Pure and Applied Geophysics

Mapping the palaeo-Piniada Valley, Central Greece, based on systematic microtremor analyses

--Manuscript Draft--

Manuscript Number:	PAAG-D-17-00181
Full Title:	Mapping the palaeo-Piniada Valley, Central Greece, based on systematic microtremor analyses
Article Type:	Regular Issue
Keywords:	seismic noise; HVSR; mapping; Thessaly; geophysical survey
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Funding Information:	
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Mapping the palaeo-Piniada Valley, Central Greece, based on systematic microtremor analyses

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Abstract

The application of seismic noise-based techniques has become particularly popular in the last decades, as they are not invasive and do not require large teams or expensive equipments. The Horizontal to Vertical Spectral Ratio (HVSR) is commonly used not only in seismic microzoning studies as far as from noise recording constraining the fundamental resonant frequency, it is possible to infer the depth of the bedrock knowing the average shear wave velocity of the overlying sedimentary cover, or viceversa (*i.e.* resonance equation). For the purposes of the present research, more than 300 single-station noise measurements (HVSR approach) were carried out across the Piniada Valley (Central Greece), along and between several transects planned roughly perpendicular to the mean valley trend. In order to understand the palaeogeographic and tectonic evolution of this area, we needed an estimation of the geometry at depth of the bedrock underlying the fluvial deposits of the present-day Pinios River. As a result, for each measured site, we calculated the depth of the bedrock and, afterwards, such values were opportunely interpolated for obtaining a 3D model of the palaeo-Piniada Valley documenting for the first time the recent (Late Quaternary) inversion of the topographic gradient.

Keywords: seismic noise, HVSR, mapping, Thessaly

Introduction

Alluvial plains are generally the locus of fluvial deposition, whose accumulation rate depends on several factors, like the creation of accommodation space generally by tectonic activity, the dimension of the upstream hydrographic basin, the regional climate conditions and the water discharge and its seasonal regimes, the outcropping lithologies in the catchment area and hence the amount of bed and suspended load and their proportion, the mean gradient of the plain as well as of the main water course, the occurrence and/or formation of local base levels and/or knick points and their relative altitude, etc. When alluvial plains develop in intermountain conditions, the overall geometry of the sedimentary bodies infilling the lower part of the valley is obviously not tabular but characterized by a lense shape in section view with a roughly flat top surface and a more or less concave lower surface.

The longest river draining Greece is represented by the Pinios (216 km) that collects waters from large sectors of the Antichasia, Pindos and Othris mountains as well as the western Pilion and southern Olympus, with a total extension of *ca.* 9500 km^2 (Figure 1). If we consider the whole drainage pattern, the existence of some major hydrographic anomalies could be observed and particularly the occurrence of subsequent reaches alternatively flowing across wide alluvial plains, like the Karditsa Plain to the west and the Larissa Plain to the east, narrow valleys like the Piniada and the Gonnoi ones, and even three gorges (Kalamaki, Rodia and Tembi; Figure 1).

It is noteworthy that the general gradient of the numerous affluents that progressively merge downstream from Antichasia, Pindos and Othris rapidly decreases once the water courses get into the Karditsa Plain. Indeed, they commonly enter the plain at about 130-150 m altitude, while the Pinios River exits the plain near Farkadona at *ca.* 90 m a.s.l. (Figure 2), from where it still has to flow for *ca.* 150 km before reaching the delta and hence the final base level of the Aegean Sea.

In the present paper, we focus on the hydrographic anomaly characterizing the reaches between the two major plains, Karditsa and Larissa, west and east respectively, and particularly where the Pinios River flows across the Piniada Valley and the Kalamaki Gorge. The former morphological feature is characterized by a 1-3 km-wide alluvial plain bordered by the Palaeozoic-Triassic bedrock belonging to the Pelagonian Zone (Figure 2; IGME, 1985; 1998; Caputo, 1990). This intermountain valley bottom progressively narrows downstream to few hundreds meters north of the village Koutsochero and completely disappears in correspondence of the Kalamaki Gorge, where the river bed is directly entrenched in the sloping bedrock. In the former reach, the river is characterized by several meanders with a sinuosity index of *ca.* 1.6, while in the final sector and especially within the gorge the river geometry is almost linear and sinuosity drops to *ca.* 1. Due to the reduced width of the Piniada Valley and the paucity of permanent agricultural crops, no major land reclamation works took place in this sector of Pinios River, allowing the river meanders to evolve and migrate naturally up to this date.

Following these morphological and hydrological premises, the major aim of our research is to reconstruct the geometry at depth of the Piniada Valley and particularly of the bedrock underlying the fluvial deposits that have been aggraded during Late Quaternary, partially infilling the intermountain valley. In order to achieve this goal, we systematically investigated the area and carried out more than 300 single station seismic noise measurements that allowed to map the lateral variations of the natural frequency within the fluvial plain. Based on the available stratigraphic logs in correspondence of some deep boreholes for irrigation purpose, we could also calibrate the peaks observed in the corresponding HVSR curves and hence constrain the depth of the major impedance contrast (*i.e.* the seismic bedrock).

The investigation strategy was, firstly, to produce several pseudo-2D transects based on high-density aligned measurements across the valley and subsequently to cover the entire area with a less dense, but relatively regular, grid of measured sites. All depth converted measurements were then properly interpolated for obtaining a 3D model thus reconstructing the geometry of the seismic bedrock along the Piniada Valley. We anticipate here the major result of this research that clearly documents the presence at depth of a palaeovalley sloping in the opposite direction of the present-day river flow.

Methodology

The passive seismic measurements have been carried out using the digital tromograph Tromino(R), an all-in-one instrument with a 3-component short period seismometer (proper frequency equal to 4.5 Hz) expressly designed for noise measurements and maximum portability.

The background noise, also referred to as microtremor, is present everywhere at the Earth's surface and its sources, and thus its frequency content, are related to both atmospheric phenomena and anthropogenic activities (Gutenberg, 1958; Asten, 1978; Asten and Henstridge, 1984). It is generally characterised by very small oscillations (10^{-4}-10^{-2} mm) with spectral components poorly attenuated in space and measurable with passive recording techniques. All elastic waves during their path from the source to a site suffer some attenuation which is basically geometric, due to the increasing dimensions of the wave front, and anelastic (or intrinsic), due to the real not perfectly elastic behaviour of all rocks and especially sediments. In all cases, the amount of attenuation is a function of frequency; indeed, assuming a constant velocity for all frequencies, the shorter the wavelength (*i.e.* the higher the frequency) the greater the number of cycles and hence of the intrinsic attenuation that occurs. Accordingly, stratigraphic layering governs the distribution of the mechanical and geophysical properties; therefore, such information is included in the recorded microtremors together with random noise (*e.g.* Castellaro *et al.*, 2005). Information on the subsoil can be deduced by means of several geophysical methods like that proposed by Nakamura (1989) with his horizontal to vertical spectral ratio (HVSR). This technique is nowadays largely used in order to determine the local seismic amplification and to estimate the principal resonance frequencies characterising the shallow subsoil, say from tens to few hundreds of meters (*e.g.* Mucciarelli and Gallipoli, 2001 and references therein).

Both outcomes are crucial for engineering antiseismic planning (*e.g.* Mucciarelli and Gallipoli, 2001; Gallipoli *et al.*, 2004; D'Amico *et al.*, 2008; Albarello *et al.*, 2010), but also for mapping subsoil interfaces (*e.g.* Ibs-von Seht and Wohlenberg, 1999; Parolai *et al.*, 2001; Hinzen *et al.*, 2004; Gosar and Lenart, 2010; Mundepi and Mahajan, 2010; Matsushima *et al.*, 2014; Mantovani, 2016; Tarabusi and Caputo, 2016).

Even if the theoretical basis of the H/V still remains a matter of debate, the outcome is an experimental curve representing the ratio between the mean spectral amplitude of microtremors (horizontal to vertical components) as a function of frequency. The H/V curve exhibits peaks linked to the resonance frequencies of the soil beneath the measured site. Therefore, as already mentioned, this method highlights the occurrence of resonance phenomena and provides an estimation of the frequencies at which the ground motion can be amplified, as a result of site effects induced by the presence of stratigraphic discontinuities, and thus modifications in the geophysical properties within the subsoil.

In case of a single layer one-dimensional stratigraphy overlying a highly contrasted infinite bedrock (Lermo and Chavez-Garcia, 1993; 1994; Lachet and Bard, 1994; Ibs-von Seht and Wohlenberg, 1999; Fäh *et al.*, 2001), the principal S-wave resonance frequency of the sedimentary cover, f_0, also referred to as fundamental resonance frequency, is linked to its average shear wave velocity, v_s, and thickness, h, according to the following formula (*i.e.* the so called resonance equation):

$$f_0 = \frac{v_s}{4 \cdot h} \qquad [1]$$

Therefore, once f_0 is constrained, the H/V technique can provide stratigraphic information as it is possible to obtain the thickness of the sedimentary cover knowing its average shear wave velocity, or viceversa.

In case of multilayer subsoil system, more complex approaches and hence modelling strategies are needed (Tsai and Housner, 1970; Ben-Menahem and Singh, 1981; Aki and Richards, 2002; Scherbaum *et al.*, 2003; Ohrnberger *et al.*, 2004; Castellaro and Mulargia 2009; Lunedei and Albarello, 2010; 2015). This led to the implementation of different computation methods in dedicated software for the elaboration and/or inversion of the H/V curves, as for example Grilla (www.moho.world), Geopsy (www.geopsy,org), ModelHVSR (Herak, 2008) and OpenHVSR (Bignardi *et al.*, 2016).

At a first approximation, the geological setting of our investigated area satisfies the former condition above described.

Data acquisition and analyses

During the field work several tests have been performed by repeating the measurements at a same site at different times for checking repeatibility of results. Sampling was set at 128 Hz with recording times between 30 and 18 minutes, in line with the recommendations of the SESAME guidelines (Koller *et al.*, 2004; Bard *et al.*, 2005) due to the expected resonance frequency(ies) around or greater than 1 Hz. The Grilla software (www.moho.world) was used for elaborating the seismic records within the frequency interval 0-64 Hz, considering time windows of 30 s and a smoothing function based on a 10% wide triangular window.

Within a narrow intermountain valley flanked by rocky slopes and partially infilled by Late Quaternary loose or poorly condensed fluvial deposits, it is reasonable to expect a high density contrast and hence an abrupt seismic velocity change in correspondence of the interface separating the Late Quaternary terrigenous deposits and the underlying carbonate and metamorphic rocks (Late Palaeozoic-Mesozoic). Accordingly, these geomechanical conditions are favourable to be detected on the basis of the Nakamura (1989) technique and indeed, most of our HVSR curves are characterized by a clear and often sharp peak locally reaching an amplification factor greater than 10.

As previously mentioned, our research strategy foreseen two major phases: firstly, we carried out the measurements at shortly-spaced sites (100-200 m in average) aligned along transects planned roughly perpendicular to the mean valley trend (Figure 3). We carried out seventeen of such profiles from near Farkadona, downstream to the Kalamaki Gorge, respectively west and east along the Piniada Valley. With the exception of some points located practically at the foot of the bounding slopes for instrumentally verifying the lack of amplification (*i.e.* bedrock at the zero depth), for each profile all points have virtually the same altitude corresponding to a basically flat topography, which is horizontal in section view. By projecting on the selected profile the HVSR curves of all sites measured within a distance of less than 100 m from the trace and correlating the fundamental frequency peaks, it was possible to reconstruct pseudo-2D sections. To this aim we exploited the Matlab code HVSR-profile proposed by Herak *et al.* (2010). An example of pseudo-2D section in the frequency domain is represented in Figure 4a.

Seismic bedrock

Based on the geology of the broader area (IGME, 1985: 1998; Caputo, 1990), the bedrock underlying the Late Quaternary infilling of the Piniada Valley basically corresponds to the Triassic limestone and the Palaeozoic schists-gneiss, both belonging to the Pelagonian Zone and largely outcropping within the investigated area and particularly along the slopes bounding the intermountain valley. As previously described, in the Central Hills east and southeast of Koutsochero village the Pliocene clastic deposits of fluvio-terrestrial origin crop out. In this sector of the plain, which is in any case outside the area investigated with microtremor measurements, these Neogene deposits could be possibly interposed stratigraphically between the Mesozoic rocks and the Upper Pleistocene sediments.

A particular discussion deserves the identification of the bedrock top surface from a seismic point of view, that is to say in correspondence of the major impedance contrast occuring in the subsoil of the alluvial plain. As above mentioned, the lateral slopes of the Piniada Valley are affected by erosional phenomena mainly associated with, and consequence of, several minor entrenched valleys. In correspondence of these morphological features typical ejection cones have been formed. Where carbonate rocks (*i.e.* Triassic limestone) prevail in the hydrographic basin, the cones developed at the base of the minor valleys consist of more or less well organized carbonate breccias, locally alternating with thin red soils. The breccia layers contain heterometric, but generally coarse, carbonate subangular clasts. Especially the upper levels are typically characterized by a diffuse and pervading spatic calcite that makes the whole depositional succession particularly hard in terms of mechanical and seismic behaviour. At this regard, where such cones are exposed, for example along road cuts or quarries, they always appear well cemented and completely lithified (Figure 5). Some of the microtremor measurements have been purposedly carried out in this geological-morphological contest on top of these ejection cones; the lack of any amplification frequency *de facto* confirms the assumption that these materials could represent the local seismic bedrock within the investigated area. Accordingly, also this lithology shows a high impedance contrast with the overlying loose-to-poorly consolidated alluvial sediments.

Shear-wave velocities

The code HVSR-profile (Herak *et al*., 2010) also permits to convert the single curves, and hence the entire profile, from the frequency domain to the depth domain by introducing the average shear-wave velocity of the sediments overlying the impedance contrast surface. At this regard, we spent a particular care in analysing the available stratigraphic logs from boreholes drilled in the '70s within the Piniada Valley for irrigation purposes. In particular, we carried out microtremor measurements in correspondence of these boreholes and compared the obtained HVSR curves for correlating the natural frequency with the local stratigraphy. The prevailing overlying sediments consist of clay, silt and sand occasionally containing some gravels, always loose or poorly consolidated. The peak observed in the corresponding HVSR curves has been associated to the occurrence of the bedrock, which is commonly represented by the Triassic limestones. In correspondence of the ejection cones descending the minor lateral valleys and buried by the fluvial deposits, the local bedrock is represented by well cemented conglomerates and breccias as largely observed in outcrops. Based on the depth of the stratigraphically constrained seismic bedrock and the geophysically obtained natural frequency, the average shear-wave velocity of the upper layer has been calculated using equation [1] for each borehole. All obtained velocities range between 321 and 437 m/s (Table 1), which are realistic values for the drilled lithologies (Bourbié *et al.*, 1987; Gomberg *et al.*, 2003; Herak *et al.*, 2010; Parker and Howman, 2012).

In order to exploit this punctual information and for extending it to the whole dataset of more than 300 HVSR measurements, we also took into account the overall geological setting of the area. In particular, we should consider that the sedimentary infilling of the Piniada Valley has two major sources: one is associated with the fluvial dynamics of the Pinios River draining a wide area in Central Greece (Figure 1), the other has a more local provenance with clastic materials produced from the reliefs directly surrounding the investigated valley (Figure 2). The former type of sediments commonly consist of fine-grained clastics and clay transported as bed-load and suspended-load, respectively, and mainly accummulated in the plain by the repeated flooding events. Diffuse marsh conditions associated with topographic lows and abandoned meanders are also common. The other major sedimentary source contributing to the infilling of the Piniada Valley was represented by the clastic deposits basically eroded from the rocky slopes of the several lateral valleys bordering the intermountain alluvial plain (Figure 2). At this regards, it is noteworthy that the source areas of these ejection cones are largely represented by Triassic recrystallized limestone. Only locally, Palaeozoic schists and gneiss of the Pelagonian Zone and Pliocene fluvio-lacustrine deposits of the Central Hills dominate some of the hydrographic basins feeding the lateral ejection cones, west of Zarko and south of Koutsochero villages, respectively (Figure 2; Caputo, 1990; IGME, 1985; 1998). As a consequence, while the prevailing materials from the Palaeozoic and Pliocene source areas locally accumulated within the Piniada Valley are represented by medium-to-fine-grained sands or silt, the sedimentary contribution from the areas characterized by carbonate outcrops mainly consist of monolithic coarse-grained breccias and/or conglomerates.

As above mentioned, it should be noted that in these geological conditions, even the chemistry of the drained waters was likely different. Indeed, the latter hydrographic basins were obviously much richer in carbonate solute and, as a further consequence, also the (incipient) diagenetic processes were laterally variable along the Piniada Valley infilling; cementation (mainly spatic calcite) was certainly more diffuse and intense in the cones of carbonate provenance and almost absent in the other ones. Also for this reason it is therefore reasonable to assume a slightly lower shear-wave velocity in correspondence of the lateral hydrographic basins that mainly drain the Palaeozoic schysts-gneiss and the Pliocene clastics. On the other hand, this seismological inference obtained from the geological and stratigraphic constraints is in perfect agreement with the shear-wave velocity values calculated in correspondence of the available boreholes (Table 1). Fortified by these results and taking into account a reasonable uncertainty of ±10%, we attributed smoothly variable velocities to the deposits infilling the Piniada Valley ranging between 320 and 440 m/s, which are typical values for loose-to-poorly consolidated alluvial deposits (*e.g.* Abu-Zeid *et al.*, 2014; Paolucci *et al.*, 2015; Minarelli *et al.*, 2016; Tarabusi and Caputo, 2016).

Profiles depth conversion

Based on the above discussed velocities and using the Herak *et al.* (2010) code, through a side-by-side stacks of the "converted“spectra along the profiles indicated in Figure 3, we reconstructed pseudo-2D sections showing the geometry at depth of the bedrock top surface and the thickness of the Late Quaternary infilling. An example of this procedure is represented in Figure 4b, which clearly shows that the bedrock depth progressively increases moving away from the external points of the profile, where indeed the bedrock is directly outcropping (*i.e.* no amplification), reaching a maximum value in a more or less central sector. Altogether, the deposits describe a lower concave upwards geometry topped by the flat topography.

It is worth of note that all pseudo-2D sections crossing the Piniada Valley similarly document the presence of the bedrock at depth with basically the same pattern (Figure 6) characterized by the deepening towards the central part of the section and a progressive shallowing towards the boundaries of the alluvial plain. Moreover, when observing all profiles in a perspective view following the path of the Piniada Valley (Figure 6), a lateral progressive decrease of the maximum reconstructed depth to the bedrock is manifest. What is surprinsing however is the fact that the shallowing of the palaeovalley bottom and the associated thinning of the Late Quaternary deposits occur downstream relative to the modern Pinios River and not upstream, that is to say from the Farkadona section towards the Kalamaki Gorge.

3D modelling

As anticipated above, in a second working phase we carried out ca. hundred more microtremor measurements along the Piniada Valley in order to investigate the sectors of the alluvial plain in between the several profiles (Figure 3). Sites were selected in the attempt of generating a regularly distributed grid of measurements. The single records were elaborated in the same way of the other sites along the transects, therefore producing as many HVSR curves each characterized by its natural frequency.

Based on the above discussed distribution of the shear-wave velocities within the alluvial deposits infilling the Piniada Valley, we thus migrated all these additional measurements from the frequency domain to the depth domain, therefore identifying the local depth of the seismic bedrock.

Finally, in order to reconstruct the 3D model of the palaeovalley underlying the recent alluvial deposits of the Pinios River, we thus interpolated on a GIS environment all depth values seismically obtained within the alluvial plain (*i.e.* inside the dashed line in Figure 3) together with the present-day digital elevation model outside of it. The latter data have been combined by assuming as a first approximation that the 'outside' topography was not very different from the Late Pleistocene one. This trick allowed to give a major continuity to the buried valley slopes reconstructed on the basis of the less dense seismic information. The results of this interpolation process are shown in Figure 7. The present-day absolute altitude of the palaeo-valley bottom varies between 40-45 m a.s.l., west of the Kalamaki Gorge, and *ca.* -75 m (*i.e.* b.s.l.) near Farkadona.

Concluding remarks

In this paper, we present the results of an extensive field campaign based on the systematic measurement of the seismic noise within the alluvial plain of the Piniada Valley (Figure 2), which represents a major morphological anomaly along the hydrographic network of the Pinios River, the longest water course in Greece (Figure 1). In order to shed some light on this geographic and geological issue, the so called local microtremor was recorded with a triaxial seismometer at more than 300 sites (Figure 3). By applying the procedure proposed by Nakamura (1989), it was thus possible to obtain as many HVSR curves, most of them showing a well marked peak varying between 20 Hz and 0.6 Hz.

Moreover, based on the careful analysis of the available stratigraphic logs from boreholes drilled for irrigation purposes (Table 1) and performing dedicated measurements for their seismic noise calibration, the shear-wave velocities characterizing the infilling sediments overlying the bedrock have been attained ranging between 320 and 430 m/s, which are typical values for loose-to-poorly consolidated alluvial deposits (*e.g.* Abu-Zeid *et al.*, 2014; Paolucci *et al.*, 2015; Minarelli *et al.*, 2016; Tarabusi and Caputo, 2016 Tarabusi and Caputo, 2016). It was consequently possible to convert each HVSR curves from the frequency domain to the depth domain (Figure 4) and therefore obtain the depth to the (seismic) bedrock from the field surface. Finally, working in a GIS environment and using both the present-day altitude of the measured sites and the corresponding obtained depths of the bedrock underlying the alluvial infilling, it was possible to interpolate all values for reconstructing a fully georeferenced 3D model of the palaeo-valley bottom (Figure 7). This model clearly shows that the palaeo-topographic gradient of the Piniada Valley was directed south- and westwards (north and west of Koutsochero, respectively). In other words, during Late Pleistocene the hydrographic drainage was certainly flowing towards the present-day Karditsa Plain. Indeed, based on this combined digital elevation model and using another GIS tool included in the SAGA software, we also automatically reconstructed the hydrographic network that likely characterized the palaeo-valley and its flanks sometimes during Late Pleistocene. This tentative drainage is represented in Figure 7.

In terms of palaeogeographic and tectonic evolution of this sector of Central Greece, the obtained results are remarkable because they clearly document for the first time that the two major Thessalian basins (Karditsa to the west and Larissa to the east) were not hydrographically connected till recently. On the other hand, the occurrence of very thick clay and turf sedimentary successions drilled in the Karditsa area (Kallergis *et al.*, 1973), even few kilometers west and southwest of Farkadona and just few meters below the Pinios River alluvial deposits document the presence of a wide lacustrine-marsh environment, the socalled Karditsa Lake, before the creation of the subaerial sedimentary conditions that we observe today. Remnants of this palaeo-environment in the form of widespread swamp areas in the central and western parts of the Karditsa Plain could be observed up to mid-20th century when the last major artificial draining and irrigation works modified the hydrography and morphology of the region. A similarly complex environmental and palaeogeographic evolution has been also reported for the Larissa area during Holocene times (Caputo *et al.*, 1994). Accordingly, sometimes during the Late Quaternary the Piniada Valley was firstly abandoned, possibly due to a tectonically induced upstream capture, and then progressively and rapidly infilled by the materials coming from the 'western' rivers and representing the major geophysical focus of the present research. As a consequence, the hydraulic gradient along the Piniada Valley was inexorably reversed, thus generating the definite connection between the western and the eastern plains.

Although more precise chronological data would be important for better constraining the above described evolution, the final stages of this drastic and dramatic hydrographic and geographic changes probably occurred after the last glacial maximum and mainly during the Holocene, as far as the environmental consequences induced by these natural events also influenced the Neolithic settlements distribution within the Piniada Valley (Caputo *et al.*, in prep.).

Acknowledgments

The present research was carried out in the frame of the Plateia Magoula Zarkou Project (resp. Eva Alram, Österreichische Akademie der Wissenschaften), which also financed the geological and geophysical campaigns.

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Table

borehole	bedrock depth [m]	# HVSR measurement	f_c [Hz]	HVSR ratio	v_s [m/s]
LB188	103	224	0.78	5.4	321
SR85	77	166	1.06	3.9	326
LB184	77	228	1.10	2.7	339
SR56	155	237	0.59	6.3	366
TB78	102	243	0.94	5.5	384
SR45	89	275	1.09	5.1	388
SR57	90	227	1.13	2.7	407
LB185	60	229	1.75	4.2	420
LB183	67	230	1.63	3.6	437

Table 1

Figure captions

Figure 1: Hydrographic network of the Pinios River draining large sectors of Central Greece and location of the Piniada Valley, investigated in the present research, separating the western Karditsa Plain from the eastern Larissa Plain.

Figure 2: Simplified geological map of the investigated area. 1: Palaeozoic gneiss and schysts; 2: Triassic-Lower Jurassic recrystallized limestones; 3: Pliocene-Early Pleistocene fluvio-lacustrine deposits; 4: Late Pleistocene ejection cones (from carbonate rocks); 5: Late Pleistocene ejection cones (from Palaeozoic and Neogene-Quaternary rocks): 6: Holocene alluvial deposits. The black dashed line borders the present-day alluvial plain of the Pinios River. Green arrows indicate the transport paths of the fine-grained clastic material eroded from the Central Hills and the Antichasia Mountains. See text for discussion on their role in varying the shear-wave velocity of the Piniada Valley infilling.

Figure 3: Shaded relief map showing the location of the HVSR measurements within the Piniada Valley (black dots) and the traces of the pseudo-2D sections (white segments) reconstructed in the first working phase. Capital letters label the traces. The boreholes used for costraining the shear-wave velocity of the sediments infilling the valley are also represented (triangles). The path of the modern Pinios River (thin double line) and the boundaries of the alluvial plain (dashed line) are also shown for reference.

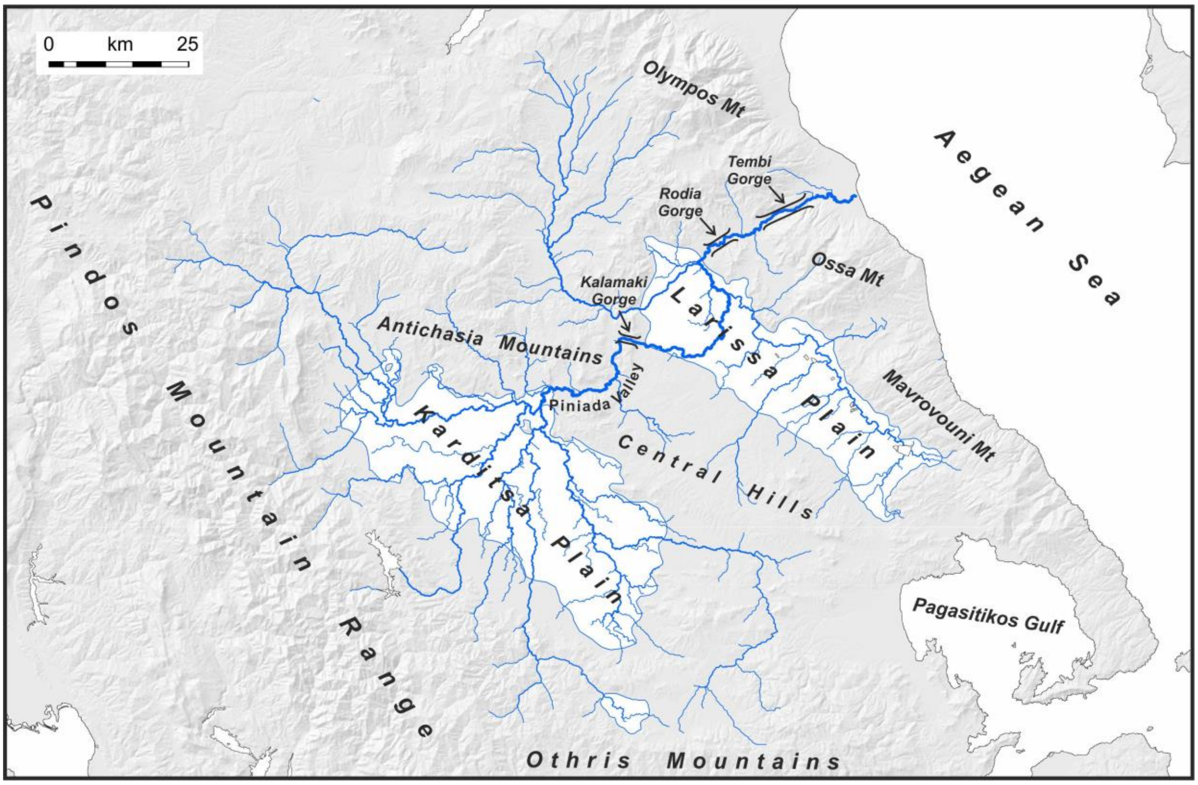
Figure 4: Example of pseudo-2D section reconstructed on the basis of the numerous HVSR measurements using the Matlab code developed by Herak *et al.* (2010) represented in the frequency domain (a) and depth converted (b) based on the shear-wave velocity inferred for this section (see text for discussion). Triangles indicate the projection of the measurement points along the transect (*E* in Figure 6). The dashed line in figure (b) correlates the depth-converted natural frequency peaks corresponding to the major resonant surface underlying the alluvial plain. This surface represents the top of the seismic bedrock, here corresponding to the Triassic limestones. The position of the borehole SR-85 is also reported.

Figure 5: Example of ejection cones characterised by coarse-grained carbonate breccias particularly well cemented especially on their top layers.

Figure 6: Pseudo-2D sections across the Piniada Valley showing the depth of the resonant surface (*i.e.* seismic bedrock) obtained by interpolation of several aligned HVSR analyses. Triangles indicate the projection of the measurement points along the transects. See Figure 3 for traces location.

Numbers in italics indicate the local depth from the field surface and in brackets the absolute altitude a.s.l.; all values are in meters. Approximately between the I and L sections occurs the progressive switch from a present-day flooding behaviour to a linear entrenching process by the Pinios River. PMZ indicates the location of the Plateia Magoula Zarkou archaeological site.

Figure 7: Digital elevation model of the investigated area showing the present-day topography and the interpolated palaeo-valley bottom underlying the Late Quaternary infilling. Note the two different color-coded scales for the areas respectively outside and inside the dashed line bordering the alluvial plain of the Piniada Valley. It is noteworthy that the recently buried south- and westwards palaeo-gradient was in the opposite direction with respect to the active Pinios River (Figure 1). The likely palaeo-hydrographic network as automatically obtained using a conventional GIS tool (SAGA software) is also represented.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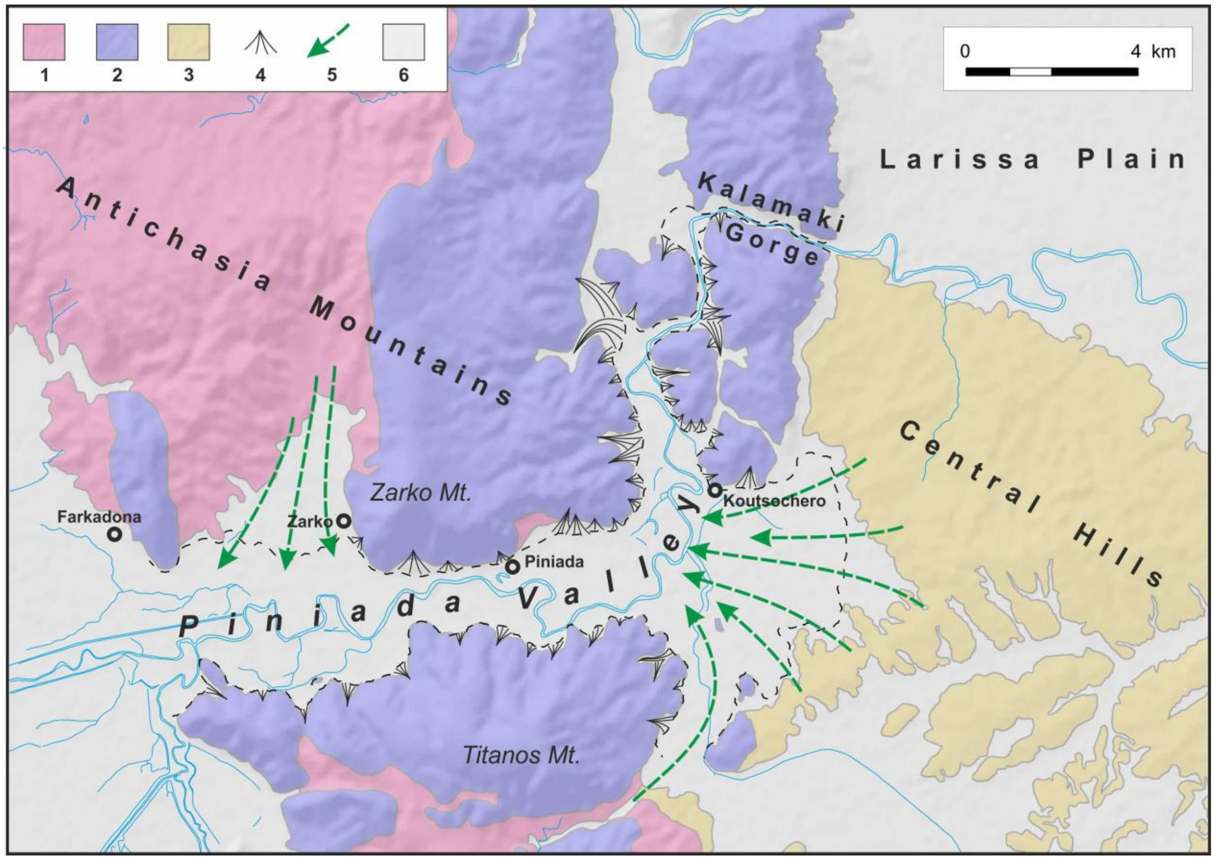
Piniada Valley
Karditsa Plain
Central Hills
Pagasitikos Gulf
Othris Mountains

Figure 1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Farkadona
Zarko
Piniada
Piniada Valley
Titanos Mt.

Figure 2

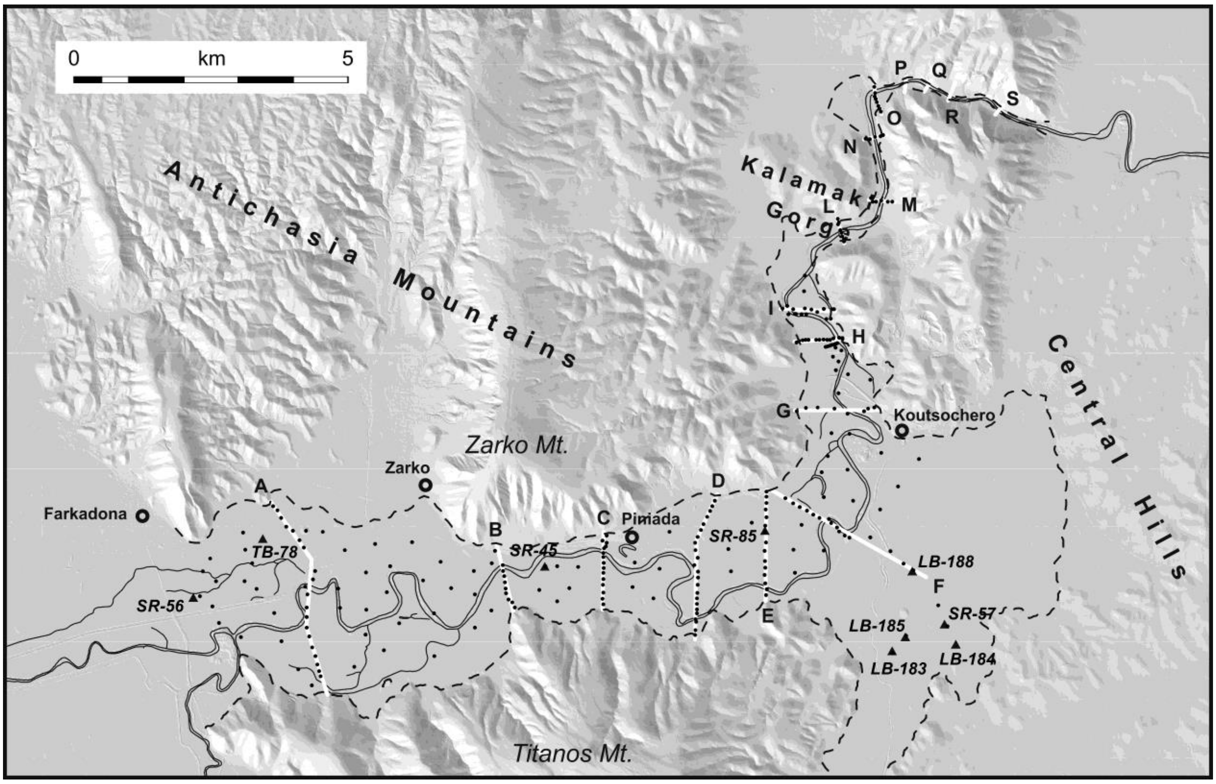
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Figure 3

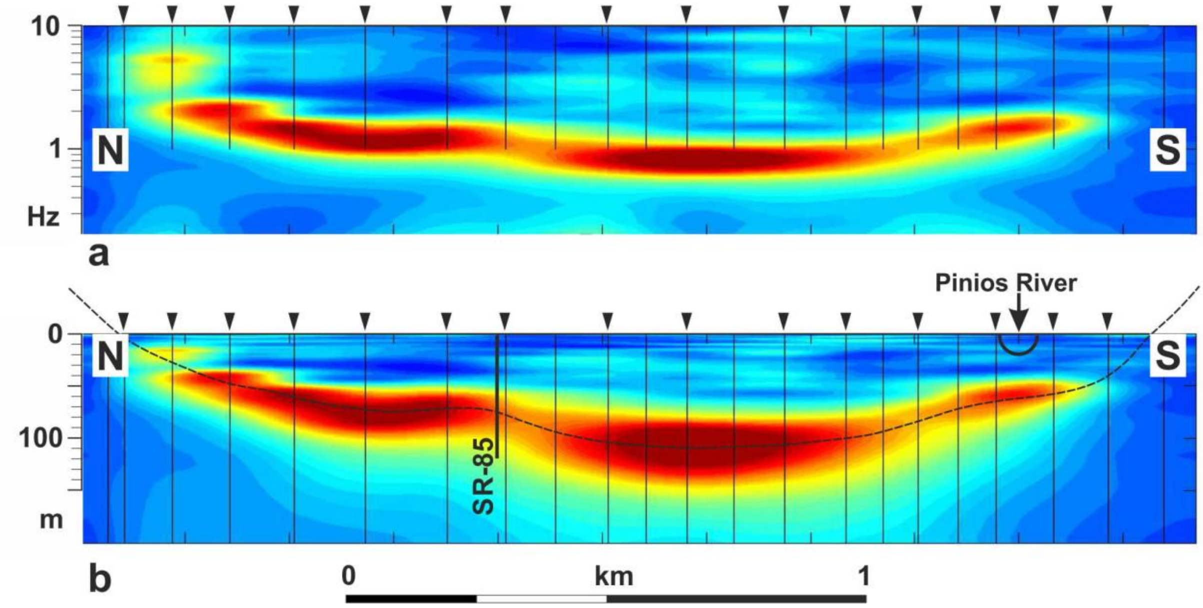

Figure 4

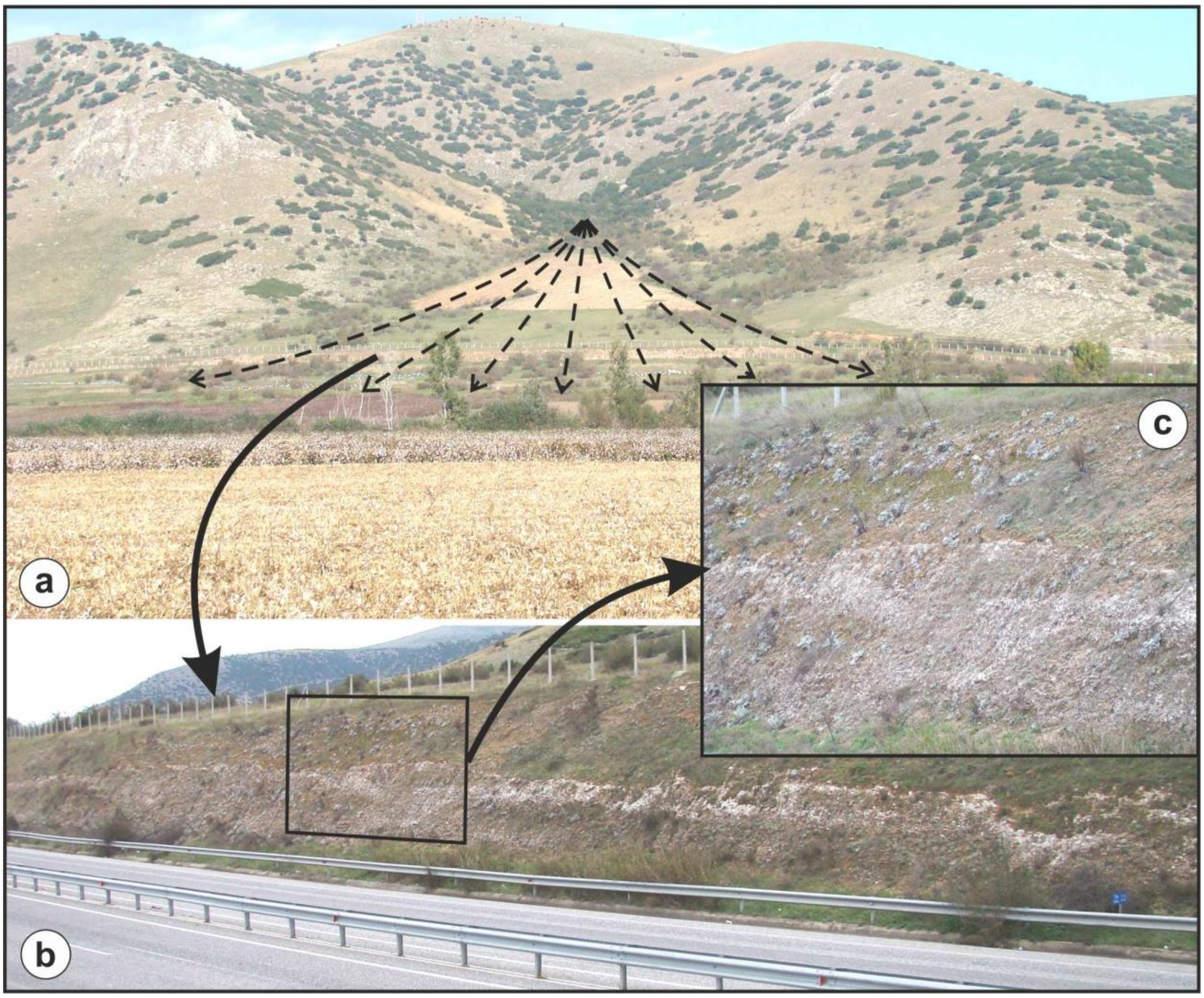

Figure 5

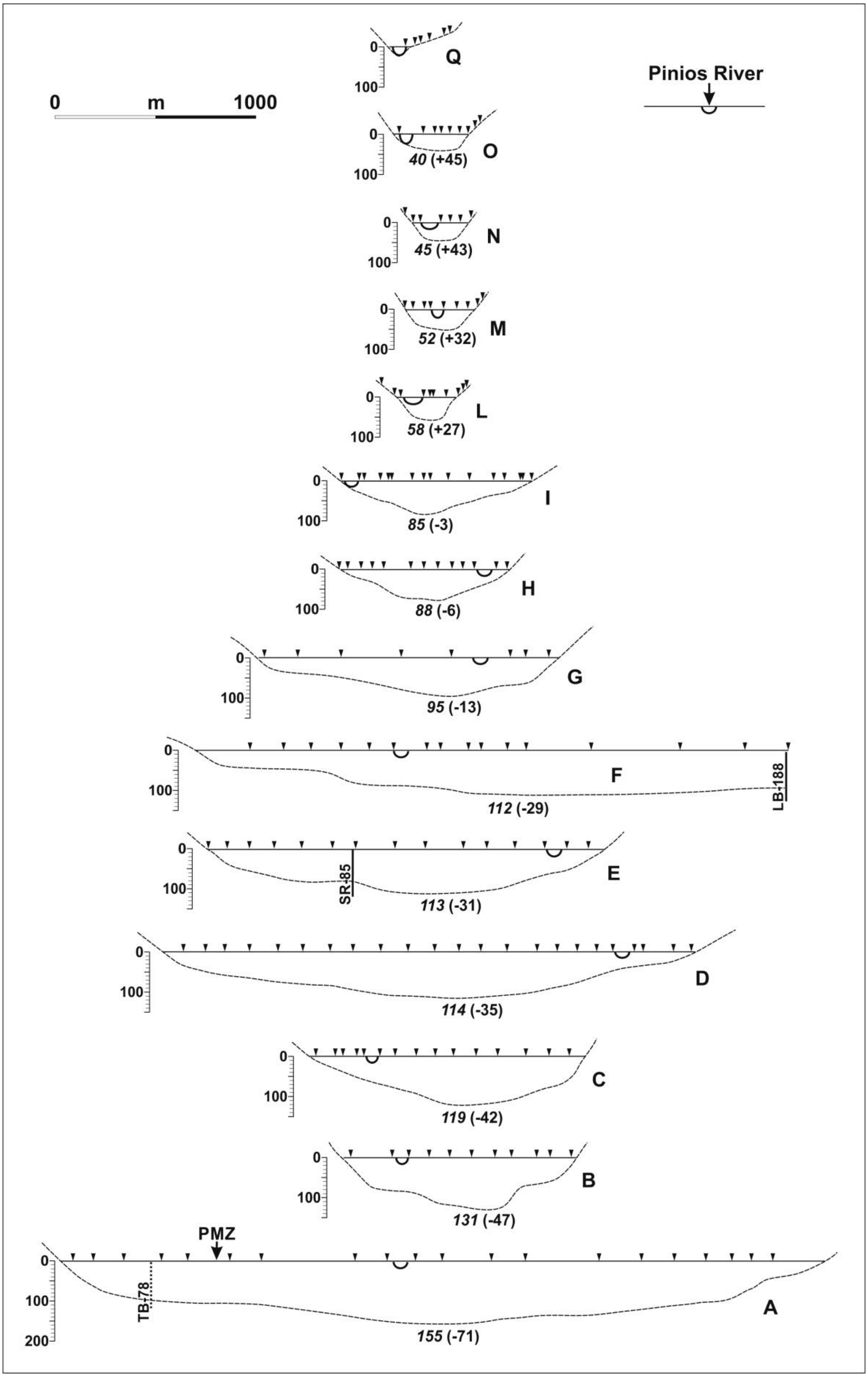
Pinios River
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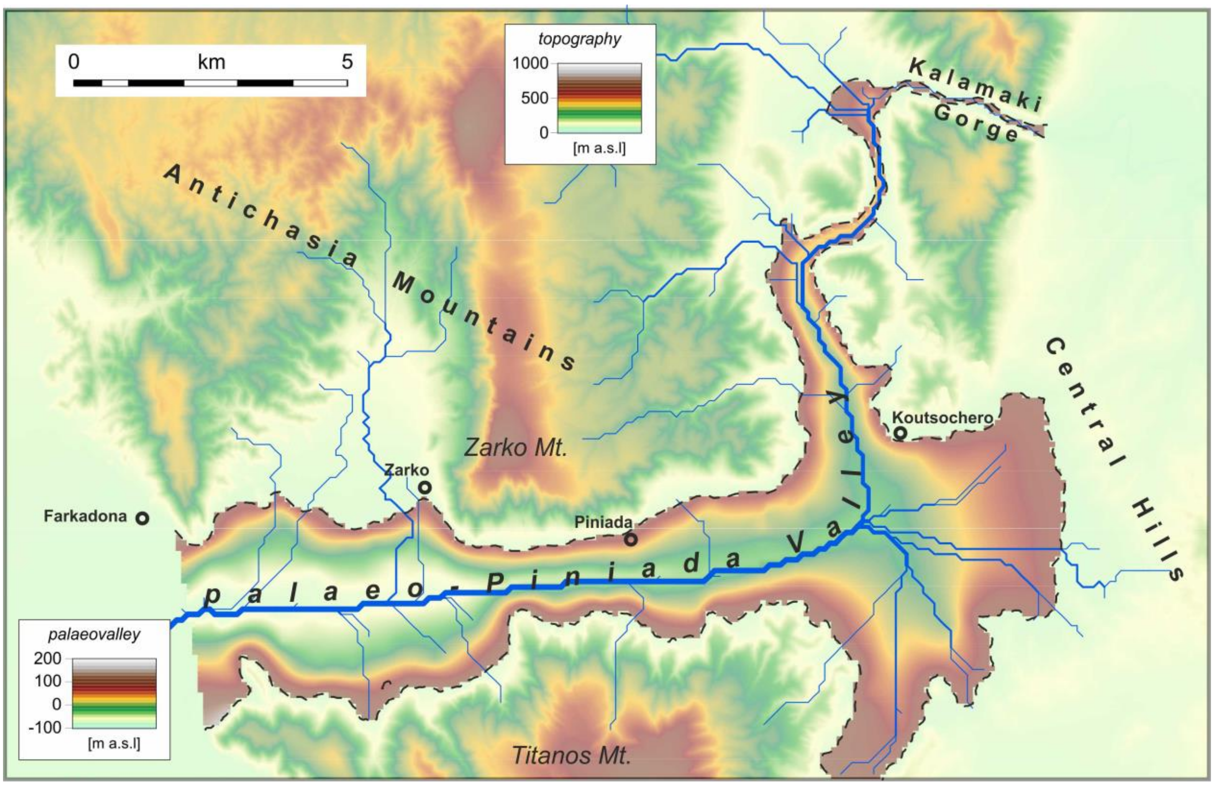
Figure 6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Zarko
Farkadona
Piniada
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Titanos Mt.

Figure 7