \approx (l_{h}d)^{1/2}$, where $l_{h}$ is the wavelength in the hanging wall and $z$ is the interface depth (e.g. Kvasnicka & Červený, 1996; Rabbel, 2008). We obtain $R_{FH} \approx 14-22$ m at $z = 20-30$ m depth for wave lengths $l_{h}$ of 10 to 17 m and 500 m/s average velocity of the hanging wall. Principally, this is in agreement with numerical tests of Polymenakos and Tweeton (2015) suggesting, too, that the practical resolution limit of traveltime tomography is smaller than the Fresnel zone diameter. Anyway, since the focus of the present article is on the bulk stratigraphic structure of the tumulus, we do not consider horizontal resolution as a critical issue. The imaging of small-scale targets within the major stratigraphic units requires seismic reflection sounding, which is not an aim of the present study.

3.2.3 Visco-elastic forward modelling of P/SV-wave

While checkerboard or other similar tests provide a general estimate of possible structural resolution of a seismic survey, they are not meaningful as a tool for evaluating concrete seismic subsurface models. Therefore, we decided to test the models in a more rigorous way by computing synthetic seismograms and comparing them to measured seismograms. Whereas this comparison is an inherent component of full-waveform inversion, it has been a rather unusual test so far for seismic velocity models derived from refraction traveltime tomography, at least in near-surface applications.

Since near-surface sediments show considerable seismic absorption we applied a visco-elastic forward modelling code. The computation of the synthetic seismograms was performed with a 2D FD time-domain implementation of the wave equation for isotropic, linear visco-elastic media (DENISE software; Köhn, De Nil, Kurzmann, Przebindowska, & Bohlen, 2012). Parameters for the forward modelling can be found in Appendix A (Table AT4).

In the computations variations of density were neglected because they are usually minor compared to seismic velocity variations. The source wavelet was modelled by a 10–60 Hz band-pass filtered spike. This frequency range was chosen because it contains the main energy content of the field data near the source point. Figure AF3 (Appendix A) shows a comparison of the amplitude spectra of a measured and a calculated example shot gather, where the similarities of the initial frequency contents at the source point and of the decay of main energy frequency with offset are demonstrated. Time and spatial grid discretization of FD wave field modelling were chosen according to the common stability criteria (e.g. Köhn et al., 2012).

The observed offset-dependent frequency decay of the field data (Figure AF3) is caused by absorption. For modelling this effect, we assumed that the seismic quality factor $Q$ of the soil is constant in the relevant frequency range. In the time-domain FD-algorithm this is realized by considering four standard linear solids with correspondingly adjusted relaxation times (Blanch, 1995). To estimate a representative $Q$-value we computed synthetic seismograms for a set of assumed $Q$-values between 6 and 50 and compared them with field records to maximum offset. It turned out that the highest similarity of waveforms was obtained for $Q = 10$.

The velocity model derived from picked traveltimes refers to the frequency band of the field data, whereas the modelling equations are usually set-up for a certain, but different, reference frequency $\omega_r$, for example, 1 Hz. Therefore, the velocity model must be corrected in order to account for velocity dispersion using the following equation (Müller, 1983):

$$c(\omega) = c(\omega_r)^\frac{\omega_r^2}{\omega^2} \tan^2 \frac{\omega}{2 \omega_c},$$

where $c$ is phase velocity and $\omega$ is the centre frequency of field data. In the present case the velocity dispersion amounts to ~20% for $Q = 10$ at the main signal frequency of 50 Hz of the field data.

3.3 Electric data acquisition and interpretation

Several ERT profiles were recorded across the tumulus with length that span from 20 to 96 m (Mecking et al., 2015, 2016, 2018). However, we are showing only one of them which is of particular importance for the interpretation of the seismic data.
The electric data were acquired with a RESECS multi-electrode equipment (manufactured by GEOSERVE, Kiel, Germany) with 1 m electrode spacing in Wenner-Alpha configuration.

Prior to inversion, field data were edited by rejecting data points that showed standard deviations > 3%. For the ERT, we applied the Res2DInv software (Loke & Barker, 1995; Loke, Chambers, Rucker, Kuras, & Wilkinson, 2013). The applied tomographic inversion is based on minimizing the sum of absolute values of the residuals of apparent resistivities (L1-norm) which is less sensitive to outliers and scattering data points than a least-squares fit (L2-norm). The topography was incorporated in the inversion. Parameters for the inversion are given in Appendix A, Table AT5. Measured and calculated pseudosections as well as the inverse model prior to topographical correction for profile E-Y2 are shown in Appendix A, Figure AF4. The final model reached after three iterations shows an RMS error of 4.3%. The geological interpretation of the ERT profile and a comparison to seismic data is discussed in Section 5.1.

3.4 Digital elevation model

The digital elevation model was computed by drone-borne photogrammetry in 2015 with a Sony Alpha 5100 camera on an MK Oktokopter XL. Parameters of the measurement can be found in Appendix B, Table BT1. Processing was done with the Agisoft PhotoScan software. Trees in the whole area and houses outside the trench were cut out and the resulting gaps interpolated for the use as an elevation model. Since the accuracy of the model was oversized for the volume calculation, the model was sampled down to dx = 1 m.

3.5 Original shape and volume balance of the Yıgma Tepe

For estimating the original shape of the Yıgma Tepe and its surrounding trench and for checking the volume balance between tumulus and trench the following volumes need to be considered based on the geophysical and geodetic data (see Figure 4):

- The present volumes of the tumulus ($V_M$) and the surrounding trench ($V_T$) from a digital elevation model, which was acquired by photogrammetry.
- The volumes $V_i$ of the $i = 1$ to $n$ different construction phases of Yıgma Tepe as far as they can be deduced from the depths of the seismic interfaces and the present topography.
- The relative volume increase $D_i$ ($i = 1$ to $n$) of the tumulus strata caused by decompaction of the originally consolidated soils of the trench when they got piled up to form the tumulus.
- Estimates of the volumes of debris from the tumulus ($V_{DM}$) and the outer edge of the trench ($V_{DT}$) and the respective volume increase due to decompaction ($D_{DM}$ and $D_{DT}$) to be determined from the seismic layering and velocities.

The present volume $V_M$ of the Yıgma Tepe then is.

$$V_M = V_1 + ... + V_n, \quad (1)$$

the original volume $V_{OM}$ of the tumulus reads.

$$V_{OM} = V_1 + ... + V_n + V_{DM}, \quad (2)$$

**FIGURE 4** Sketch of the different volume units that are considered in the volume balancing of the Yıgma Tepe (for further explanation see Section 3.5); reconstructed original tumulus with volume $V_{OM}$ (a) and present topography with volume $V_M$ (b); the reconstructed original trench with volume $V_{OT}$ is denoted by the red dotted line (Appendix B, Table BT2), the differences between the original trench volume $V_{OT}$ and the present volume $V_T$ is separated into the debris originating from the tumulus $V_{DM}$ and the debris originating from the surrounding area $V_{DT}$ [Colour figure can be viewed at wileyonlinelibrary.com]
the original volume $V_{DT}$ of the trench is.

$$V_{DT} = V_T + V_{DM} - V_{DT}, \quad (3)$$

and the balance of tumulus and trench reads:

$$(1 - D_1)V_1 + ... + (1 - D_n)V_n + (1 - D_{DM})V_{DM} = V_T + V_{DM} + V_{DT} \quad (4)$$

The volume of the Dörpfeld tunnel system can be determined from the extension of the tunnel system known from Dörpfeld (1905), where cumulative length (155.8 m), width (1.2 m) and height (1.8 m) of the tunnel segments are given, resulting in a tunnel volume of 336 m$^3$. Also, the original volume of the ring wall which corresponds to stones that do not originate from the tumulus area, can be quantified from Dörpfeld (1905), where radius (79 m), average height (2 m) and width (2 m) are given, resulting in a volume of 1985 m$^3$. Obviously, both volumes are small in comparison to the volumes of the tumulus strata and the surrounding trench, so they can be neglected.

## RESULTS

### 4.1 | Stratigraphy of the Yığma Tepe

#### 4.1.1 | Seismic layering from raytracing

In the seismograms of the four central profiles direct and refracted P-wave arrivals from four major layers can be clearly recognized (Figure 5). They can be followed up by raytracing through the entire tumulus (P1–P4 in Figure 6) suggesting that the tumulus consists basically of three layers, each identifiable by a separate P-wave velocity. The value of $V_p$ is 350–420 m/s for the surface layer, about 500 m/s for the middle layer, 750 m/s for the bottom layer and about 1200 m/s for the base layer below the tumulus.

The top of the base layer coincides topographically approximately with the geometrical base of the tumulus and is thus considered its base level. The surrounding topography is slightly inclined to the south (0.8°) which means a terrain drop of the base of about 2 m from

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**FIGURE 5** Sample shot gathers from profile P2. Different refracted P-waves can be distinguished and associated with different layers; note that the slopes of the traveltime branches are affected by the topography. The assignment of the traveltime branches to the respective units is indicated by coloured lines [Colour figure can be viewed at wileyonlinelibrary.com]
the northern to the southern edge of the tumulus. This cannot be resolved by refraction seismic methods.

The overlying layers are each up to 10 m thick. They are tentatively considered as different construction phases of the tumulus, such that, from bottom to top, the 750, 500 and 400 m/s layers represent phases 1, 2 and 3, respectively. A special feature is a zone of increased $V_p$, about 10 m wide, located near the top of Yigma Tepe. It results from bulges in overlapping traveltime branches, which could not be interpreted in a different way. This high-velocity anomaly is of particular interest because it could be examined by excavation as described later in this article.

Profiles P1–P3 show a change in the velocity of the base layer, most prominent on profile P1 to the west, where $V_p$ decreases from 1200 m/s to 800 m/s. Results of several profiles made in the surrounding area of the tumulus, to investigate the original stratigraphy (e.g. profile GRB2P, AGP1, AGP2, AGP3, Appendix A, Figure AF5), show that the base layer below the tumulus ($B$, $V_p = 1200$ m/s) is dipping approximately from south to north and is covered by a layer with significantly lower seismic velocities ($A'$, $V_p = 800$ m/s). In profile GRB2P south of the tumulus (Figure AF5(e)) Layer A is missing completely, with a thin weathering layer ($V_p = 500–650$ m/s) covering layer B. The thickness of layer A increases from ~5 m at profile AGP2 east of the tumulus (Figure AF5(f)) to ~10 m at profile AGP3 north of the tumulus (Figure AF5(b)). On profile AGP1 northwest to the tumulus layer B is missing completely (Figure AF5(a)). The generic resulting topography of layers A and B is presented in Figure 7(a). The detailed topography of layer B and the thickness of layer A which result from
all seismic profiles are presented in Figure 7(b, c), respectively. The earlier results suggest that the spatial differentiations in velocity and topography of the base layer is not a construction-related feature but of geological origin.

The interfaces from the profiles P1–P4 were interpolated to construct a 3D layered model of the tumulus (Figures 8, 9). The model shows that the tops of phases 1 and 2 (Figure 8(b, c)) are relatively flat across the whole area of the tumulus. The base layer was not subdivided into the layers A and B at this point as the change in the natural soil below the tumulus is not part of its construction. The constructed model (Figure 9) shall serve as a base for future small-scale investigations with reflection seismic methods.

### 4.1.2 Traveltime tomography

Seismic traveltime interpretation based on interactive raytracing contains subjective elements in so far as it depends to a certain degree on the experience of the interpreter. Therefore, an attempt was made to verify the results based on the raytracing model by applying automated 2D-traveltime tomography to profile P2 which is the only profile with a sufficient number of source points and receivers (Table AT1). Attempts to use 2D-traveltime tomography on other profiles failed as the results were too dependent on the starting models. Since the seismic velocities increase by 300% from top to bottom of the tumulus, resulting in strong ray bending which needs to be accounted for already in the starting model to avoid convergence problems, the starting models must not be too detailed to reduce bias. Therefore, we created two starting models, which show the same $V_p$ at the surface and a different linear velocity increase with depth. The velocity gradients were adjusted such that the two starting models end at the bottom with notably lower and higher velocity values than the raytracing model (Figure 10). The questions to be answered by the tomography are then:

a. Do the tomographic computations converge to the same final model? If so: (a1): Do the smooth gradient starting models result in a layered structure? and (a2): Do the depths of the interfaces agree with the raytracing model?

b. Is it possible to reproduce the small-scale high-velocity anomaly found by raytracing near the top of the tumulus.

**FIGURE 7**  (a) Profile across the Yığma Tepe showing the northward down-dip of base layer B (see Section 4.1); pink and blue colours show the possible origin of the sediments the tumulus consists of (b) topography of the sediment layer B with seismic velocities of 1200 m/s; (c) thickness of the overlaying sediment layer A with velocities of about 800 m/s. The green line shows the position of the cross profile (a). Tumulus and outer trench border are marked in yellow [Colour figure can be viewed at wileyonlinelibrary.com]
c. Do any new features occur in the tomograms that were not present in the raytracing model?

The results of the tomographic inversion are shown in Figure 10. Within the numerical limits, both starting models converge after 20 iterations into the same final models (RMS error < 5 ms, Table AT2) (Figure 10(a, b)). The middle areas of the final models have a somewhat streaky appearance, which is an artefact caused by the low density of source points and the resulting lower ray coverage in some parts of the model space.

**FIGURE 8** Topography of the different construction phases of the Yiğma Tepe. (a) present surface; (b) top of phase 2; (c) top of phase 1; (d) basal surface [Colour figure can be viewed at wileyonlinelibrary.com]
Nevertheless, the layered structure of the raytracing model (Figure 10c) is well reproduced in both layer thickness and average velocity (question ‘a’, above). Even the small near-top velocity high is reproduced (question ‘b’, above). In assessing this result, it has to be considered that every tomography contains structural smoothness constraints.
reducing principally the sharpness of recoverable structure (Table AT2).

A new feature in the tomographic images resulting from both gradient starting models is that the high-velocity base layer occurs at a somewhat shallower level underneath the tumulus flanks, leaving a lateral velocity low at the bottom in the centre of the tumulus (question ‘c’, above). The velocity low coincides in position and horizontal extent with the central tunnel system created by Dörpfeld’s team at the beginning of the twentieth century (Figure 2).

Overall, tomographic inversion verifies the seismic velocity structure and enhances it by providing additional details not derived from simpler processing of the refraction data.

4.1.3 Verification of seismic stratigraphy by visco-elastic wavefield modelling

Visco-elastic forward modelling was performed as an additional attempt to assess the plausibility of the stratigraphic model derived from raytracing. Sample measured and computed shot gathers are shown for comparison in Figures 11 and 12. Results using a non-smoothed velocity model (Figure 11) illustrate that first arrival times, as well as secondary phases and surface waves, fit surprisingly well, despite the complexity of the measured wave field and the comparatively simple layer structure. Basically, all major features of the wave fields are reproduced, and only some minor phase deviations could not be modelled.

Compared to the earlier result, first arrival times calculated after forward modelling of a heavily smoothed version of the original model (Figure 12), are similar to those calculated using the non-smoothed model (Figure 11). Later phases are better reproduced in terms of arrival time waveform in the original model than in the smoothed version. The earlier results confirm that the layer interfaces are indeed first-order discontinuities as derived from the initial raytracing interpretation.

4.2 Volume balance of tumulus, surrounding trench and original surface

4.2.1 Volumes of tumulus construction and surrounding trench soils

The calculation of the volume of the tumulus depends on the topographic height of the basal surface below the tumulus. For an estimation, we considered the topography of the surrounding area as determined from photogrammetry. We interpolated the flat areas from outside the trench across the area covered by the tumulus thus creating a smooth base topography underneath (Figure 8d). The interpolated basal surface turned out to dip slightly from 42.6 m at the northern border to 40.6 m at the southern border of the tumulus. Using this surface as the original basal surface, we estimated the volume of the tumulus at about \( V_M = 262,300 \text{ m}^3 \) (Equation (1)) and the volume of the trench at about \( V_T = 212,000 \text{ m}^3 \) (Appendix B, Table BT2).

Construction phase 1 (\( V_1 \), Table BT2), interpolated from the results of refraction seismic (Section 3.1) accounts for about half of the entire tumulus volume, whereas phase 2 and 3 (\( V_2, V_3 \), Table BT2) each account for about 25% of the tumulus volume.

To recover the original volume of the Yiğına Tepe it must be considered that erosion has taken place and that the eroded material accumulates along the tumulus slopes and at the bottom of the surrounding trench. Originating from the ditch dug in the north-western flank of the tumulus, a huge volume of soil has been deposited in the north-western part of the surrounding trench.

The present trench volume is nearly 20% lower than the volume of the tumulus. This difference is caused by two effects: (1) by soil that has been eroded at the outer rim of the trench and deposited inside of it since the construction of the tumulus and (2) by decompaction of the originally compacted soils during the piling up of the tumulus. Even without correcting for these effects, we consider the difference between the present volumes of the tumulus and the trench small enough, to conclude that the tumulus is built from the material that is absent from in the trench and that no additional material was needed.

4.2.2 Original tumulus and trench topography

For a more precise estimation of the different volumes as well as an estimation of eroded and deposited material the original shape of the tumulus must be reconstructed. Therefore, the surface coordinates of the tumulus and surrounding trench were transformed into cylindrical coordinates around the centre of the tumulus, generally assuming that the tumulus was once perfectly circular (Pirson, 2016).

The topography along the radial direction varies most in the north-western area, where the tumulus is affected by the attempted robbery, but it shows only little variation in all other directions. This implies that erosion must have been either very uniform in all directions or was relatively low in general.

We neglected the robbery affected area in the reconstruction and constructed a one-dimensional (1D)-radial model from the remaining topographic profiles (Figure 13). In the slopes the maximum elevations were chosen as indicators of the original surface. Near the centre the dented top was filled up and exaggerated slightly to get a smooth and round tumulus shape.

The circular ring wall was built at approximately 41.5 m elevation ASL. This was determined in the excavations from the remnants of the ring wall. Dörpfeld sketched the ring wall during the 1907 excavation with five stone layers, a width of about 2 m and a height of about 1.8 m (Dörpfeld, 1907b). To complete the shape of the original tumulus, we assume that an accessible path, about 2.5 m wide originally surrounded the tumulus exterior, directly in front of the ring wall (Figure 13a).

The base of the trench can be determined from two seismic profiles crossing the trench (GRB2P and GRB4P,
Figure AF5(d, e). These profiles show that the original trench bottom is at 29 m ASL in the northern part of the trench and at 28 m ASL in the southern part. The original trench bottom and the trench flanks were reconstructed and radially interpolated using the calculated layer boundaries from the refraction seismic evaluation.

FIGURE 11  Seismic field data compared to synthetic seismograms computed for the seismic velocity model derived by interactive raytracing. The velocity distribution is discontinuous as it includes discontinuities of first order (step functions) at the interfaces between the layers. The figure shows results of finite difference (FD) visco-elastic wave modelling for two sample shot gathers of profile P2. (a) P-wave velocity model and source locations. (b–e) Measured (black/white wiggle) and calculated (coloured) seismograms of source points 19 (b, c) and 10 (d, e); source locations shown in (a) [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 12  Seismic field data in compared to synthetic seismograms computed for a smoothed version of the seismic velocity model of Figure 11. The figure shows results of finite difference (FD) visco-elastic wave modelling for the same two sample shot gathers as in Figure 11. (a) P-wave velocity model and source locations. (b–e) as in Figure 11 [Colour figure can be viewed at wileyonlinelibrary.com]
Transforming the radial topography back to cartesian coordinates creates a radially symmetric tumulus (Figure 13(b)). The difference in heights between the reconstructed original and the present tumulus topography shows the overall loss of soil caused by erosion and the displacement of soil from the radial ditch into the trench in the northwest side of the tumulus (Figure 13(c)). The volume loss $dV_M$ of tumulus and volume gain $dV_T$ of the trench are estimated as:

$$dV_M = V_{OM} - V_M = 55700 \text{ m}^3 \approx V_{DM}$$

$$dV_T = V_{OT} - V_T - dV_M = 43900 \text{ m}^3 \approx V_{DT}$$

As the debris accumulated in the trench originates not only from the tumulus but also from the outer surroundings of the trench, the deposited sediments were divided into portions $V_{DM}$ and $V_{DT}$, where $V_{DM}$ is the debris volume eroded from the tumulus and $V_{DT}$ is the debris eroded from the exterior of the trench. The border between $V_{DM}$ and $V_{DT}$ corresponds to a circle of about 110 m radius centred at the midpoint of the tumulus. This radial border was chosen because it coincides with the deepest points of the present trench topography.

The difference $V_{res}$ between the present tumulus volume $V_M$ and the present trench volume $V_T$ can thus be corrected for the debris from the exterior of the trench area $V_{DT}$:

$$V_{res} = V_M - (V_T - V_{DT})$$

This yields a corrected volume surplus $V_{res}$ of the tumulus of only 6300 m$^3$ or 0.2% of the original tumulus volume $V_{OM}$. This also means that volume differences due to remaining decompaction $D_r$ are negligible.

The original tumulus volume $V_{OM}$ calculated from the reconstructed topography is about 318 000 m$^3$ and the volume of
the trench $V_{OT}$ is about 311 000 m$^3$. This means that about 7000 m$^3$ or 17% of the original volume was displaced after the construction into the trench (Equations (1) and (2)); the ditch in the northwest side of the tumulus accounts for about half of this. The reconstructed surface of the surrounding trench shows significantly steeper slopes, that is up to 60° at the inner trench slopes (~35° in present times) and 35° at the outer trench slope (~15° in present times).

In Section 4.1 we identified a decrease of $V_p$ within the basal layer from south to north indicating a change in sediment composition in the surrounding of the tumulus. The velocity change suggests that the base layer consists of an upper unit in the north (layer ‘A’, $V_p = 800$ m/s) and a lower unit in the south (layer ‘B’, $V_p = 1200$ m/s) separated by a north-dipping interface (Figure 7(a)). Correspondingly, the northern part of the original trench fill consisted of soils of layer A, and the southern part of soils of layer B, both of which were piled up onto the tumulus. Since the $V_p$ of construction phase 1 differs strongly from that of phases 2 and 3, the question arises whether phase 1 could have been constructed from the soils of layer B whereas phases 2 and 3 were piled up later using soils of layer A. To check if this is principally possible, we compare the respective volumes: volume $V_A$ of the trench fill attributed to layer A is 203 000 m$^3$ (calculated from the estimated thickness of the entire layer A, Figure 7(c)), whereas volume $V_{23}$ of construction phases 2 and 3 results from:

$$V_{23} = V_2 + V_3 + V_{DM} = 64700 \text{ m}^3 + 63300 \text{ m}^3 + 55000 \text{ m}^3 = 183000 \text{ m}^3$$

Thus, volume balancing suggests that phases 2 and 3 were constructed from soils of layer A in the north whereas phase 1 was constructed mainly from material of layer B in the south.

5 | DISCUSSION – THE CONSTRUCTION OF THE YİGMA TEPE

The seismic refraction investigation of the Yıgma Tepe, combined with historic and recent archaeological records, has shown that the tumulus exhibits a distinct stratigraphy. It consists basically of three layers, which can be distinguished by their P-wave velocities and are separated by first-order seismic discontinuities (i.e. stepwise increase in $V_p$). In the discussion of the seismic stratigraphy we are focusing on the following aspects:

1. How does the seismic refraction stratigraphy compare to archaeological records?
2. How can the seismic layering be explained, whereas the soil composition is apparently homogeneous?
3. How does the seismic-derived soil structure of the Yıgma Tepe compare with the structure of other tumuli?
4. What implications follow from the seismic stratigraphy regarding the construction of the Yıgma Tepe?

5. What is the accuracy of the reconstructed tumulus shape and volume balancing?

5.1 | How does the seismic refraction stratigraphy compare to archaeological records?

The seismic stratigraphic interpretation can be discussed on the basis of historical and recent archaeological research results.

We start at the basal surface of the tumulus. During the tunnel construction in 1907, the Dörpfeld team detected a change in soil type and structure, which was addressed as evidence of a small internal mound located in the centre at the base of the Yıgma Tepe (Dörpfeld, 1907b). The internal mound could not be distinguished in terms of P-wave velocities from phase 1 by the raytracing evaluation, although it was characterized by Dörpfeld as a completely different entity, being more solid than the surrounding soils. In this context it has to be considered primarily that the lateral resolution of seismic refraction imaging decreases with depth and is of the order of 15 m at the basal surface as shown by our checkerboard test (Figure AF2). This value is of the same order as the width of the Fresnel zone computed for head waves at the relevant frequencies (formulae see, e.g. Kvasnička & Čerjvený, 1996). Moreover, Dörpfeld described the soil surrounding the tunnel as very wet. Since P-wave velocity is very sensitive to the water content of soils, the general wetness in the deep interior of the tumulus may have equilibrated velocity contrasts and thus inhibited the seismic recognition of the inner mound. The situation might be even more complicated as the applied seismic tomography shows that there is probably an area of laterally reduced seismic velocities in the centre of the tumulus at base level. This indicates, that the intense penetration of the tumulus centre with additional crossing tunnels and search drillings, which followed the tunnel construction, may have created a mechanically weak damage zone, which may lead to lowered seismic velocities in the centre area.

Above the base level the situation gets clearer. Dörpfeld’s (1910) section of the north-western ditch shows an internal stratification of the Yıgma Tepe consisting of three soil layers separated by two almost horizontal interfaces (Figure 14(a)). The differences in soil type were not described. We could also not verify them by probing because the soil sections are not exposed anymore. However, the comparison of Dörpfeld’s drawing and the seismic layer diagram (Figure 14(a, b)) shows a close agreement although the seismic profile was not recorded exactly at the same position. The interface found in Dörpfeld’s section at ~12 m height above base level coincides with the interface between phase 1 and phase 2 of the $V_p$ model (I and II in Figure 14). The third seismic interface, which separates phases 2 and 3 (III in Figure 14), was not recognized by Dörpfeld as his section did not reach this height.

The seismic stratification can also be verified by geoelectric measurements in the flanks of the tumulus. They show the transition of a low-resistivity layer close to the surface to a high-resistivity layer underneath. Their interface fits well with the surface of construction phase 2 (III in Figure 14(c)). From geoelectric profiles and excavations
collocated at the north side on the Yigma Tepe it is known that locally increasing electrical resistivity values mostly coincide with an increase in gravel and boulder content in the soil (Mecking et al., 2016). It is assumed that the excavated gravel and boulder assemblies are part of the construction, possibly serving as drainage paths for rainwater. The increase of the seismic velocities, as well as the increase of the electrical resistivities, can thus be attributed to different sorting of the soil material.

The existence of distinct hardened soil layers, which can be associated with the detected seismic refraction interfaces, was verified in the recent archaeological excavations (Meinecke, 2019a; Pirson, 2016). Very distinctive were the beige-coloured construction debris layers of strongly weathered tuff flakes directly behind the surrounding wall at the base of the tumulus that showed a high compaction but almost the same quantity of gravel (45–65%) with a slightly elevated amount (9–11%) of finer material (fine sand, silt and clay) (Table CT1, construction layers So-02/15, So-03/17). These have been recorded by Dörpfeld (1907a) as well but are not visible in geophysical measurements due to their small size. Other hardened layers, but less clearly visible, could be recognized in small excavation trenches on top of the tumulus. One of these brown-coloured layers at the north-eastern periphery showed very small quantities of tuff fragments and a similar grain distribution, but a higher quantity of clay (Table CT1,
construction layers – So-02/17). These were only 0.5 m thick and reached only partially the same grade of consolidation.

The major parts of the interface areas are too deep to be accessed by excavation. However, the small high-velocity zone found underneath the top was within reach. Indeed, directly in the geometrical centre of the tumulus and 1 m below its actual summit, another hard-packed layer has been found (Figure 15). Its boundaries to the surrounding sandy gravel were sharp and it seemed to expand concentrically around the centre of the tumulus as it was marked by the posts found at the central part of the base level of the tumulus. It is strongly consolidated and very hard. The quantity of fine material is comparable to that of the construction debris layers, whereas the clay content is higher. Additionally, the amount of gravel (58%) is higher than that of sand (31%) (Table CT1, construction layers – So-04/17). All classes of grain sizes are almost equally well represented which is only comparable to the ancient natural topsoil. Due to this particular composition the soil could be very well compacted (Matthews, 2011, 109). For safety reasons only the upper 0.2 m of this layer could be excavated, therefore its thickness is unclear. We interpret this layer as representing the seismic high-velocity anomaly found on the tumulus top.

None of the probed layers showed any content of carbonate upon testing with a 10% solution of hydrochloric acid. Therefore, the compaction of the hard layers cannot be attributed to calcification. However, other chemical alterations that resulted in the cemented sandy gravel cannot be excluded. The rest of the excavated fill was indeed very homogeneous and consisted of intermittently graded gravel (40–70%) with less than 6% of finer material, although very small differences in grain distributions between different deposition phase could be seen. Additionally, some very loosely packed layers of almost exclusively gravel (90%) were recorded as well (Table CT1, embankment, So-01–04/17).

Based on the historical and present excavation results and on a comparison with geoelectrics we can conclude that the high-velocity zones of the tumulus are most likely associated with artificially compacted soils. This implies that the interface between phases 1 and 2 of the tumulus construction is to be regarded as a sharp discontinuity of first order (step function) rather than as a smooth transition. This justifies the layer approach of the initial raytracing interpretation in hindsight.

5.2 | How can the seismic layering be explained, whereas the soil composition is apparently homogeneous?

Because the volumes of tumulus and trench are well balanced it can be assumed that the tumulus was built from the material of its immediate surrounding. This is confirmed by the description of the soil found during the tunnel construction (Dörpfeld, 1910). Therefore, we would evidently assume that the tumulus soil structure is homogeneous, only affected by compaction continuously increasing with

**Figure 15** Photography of the excavation of the high-velocity zone at the centre of the top of the Yigma Tepe (Figure 6, seismic profiles P2 and P4) (photography by B. Ludwing, DAI Istanbul, September 2017); the excavated hardened layer identified as the high-velocity anomaly is highlighted in red. The adjacent wall structures probably served as stabilizing elements in the building process of the tumulus and were found in the top area excavations as well as behind the ring wall (Meinecke, 2019a; Pirson, 2016) [Colour figure can be viewed at wileyonlinelibrary.com]
depth due to the increasing overlying mass load. However, the seismic results show that this view is too simple because construction phases 1–3 differ significantly from phases 2 and 3 in terms of seismic velocities and the velocity changes at the interfaces are discontinuous. Possible explanations for this observation are the following:

- The phases may have been piled up from soils that were initially slightly different in composition because they originate from slightly different lithological layers. Indeed, additional seismic profiles in the tumulus surrounding show that the geology of the layers used for construction changes from south to north (Figure AF5). Thus, construction phase 1 could have been built from the material of the seismically ‘faster’ layer B, which reaches the surface in the southern part of the tumulus, whereas phases 2 and 3 may have been built from the material of the layer A, which is becoming thicker to the north/northwest.

Clearly, the P-wave velocities of the original soil layers and the tumulus construction phases cannot be compared directly but only relative to each other because of the decompaction of the material during the digging process. It is well known that P-wave velocity is correlated with rock strength (e.g. Schön, 2011, section 7.5 and the references cited therein). Therefore, P-wave velocity decreases if rocks are decompacted. If we associate the source layers with the construction phases, we can interpret the observed \( V_p \) reduction \( \Delta V \) of about 300 to 400 m/s as a decompaction effect:

Layer ‘B’ (1200 m/s) \( \rightarrow \) Phase 1 (800 m/s), \( \Delta V = 400 \) m/s.
Layer ‘A’ (800 m/s) \( \rightarrow \) Phase 2 (500 m/s), \( \Delta V = 300 \) m/s.
Layer ‘A’ (800 m/s) \( \rightarrow \) Phase 3 (360–400 m/s); \( \Delta V = 400–440 \) m/s.

- A third possible explanation of the contradiction between apparent soil homogeneity and seismic layering is that the observed increase of seismic velocities at the interfaces does not apply to the entire layer but only to a rather thin layer at its surface consisting of hard-packed soil. This view of a narrow distinct high-velocity zone (HVZ) is supported by the findings at the top of the Yigma Tepe, where a local HVZ could be resolved because of favourable raypath geometry (Figure 6) and a corresponding compacted layer could be verified by excavation.

Regarding interfaces I and II (Figure 14) this hypothesis cannot be validated by raytracing, because thin layering effects are not covered by ray theory. But it can be checked by forward modelling of the seismic wave field using FD solutions of the wave equation. For this purpose, the original raytracing velocity model (Figure 11(a)) was equipped with a 1.5 m thick, high-velocity layer of 750 m/s at the transition from phase 1 to phase 2 and the P-wave velocity of the underlying layer 1 was reduced from 750 to 600 m/s. Examples of the resulting synthetic seismograms are shown in Figure 16. The comparison with the seismograms in Figure 11 shows that the differences in the seismograms of the two models are very small which proves that a thin compacted layer may be a reasonable explanation.

In summary, we suggest the following solution to the apparent contradiction: The tumulus has indeed a relatively homogeneous composition, but the soil was locally compacted at the respective depth levels of the seismic interfaces, whereupon advantage was taken from selecting soils of suitable grain size for the compacted layer.

5.3 | How does the seismic-derived soil structure of the Yigma Tepe compare with other tumuli?

Seismic methods are able to explore deeper than standard methods of archaeological prospecting but are more time-consuming especially in a difficult environment. Furthermore, seismic processing procedures to resolute near-surface structures in areas with strongly varying topography are not standardized. Therefore, only few seismic measurements have been carried out at tumuli, to which our results can be compared.

For instance, at Kastas (Amphipolis) tumulus in northern Greece, the soil structure was investigated by first arrival traveltine tomography and attenuation tomography (Polymenakos & Tweeton, 2017). A geophone array was placed around the tumulus and ray coverage of the basal plane was achieved by shooting through the tumulus. The seismic velocity inversion gave insight into the course of the bedrock and information on areas of varying soil strength could be mapped. P-wave velocities are quite similar to those at the Yigma Tepe with \(~ 300\) m/s to \(~ 1000\) m/s (compare Section 4.1) which are connected to the tumulus’ soil. Additionally, higher velocities can be found (up to \(~ 1800\) m/s) which are connected to a bedrock with varying topography. This is where the Kastas tumulus differs from the Yigma Tepe, which was built on an almost flat surface.
Seismic field data in comparison to synthetic seismograms simulating the effect of a thin compaction layer. The underlying P-wave velocity model is a modified version of the smooth model in Figure 12(a). The modification consists in the addition of a thin high-velocity layer at the top of phase 1 and a reduction of the velocities underneath to the level of the velocities of phase 2. The figure shows results of finite difference (FD) visco-elastic wave modelling for two sample shot gathers of profile P2. (a) P-wave velocity model and source locations. (b–e) as in Figure 11 [Colour figure can be viewed at wileyonlinelibrary.com]
The Kastas tumulus is also similar to the Yiğma Tepe in its geological composition which explains the similar seismic velocity range. It consists to a large extent of the surrounding sediments with sand, pebbles and cobbles as well as portions of clay (Syrides, Pavlides, & Chatzipetros, 2017). Contrary to the situation at the Yiğma Tepe, there seems to be no horizontal deposition but laterally varying packages of sediment of different composition and moisture (Tsokas et al., 2018).

Refraction seismic measurements and 3D tomography were performed at the Nemrud Dağ in eastern Turkey. Three different seismic layers, the topography of the bedrock and large artificial terraces at the flanks were identified (Lütjen & Utecht, 1991). The measurements showed that the Nemrud Dağ is basically the enlargement of a natural rocky tumulus, in which the situation differs from the Yiğma Tepe.

Regular changes between layers of coarser and finer-grained soils such as found at the Yiğma Tepe were also identified in Hellenistic tumuli of ancient Greece, for example at the Great Tumulus at Vergina (Schmidt-Dounas, 2015) and the aforementioned Kastas tumulus at Amphipolis (Lazaridis, 1978), as well as in Turkey, for example in the Kocamutaf Tepe at Sarıds/Bin Tepe (Ratte, 1994), the Beşik-Sivritepe in the Troad (Korffmann, 1985) and the Karakuş tumulus of Komagene (Dörmer, 1975). Especially at Karakuş the internal layers are almost horizontally flattened in a similar way as in the Yiğma Tepe. This artificial stratigraphy may have served for stabilizing the embankment and enabling the creation of a uniform shape (Vokotopoulou, 1990), or for keeping rainwater from draining into the centre of the tumulus (Kyriakou, 1998).

5.4 Accuracy of reconstructed tumulus shape and volume balancing

Based on seismic and geoelectric measurements at the exterior of the Yiğma and the surrounding trench, we were able to identify and quantify the volumes of sediment that have been eroded from the tumulus and the outer rim of the trench and deposited in the trench. From this information, the original shape of the tumulus could be estimated. In this context it is necessary to discuss the accuracy of the original shape reconstruction and how it compares with the previous attempt by Dörpfeld (1910).

The reconstruction attempted in this study makes use of topographical and geophysical measurements and its accuracy is therefore limited to the resolution of the respective method. Whereas the accuracy of topographic measurements is of the order of a few centimetres, the accuracy of depths from refraction seismic is of the order of ±1 to 2 m corresponding to a velocity uncertainty of ±5%, which is a rather pessimistic value. Test computations show that the volumes of the involved soil layers are affected by this uncertainty in the following ways (Table BT2):

Base of the trench: For an assumed 1 m uncertainty of the trench bottom (Z = 28–29 m) a corresponding uncertainty of the trench volume is 5% with respect to the original value.

Base level of the tumulus: The base level of the Yiğma Tepe is constructed from the surrounding topography. But no information regarding the deposition or erosion in this area since the construction of the tumulus is available. It is possible that the base layer was somewhat lower or higher at the time of construction. It turns out that a lowering of the tumulus base by 1 m shifts the volume balancing of trench and tumulus such that the volume of the tumulus increases by ~6% whereas the volume of the trench decreases by ~11%. Thus, an additional misbalance of ±4% arises per metre depth change of the base level.

The simplifying assumptions underlying the reconstruction of the original topography lead to a smooth top area with a round, slightly flattened plateau whereas the present topography shows signs of digging and possibly landslides or cave-ins. On top of that, a radial interpolation neglects any direction-wise differences in the tumulus shape.

In comparison, Dörpfeld assumed a more pointed top of the tumulus. Our proposed slightly flattened shape offers the possibility of a building at the top. This idea is supported by the hard-packed area at the top that was identified by collocated refraction seismic and excavation. It could have served as a foundation of a small building or grave marker at the top of the tumulus. Except from the very extraordinary Beşik-Sivritepe, which shows a pointed shape, all other tumuli in Greece or Asia Minor look more like a hemisphere or have a conical shape such as the Kastas tumulus, which is especially remarkable, because it has a similar size as the Yiğma Tepe (Peristeri, 2016).

6 CONCLUSION

Geophysical methods were used to gather information about the construction and composition of the monumental tumulus Yiğma Tepe. Based on P-wave refraction sounding we were able to show that the tumulus consists of three layers of different P-wave velocity separated by distinct interfaces. Visco-elastic forward modelling shows that the transition between these layers is a sharp boundary which could be realized by a thin, artificially hard-packed layer at the transitions between different building phases. The calculated layer interfaces are in agreement with terrain drawings of W. Dörpfeld based on excavations of the early twentieth century. The existence of such layers is further proven by recent excavations which showed that a localized near-surface area of increased seismic velocities is identified with a hard-packed layer of sediments with higher fractions of fine sand and clay.

Seismic investigation of the base level below the tumulus and inside and outside of the surrounding trench suggests that soils with different grain-sizes used in the construction of different parts of the tumulus correspond to sediment changes found in the immediate surroundings.

A reconstruction of the original shape of the tumulus and seismic-based mass balancing shows that about 17% of the entire tumulus was displaced after the construction until now. Half of this volume is lost due to the attempted robbery in the northwest. The balancing
also shows that the volume of the original tumulus agrees with the volume of the reconstructed original trench. Thus, no additional material apart from building stones were needed for the construction of the tumulus.

From a methodological point of view, we were able to show that seismic P-waves generated with a hammer blow can penetrate an artificial mound of soils with a diameter of about 160 m. In spite of partly sparse ray coverage, a careful analysis of traveltime branches connected with interactive raytracing and complementary traveltime tomography was able to produce a stratigraphic model, the reliability of which was confirmed by waveform modelling. In this context, seismic waveform modelling turned out to be an essential tool for distinguishing between seismic subsurface models that are indistinguishable in terms of traveltimes alone. Besides seismic methodology the coordinated and interaction between geophysical investigations and localized archaeological excavations turned out to be essential for the archaeological success of the investigation. From the seismic depth sections a 3D layered model of the tumulus was created giving insight into the building processes. This structural model serves as a basis for ongoing and future archaeological research.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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APPENDIX A.

Details of geophysical data acquisition and interpretation

Appendix A is a complementary compilation of technical data and figures concerning the acquisition, processing and analysis of the seismic and geoelectric data presented in this article. It contains information on the following thematic groups.

a. Acquisition parameters of the seismic profile: see Table AT1
b. Parameters and specifications on the applied ray tracing and tomographic traveltime inversion:
   - A systematic test of the effect of spatial grid spacing of the accuracy of seismic traveltime computations (Figure AF1)
   - A checkerboard test for estimating the spatial tomographic resolution (Figure AF2)
   - Graph demonstrating the ray coverage applied in the traveltime tomography (Figure AF6).
   - List of traveltime residuals obtained by interactive ray tracing and tomography for the seismic velocity models presented in Figures 6, 10, AF2 and AF5 (Table AT2)
   - List of computational parameters selected for the tomographic inversion with the ReflexW software (Table AT3)
c. Complementary results of seismic refraction sounding of the trench and the surrounding of the tumulus: see Figure AF5.
d. Parameters of visco-elastic wavefield modelling:
   - List of computational parameters applied for visco-elastic wave field modelling with the DENISE software: see Table AT4
   - A comparison of measured and modelled spectra of seismograms: see Figure AF3.
e. Parameters and specifications of electric resistivity tomography
   - List of computational parameters applied for the electric resistivity tomography with the RESINV2D software: see Table AT5,
   - A comparison of measured and computed electric sounding data: see Figure AF4.

FIGURE AF1 Influence of grid spacing on FD seismic traveltime modelling. For the test we applied the ReflexW software and used the tomographic velocity model of Figure 10(b) and the source-geophone distribution of profile P2.
(a) Estimate of the numerical error introduced by coarsening the grid. The figure shows the RMS difference of synthetic seismic traveltimes calculated with grid spacings of 0.1 to 1.4 m with respect to traveltime computed with 0.1 m spacing (blue line). The numerical error caused by grid coarsening shows a linear increase (red-dotted line) with increasing grid spacing. The numerical RMS error is within the picking accuracy for grid spacings ≤ 0.5 m. (b) Influence of grid spacing on the fitting accuracy in seismic traveltime tomography. The figure shows the variation of RMS residual traveltimes calculated for the same starting model (profile P2, Figure 6) with grid spacing varying between 0.1 and 1.4 m; the red-dotted line shows the trend in form of a second-order polynomial. For grid spacings between 0.1 and 0.5 m, the increase of the RMS error is only 0.1 ms, much less than the estimated picking accuracy of 1 ms. This shows that the results of the tomography do not critically dependent on the grid spacing [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE AF2  Checkerboard test for estimating the spatial resolution of the applied traveltime tomography. Background model is model 2 (Figure 10(b), right); a velocity variation of ±10% was added on a 10 × 10 m (a), 15 × 15 m (c) and 20 × 20 m (e) grid. Traveltimes are calculated for these models. The background model was used as a starting model for the inversion computation. The velocity residuals for the three recovered checkerboard patterns are given in per cent (b, d, f) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE AF3  Amplitude spectra calculated on trace-normalized seismograms of shot gather 19 on profile P2. (a) Spectra of raw field data and (b) spectra of synthetic data from FD forward modelling (velocity model 2 from Figure 6, Q = 10 constant). Near the source point the main energy lies between 10 and 60 Hz in both measured and modelled data and decreases similarly with offset [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE AF4  Geoelectric profile E-Y2: (a) measured apparent resistivity pseudo-section, (b) synthetic apparent resistivity pseudo-section calculated from the tomographic model (c) [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE AF5  P-wave velocity models along profiles in the trench and outside the tumulus area showing the change of thickness of the basal layers A and B around the tumulus. (a) In the northwest, layer B was not found, and layer A has a thickness of about 18 m, which decreases to about 5 to 8 m in the west on profiles AGP3 (b) and GRB4P (d) and in the southeast on profile AGP2 (f). In the southwest on profile GRB2P (e) layer A is missing completely, the thin near-surface layer shows significantly higher velocities (~650 m/s) than the respective layers in the north (400–450 m/s). The bedrock layer at about 20 m ASL cannot be resolved on all profiles due to the length of the profile and the thickness of the overlying layer B [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE AF6  Ray coverage for the first arrival traveltime tomography shown in Figure 10. Except for the right-hand end of the profile below the basal surface, profile P2 shows sufficiently dense ray coverage with some lateral variation, though, which is caused by the source spacing. The centre of the tumulus is slightly less well covered than the areas below the tumulus flanks [Colour figure can be viewed at wileyonlinelibrary.com]

| Profile no. | Profile length (m) | Vertical point source | Shot points | Shot point spacing (m) | Geophones | Geophone spacing (m) |
|-------------|--------------------|-----------------------|-------------|------------------------|------------|---------------------|
| P1          | 192                | Vibro                 | 6           | 5 to 78                | 96         | 2                   |
| P2          | 216                | Hammer                | 39          | 6 to 12                | 216        | 1                   |
| P3          | 240                | Hammer                | 24          | 2 to 12                | 240        | 1                   |
| P4          | 168                | Hammer                | 19          | 5 to 10                | 80         | 2                   |
| GRB2P       | 48                 | Hammer                | 7           | 12                     | 48         | 1                   |
| GRB3P       | 48                 | Hammer                | 7           | 12                     | 48         | 1                   |
| GRB4P       | 48                 | Hammer                | 8           | 12                     | 48         | 1                   |
| AGP1        | 72                 | Hammer                | 21          | 4                      | 72         | 1                   |
| AGP2        | 96                 | Hammer                | 6           | 12                     | 24         | 2                   |
| AGP3        | 48                 | Hammer                | 6           | 12                     | 48         | 1                   |

aThe Vibro source is an ELVIS vertical mini-vibrator manufactured by GEOSYM GmbH (Hannover, Germany) run with a 10 s long 20–120 Hz up-sweep.

bGeophones were 10-Hz vertical component sensors recorded with GEODE multi-channel seismographs.
TABLE AT2  RMS residuals of the first break traveltimes corresponding to all seismic velocity models generated by interactive raytracing or seismic traveltime tomography

| Figure   | Profile no.          | RMS error (ms) |
|----------|----------------------|----------------|
| Figure 6 | P1                   | 6              |
|          | P2                   | 4              |
|          | P3                   | 4              |
|          | P4                   | 4              |
| Figure 10| P2 Tomo Gradient 1   | 4              |
|          | P2 Tomo Gradient 2   | 3              |
|          | P2 Tomo RT-Model     | 4              |
| Figure AF2| P2 Tomo Grad 2 Checkerboard | 4 |
| Figure AF5| AGP1                 | 2              |
|          | AGP2                 | 2              |
|          | AGP3                 | 2              |
|          | GRB2P                | 3              |
|          | GRB4P                | 3              |

TABLE AT3  Tomography parameters for the 2D-tomography with ReflexW (Sandmeier, 2019) on profile P2 for three starting models (Section 4.1 – Traveltime tomography)

| Model width (m) | Model height (m) | Grid spacing (m) | Starting velocity | Iter.-max | Smoothing (gridpoints) | Beam width (gridpoints) | Minimum change threshold per iteration (%) |
|-----------------|------------------|------------------|-------------------|-----------|------------------------|--------------------------|--------------------------------------------|
| 219             | 52.4             | 0.5              | RT-Model          | 20        | 4                      | 50                       | 0.1                                        |
| 219             | 52.4             | 0.5              | 380 m/s + (topo-depth)*20 m/s | 20        | 4                      | 50                       | 0.1                                        |
| 219             | 52.4             | 0.5              | 380 m/s + (topo-depth)*40 m/s | 20        | 4                      | 50                       | 0.1                                        |

TABLE AT4  Visco-elastic forward modelling parameters that were used for the modelling of profile P2 with the DENISE software (Section 4.1)

| Model width (m) | Model height (m) | Grid spacing (m) | Time sampling (s) | Maximum calculated time (s) | Source wavelet | Source frequency (Hz) | Seismic quality factor Q |
|-----------------|------------------|------------------|-------------------|-----------------------------|----------------|-----------------------|-------------------------|
| 219             | 52.4             | 0.2              | 2e-5              | 0.3                         | Spike          | 10–60                 | 10                      |

TABLE AT5  Computational parameters used for the electric resistivity tomography of profile Y2 with the RESINV2d software

| Inversion parameters – geoelectric profile Y2 (Finite element method with damped grid) |
|---------------------------------------------|---------------------------------------------|
| Profile length                             | 95 m                                       |
| Electrode spacing                          | 1 m                                        |
| Configuration                               | Wenner-Alpha                               |
| Jacobi-Matrix recalculation                | Each inversion step                        |
| Increase of damping factor with depth      | 1.05                                       |
| Robust data inversion constrain is used with cutoff factor | 0.05                                       |
| Robust model inversion constrain is used with cutoff factor | 0.005                                      |
| Effects of side blocks are severely reduced|                                            |
| Thickness of first layer                   | 0.5 m                                      |
| Block width (regular)                      | 2 m                                        |
APPENDIX B.

Details of volumetric data interpretation

Appendix B is a complementary compilation of technical specifications and data concerning the presented volume balancing it contains information on the following issues:

a. Acquisition and processing parameters of the photogrammetry: see Table BT1
b. An overview of abbreviations and sizes of the volume units considered in the volume balancing: see Table BT2

### Table BT1: Photogrammetry parameters

| Parameter                                | Value                  |
|------------------------------------------|------------------------|
| Camera model                             | ILCE-5100 (20 mm)      |
| Resolution                               | 6000 × 4000            |
| Focal length                             | 20 mm                  |
| Pixel size                               | 4 × 4 μm               |
| Precalibrated                            | No                     |
| Images                                    | 582                    |
| Flying altitude                          | 83.7396 m              |
| Ground resolution                        | 0.014992 m/pix         |
| Pixel width in x-direction               | 0.0240 cm              |
| Pixel width in y-direction               | 0.0365 cm              |
| Coverage area                            | 0.159944 km²           |
| Camera stations                          | 582                    |
| Tie-points                               | 21430                  |
| Mean x-error (18 control points)         | 0.018 m                |
| Mean y-error (18 control points)         | 0.013 m                |
| Mean z-error (18 control points)         | 0.02 m                 |
| Ground control points for georeferencing | 19                     |
| Volume unit | Description | Volume (m³) |
|------------|-------------|-------------|
| $V_1$      | Construction phase 1 | 134300 |
| $V_2$      | Construction phase 2 | 64700 |
| $V_3$      | Construction phase 3 | 63300 |
| $V_M$      | Present total volume of phases 1-3 | 262300 |
| $V_T$      | Present trench volume | 212000 |
| $V_{CM}$   | Reconstructed original total tumulus volume | 316000 |
| $V_{OT}$   | Reconstructed original trench volume | 311000 |
| $V_{tunnel}$ | Exploration tunnel system of Dörpfeld (1904 to 1909) | 336 |
| $V_{ring wall}$ | Circular ring wall (crepis) | 1790 |
| $V_{DM}$   | Debris from the tumulus deposited in the trench | 55000 |
| $V_{DT}$   | Debris from the surrounding deposited in the trench | 44600 |
| $V_{CM,B-1}$ | Reconstructed original tumulus volume at a basal surface elevation drop of 1 m | 335600 |
| $V_{OT,B-1}$ | Reconstructed original trench volume at a basal surface elevation drop of 1 m | 275600 |
| $V_A$      | Volume of the original layer A | 203000 |
APPENDIX C.

Soil analysis

Appendix C contains the detailed soil analysis from the different archaeological trenches at the Yıga Tepe (Table CT1).

### Table CT1  Grain size analysis of soil samples at the Yıga Tepe

| Year/trench | Layer | Characterization | Elevation (m ASL) | Gravel (20 mm > Ø > 2 mm) (%) | Sand (2 mm > Ø > 0.2 mm) (%) | Fine sand + silt + clay (Ø < 0.2 mm) (%) |
|-------------|-------|------------------|-------------------|------------------------------|-----------------------------|---------------------------------|
| **Natural base layers** | | | | | | |
| PE17-So-03  | 020   | ancient topsoil  | 41.52–41.77       | 43                           | 39                          | 18                              |
| PE17-So-03  | 030   | upper river sediment | ?–41.6           | 57                           | 35                          | 8                               |
| PE17-Säu-01 | 015   | lower river sediment | 40.1–40.7        | 70                           | 28                          | 2                               |
| PE17-Säu-01 | 030   | gravel layer     | ?–40.1            | 74                           | 24                          | 2                               |
| PE17-Säu-01 | 031   | sandy layer      | 39.7–40.1         | 50                           | 49                          | 1                               |
| **Construction layers** | | | | | | |
| PE15-So-02  | 007   | construction debris layer crepis | 42.53–42.57 | 45 | 45 | 10.0 |
| PE17-So-02  | 004   | hard packed layer of upper tumulus fill | 68.46–68.9 | 40 | 51 | 9.0 |
| PE17-So-03  | 019   | construction debris layer foundation trench of crepis | 41.57–41.84 | 57 | 32 | 11.0 |
| PE17-So-03  | 028/29 | sandy filling foundation trench of crepis | 41.29–41.48 | 65 | 28 | 7.0 |
| PE17-So-04  | 015   | hard packed layer in the centre of the top (Seismic HVZ) | 69.21–69.55 | 58 | 31 | 11.0 |
| PE17-So-02  | 008   | hard packed layer of upper tumulus fill | 68.45–52 | 43 | 46 | 11 |
| **Embankment** | | | | | | |
| PE17-So-01  | 006   | gravelly layer of upper fill | 66.94–67.54 | 89 | 10 | 1.0 |
| PE17-So-01  | 007   | sandy layer of upper fill | 66.92–67.6 | 62 | 37 | 1.0 |
| PE17-So-01  | 011   | upper fill | ?–67.2 | 50 | 48 | 2.0 |
| PE17-So-02  | 012   | upper fill | ?–68.9 | 60 | 34 | 6.0 |
| PE17-So-03  | 014   | lower fill near crepis | 42.1–42.74 | 61 | 37 | 2.0 |
| PE17-So-03  | 016   | lower fill near crepis | 41.85–42.1 | 62 | 36 | 2.0 |
| PE17-So-03  | 018   | lower fill over ancient topsoil | 41.77–42.1 | 70 | 29 | 1.0 |
| PE17-So-04  | 011.1 | upper fill | 68.8–69.55 | 65 | 33 | 2.0 |
| PE17-So-04  | 011.2 | upper fill | 68.6–69.21 | 60 | 37 | 3.0 |