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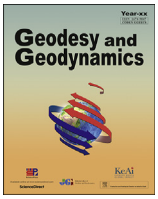

Potential traces of earthquakes in the ancient city of Kytaia, Kerch Peninsula, Crimea☆

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ABSTRACT

In this paper, the authors studied the traces of destruction in the fortress walls and houses of the Bosporan city of Kytaia. The study of this city has been ongoing since 1970. Over the past time, numerous damages have been identified at different sites of the ancient settlement. In the article, an attempt is made to compare some of them with the results of earthquakes on the Bosporus, about which the data of ancient authors were preserved.

1. Introduction

In the past 20–30 years, archaeoseismic studies have been demonstrated as more and more important in seismic hazard assessment. The reason is that the available literature sources and instrumental seismic data are scarce, while the computation of earthquake probabilities require data for periods of hundreds and thousands years. Along with the improvement of earthquake-related damage typologies [1–5], more attention has also been paid to quantitative methods of testing the origin of damage to archaeological sites [6,7], identifying the source areas of historical earthquakes [8–10], and measuring the ground shaking intensity [11–13] based on archaeoseismic data. The most representative cases are those where ruptures of strong earthquakes reached the surface, ripping apart and displacing buildings and structures [14–19]. Such deformations are the markers of surface-rupturing events, since buildings and cultural layers are reliable benchmarks that help determine the occurrence time and magnitude of an ancient earthquake, as well as its kinematics of the displacements.

There are very few ancient settlements with traces of surface ruptures. Usually archaeologists deal with numerous deformations of buildings and other structures, which conventionally attribute to military invasions or voluntary abandonments of towns by the inhabitants, or result from other natural effects (e.g., hydrological changes) in the area. Archaeologists cannot always tell whether the deformations and damage were caused by military action (or static "dead" load over time) or caused by seismic shaking or surface ruptures. Available instrumental data and field measurement (carried out in this study) data from earthquake epicenters provided a framework for identifying types of seismic damage patterns in buildings and cultural strata in the ancient town of Kytaia.

The ancient town of Kytaia is located on the southern shore of the Kerch Peninsula, Crimea (see Fig. 1). Based on modern instrumental seismic data, seismic activity at the Kerch Peninsula is relatively low today [20,21]. However, there are quite many traces caused by relatively strong earthquakes that took place in the region in the ancient time. This is supported by both written sources (Dio., Cass. XXXVII, 11,4; Oros., VI, 5, 1) and modern archaeo- and paleoseismic studies [22–34]. For example, one of the strongest earthquakes described by the aforesaid ancient authors occurred in 63 BC. Blavatsky [1977] studied its traces in the Panticapaeum city [35].

In our recent study we have discussed the potential traces of ancient earthquakes in defensive walls of the Bosporan city of Kytaia [28]. In this paper, we will further study this issue and

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☆ This paper discusses the deformations in the fortress walls and buildings of the Bosporan city of Kytaia. The ancient deformations in this city have been under study since 1970. Over these years, numerous deformations have been identified in different parts of this ancient settlement. This paper attempts to compare some of them with the damage caused by the Bosporan earthquakes, which are known from ancient written sources.

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Fig. 1. An overview map of the study area (top) and the map of ancient cities and active faults in the Kerch-Taman area (bottom), showing information as follows: 1 – archaeological monuments with the evidence of earthquake activity; 2 – active faults with the traces of seismotectonic movements; and 3 – active faults inferred from the structural and geomorphological data, active faults of the mud volcano type, and flexural fault deformations of Late Pleistocene and Holocene deposits and landforms.

provide an update for the previous findings and make some new insights according to updated data.

Based on archaeological data, the city was founded in the late 6th or early 5th century BC and existed until the second quarter of the 6th century AD. During the last years of its existence, the town played the role of a Byzantine fortress [36]. According to the ancient standards, Kytaia was a relatively well fortified city. Its defensive walls show numerous traces of damage. However, no signs of targeted wall damage from past military action have been identified yet in the exposed areas [36]. It is possible that some of this damage was caused by earthquakes that occurred in this region in the ancient time. The possibility of such natural processes in our region is evidenced by colossal cracks, ruts and scarps that cut the Mt. Opuk. According to the researchers who studied these deformations [26], they seem to be seismotectonic by origin, i.e. they were caused by the surface rupture(s) of a strong earthquake. Similar deformations are observed in abrasion-exposed Neogene-Quaternary deposits on the Black Sea coast, up to the Kytaia city. It appears that the archaeological site under discussion is located closely to a major seismogenic structure (see Fig. 1).

Since the Kytaia city stands on the very edge of a steep abrasion cliff up to 25 m in height and shows no signs of easy access to the sea or coastal structures, it suggests that a significant part of the city was destroyed by the abrasive action of the Black Sea. Marine abrasion is still very active today. Thus it is quite reasonable to infer that the abrasive process of cliff shaping was accompanied by major rockfalls and block slides and facilitated by earthquakes as clearly evidenced by specific damage patterns and deformations in the city walls and buildings.

2. Research methodology

We use both the archaeo- and paleo-seismic methods to identify and date the traces of strong earthquakes.

Archaeo- and historical seismology is aimed at discovering and parameterizing seismic events through analysis of ancient architectural monuments and written sources. The most reliable way to recognize seismic damage in architectural monuments is to find systematically oriented failures and deformations of structural elements. Systematic tilting, displacements, failures, and rotations of ancient structural elements that are typical for walls of certain trends, are kinematic indicators suggesting the seismic nature of deformations [8,11].

The paleoseismic approach is based on the idea that distant destructive earthquakes, often prehistoric, leave their traces on the ground surface — with geological evidence knowns as paleoseismic dislocations [37]. The main objective of such studies is to identify and examine all possible traces of seismic activation in young sediments and landforms — as primary seismotectonic ruptures indicative of surface faulting, landslides, rockfalls, etc. [38].

The above methods allow researchers to reconstruct the seismic history of a region in a step-by-step manner, and thus provide a fundamental basis for the assessment of actual seismic hazards.

3. Archaeoseismic studies

Buildings, walls and other structures built of cut stone or clay blocks or bricks form a system of geometric lines making rectangles, and allow researchers to determine the type and size of the deformations with an accuracy of a few degrees or centimeters. Set out below is the list of seismic damage patterns in building elements [8], equivalents of which were identified in Kytaia during our fieldwork.

Systematic tilting and collapse of walls as well as horizontal displacement (push-out) of individual building elements are the results of strong earthquakes. In such cases, the lower part of a building element moves together with the ground in the direction of the seismic action, while the upper part stays where it was due to inertia.

Rotations of individual blocks, bricks, stones or column pedestals (bases), as well as significant fragments of walls or entire walls, are common in seismically affected areas. Such rotation is caused by a force (shear) couple applied to a planar structure. The maximum seismic action that is parallel or perpendicular to the wall will result in collapse, displacement or tilting, without any rotation. Rotation only occurs in cases when the main forces are applied to the structure at a certain angle so that the resulting shear stresses are high. Therefore, rotated elements in/on perpendicular walls will show opposite directions of rotation if the seismic shock arrived along the bisector between two walls.

Cracks running through several adjacent wall blocks or even through the entire wall are indicative of a strong earthquake, because significant energy is needed for a crack to propagate through the space between the adjacent blocks. Of course, such cracks can also be caused by explosions or battering rams, but never by static load. Cracks that propagate along the boundaries of wall blocks or bricks can be produced by earthquakes, but also can be caused by static loading or ground subsidence.

It should be noted that the traces of a destructive earthquake at an archaeological site can become particularly obvious when there are many seismic damage patterns of many types, and when such deformations are younger than the original buildings and structures but older than the signs of subsequent repairs or overlapping structures.

The seismic damage patterns in the defensive walls of Kytaia have a number of distinctive characteristics, which are described as follows.

3.1. Tilted and displaced walls

Leaning walls are the first thing that strikes even an untrained eye in the Kytaia ruins. For example, in the eastern part of the excavation site I, three neighboring walls (##39, 27 and 15, see Fig. 50 in [36]) trending in a nearly N–S direction (with an azimuth of about 160°) are tilted systematically to the east at up to 71°. It should be noted that the walls #27 and #39 used to be parts of accessory building Γ, which were constructed in the second half of the 1st century BC, while the wall #15 was built much later, in the 4th century AD.

In the same part of the excavation site, another wall of the same orientation contains a fragment that is pushed outward entirely to the west by 6–7 cm (see the wall #1a). The upper stone rows show an even greater displacement — the upper wall fragment is displaced by 11 cm to the west with respect to the lower row. This wall is dated to the second half of the 3rd century BC.

A SSW-trending wall (with a 148° azimuth) is tilted at about 45°, with stone rows displaced up to 20 cm to the east (in a row-by-row manner), which is located in the *western part of excavation site I* west of the SW tower (see Fig. 2).

3.2. Rotations of wall fragments and individual blocks

The most striking example of such rotation was discovered in the SSE wall (60° azimuth) of the SW tower (*western part of the excavation site I*) [36]. Here, the lower row of 4 stone blocks is rotated counterclockwise by 14° (Fig. 2). During the rotation, the western corner of the rotated row was pushed outwards by 45 cm. The rotation process also affected, though to a lesser extent, the upper row. The upper row shows a displacement of 20 cm and a rotation angle of 5°. The tower is dated to the second half or the end of the 2nd century BC [39,40]. Therefore, it is quite possible that these tower deformations were caused by the 63 BC earthquake mentioned by Cassius Dio (XXXVII, 11) and Paulus Orosius (VI, 5, 1).

Three adjacent blocks rotated systematically counterclockwise were identified in the eastern face of the eastern city wall (*northern part of the excavation site IV*). The main trend of the wall is 160° and the rotation angle of the southern block is up to 8° (Fig. 3). The wall is dated to the late 4th century BC.

The eastern wall of the eastern gate tower (the *excavation site III*) was split in two parts by the strong seismic shaking whose orientation was perpendicular to the trend of the wall. The northern segment of the wall (with the azimuth of 150°), which is connected to the northern tower wall, did not have significant deformations, but the southern segment (an unsupported end near the gate) was rotated 10° clockwise and tilted to the west at 83°.

3.3. Through-wall cracks

Areas of significant seismic stress concentration that had triggered through-wall cracking were identified in the southwestern part of the city (the *excavation site I*) [36]. The NNW tower wall (with a 60° azimuth) has a crack that runs through two stones. A similar crack was discovered in the adjacent (in the east) wall with an azimuth of 148°.

It should be noted that there are traces of several earthquakes in some places. Logical, though indirect, indicators of multiple seismic movements are the signs of wall repair, buttresses and use of fine

Fig. 2. An on-site photo showing the location of the SSW-trending wall.

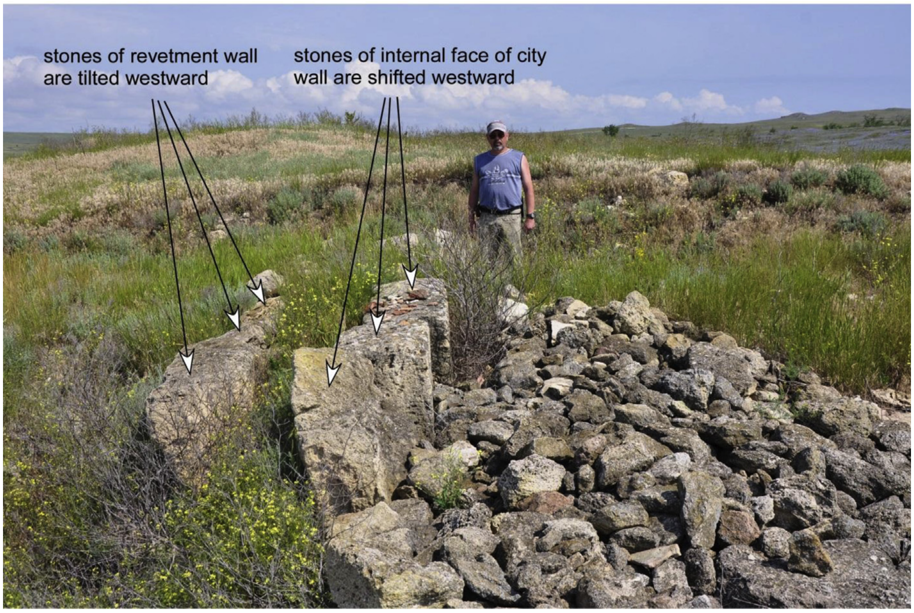

Fig. 3. The on-site photo of the stones of revetment wall and the stones of internal face of city wall, showing the main trend of the wall and the rotation angle of the southern block.

and expensive structural elements as wall patch-ups. For example, the eastern city wall shows traces of at least two strong earthquakes. The first earthquake damaged the western side of the wall as evidenced by the detachment and 74° westward tilting of four large facing blocks (Fig. 3). This strong earthquake is dated to the first half of the 1st century BC. To prevent the wall from collapsing, a crepidoma-type (with a stepped base) buttress was built on the inner side of the wall in the second half of the century (the *excavation site IV*) [36]. However, the buttress was also detached and tilted 51° to the west apparently during the second earthquake in the middle or within the second half of the 3rd century AD (based on the archaeological context). Traces of the coeval earthquakes have been identified in other Bosporan settlements, too [41].

Similar deformations are observed in the southern walls of the gate towers and in the city wall east of the towers (*the excavation site III*). These walls (with a 50° azimuth) appear to have been damaged seriously during the first earthquake (i.e., in the first half of the 1st century BC). As a result, the ancient inhabitants of Kitaya decided to reinforce these walls by crepidoma-type buttresses. The buttresses were attached to the southern sides of the walls. However, this additional support did not help much during the next strong earthquake.

Of interest is a well-cut block with rustication on the four sides in the internal, northern side of the southern wall of the western gate tower (*the excavation site III*, whose azimuth is 50°, Fig. 4). This block was used to repair the wall after the first earthquake and was apparently taken from the ruins of an important administrative building. However, this block became part of the lower 4-block wall fragment that was rotated 5° counterclockwise and tilted 85° to the north during the second earthquake.

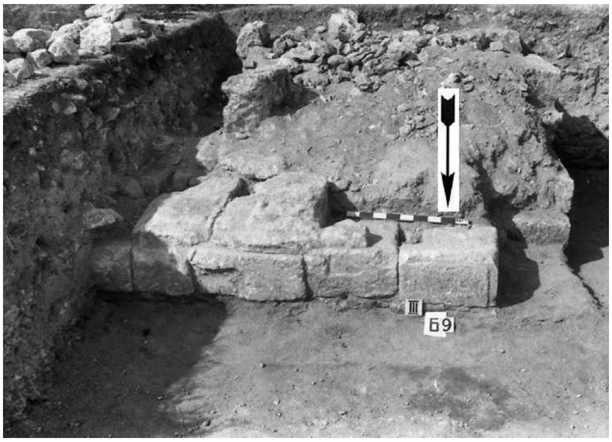

Fig. 4. The on-site photo of a well-cut block with rustication on the four sides in the internal, northern side of the southern wall of the western gate tower.

4. Paleoseismic studies

The Kytaia city is located on a high coastal cliff that exposes a continuous sequence of the Upper Miocene rocks. The sequence consists of three main parts (Fig. 5). The base of the sequence is composed of dark-grey argillites (clays), siltstones (aleurolite) with thin sandstone interbeds, and a thick (with the thickness of a few meters) limestone bed. The middle consists of interbedded light-colored and brownish-yellow shell limestones, marls, sands and clays with small bioherms. The top is composed of dark-grey clays and argillites with large bryozoan reefs. Based on geological mapping data, the upper member is of the Maeothian age and the other two are of the Sarmatian age.

Near Kitaya, deformations in the Miocene rock beds are concentrated within two relatively narrow areas. The city is located on a raised block of land between these deformations. The rocks within the block show normal bedding. The absence of the Late Pleistocene loess deposits in the city area, and their presence on the western slope of the raised block suggests that the block experienced tectonic tilting (or minor uplifting) in the Late Pleistocene or Holocene time.

In the west of Kytaia, the Miocene beds are folded into an anticline whose limbs are ripped by thrust faults. In the anticline limbs, ruptures are pronounced in relatively hard limestones only. In clayey rocks, deformations occur as disharmonic drag folds, minor slips and flow structures. In the hanging wall of the eastern thrust fault, limestone beds are folded into an asymmetrical anticline that bends the base of overlying Late Pleistocene loess deposits upwards (Fig. 6). The loess deposits contain a lens of coarse colluvial material that lies on the gentle limb of the anticline. This colluvium appears to have accumulated as a result of anticline growth before the loess deposition, i.e., during the Late Pleistocene time. There were more deformations later on, during or after the loess deposition, because the top of the colluvium layer is pulled onto the anticline top. The fold near the western thrust fault has a

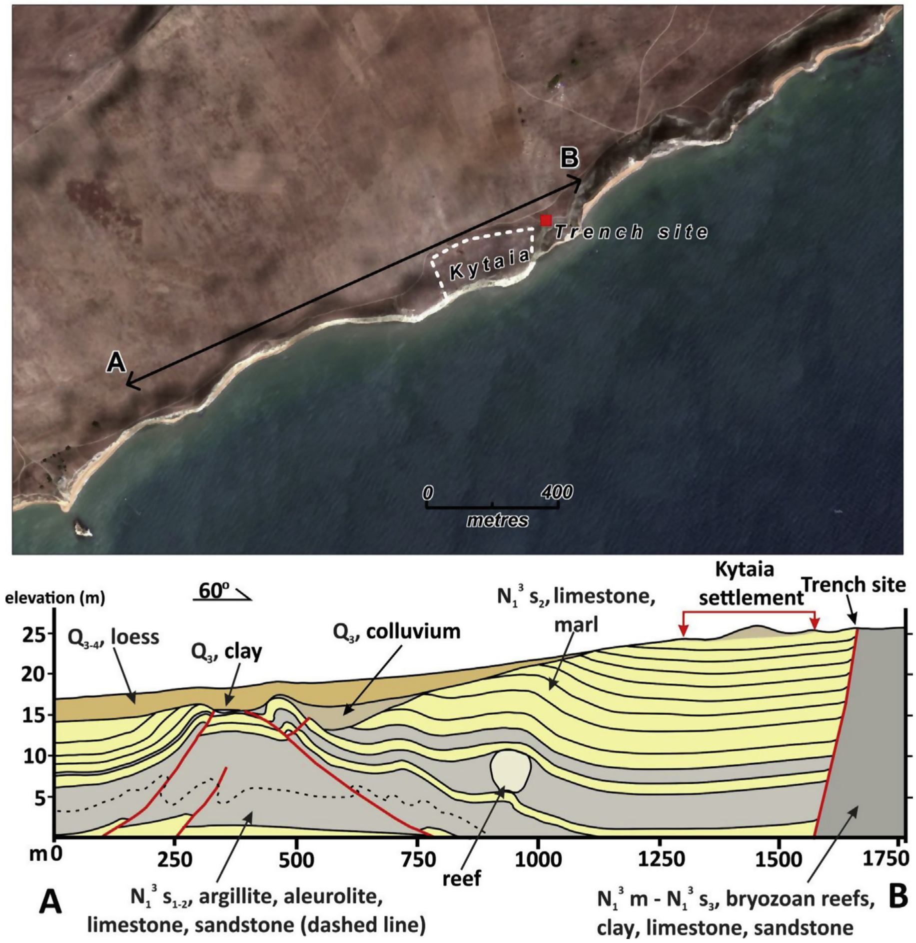

Fig. 5. Location map and geological cross section of the Kitaya city.

Fig. 6. The on-site photo of the near-thrust anticline southwest of Kytaia.

similar structure (Fig. 6). Between the thrusts, at the top of the major anticline, the loess deposits overlie, without any apparent break, laminated lacustrine-marine clays with shell fragments that are dated roughly to the Late (or Middle) Pleistocene.

Deformations also took place during the deposition of the Late Miocene rocks. This is evidenced by the changes in their thicknesses in conformity with the style of tectonic deformations.

In the east of Kytaia, there are signs of displacements that occurred in the Late Holocene time. In particular, within 30–40 m to the east of the city wall, the coastal cliff exposes a tectonic/fault contact between dark-grey clays and a member of rhythmically interbedded marls, clays and limestones (carbonate flysch) that comprise the lopsided block with the Kytaia city on it (see Fig. 7, for a general view). The rocks on both sides of the contact contain bryozoan reefs, with the largest ones (up to 20 cm in height) locating in the clay sediments. To the east of the fault, due to the presence of the clays, the coastal slope is covered by a continuous chain of landslides. The tectonic contact is exposed in the scarp of a landfall/landslide that is almost completely destroyed by the marine abrasion today. The fault plane dips steeply (by 70°–80°) to the west and strikes northwest at 340°.

The fault was examined in detail in a trench near the cliff edge (see the trench in Fig. 8). In bedrocks, the contact between the clays and the carbonate flysch forms a shear zone. The dip of the rigid limestone beds changes abruptly near the main fault plane and becomes steep, i.e., the beds are lifted up in this place. In the west of the shear zone, the same rocks show a shallow westward dip. In the bedrocks, the contact forms a narrow (with the maximum of 0.5 m) crush zone that splits into several ruptures (splay faults) in the loose sediments and soils. They extend upwards, broadening the fault zone without any visible extension and forming a “flower structure” that is typical for strike-slip faults.

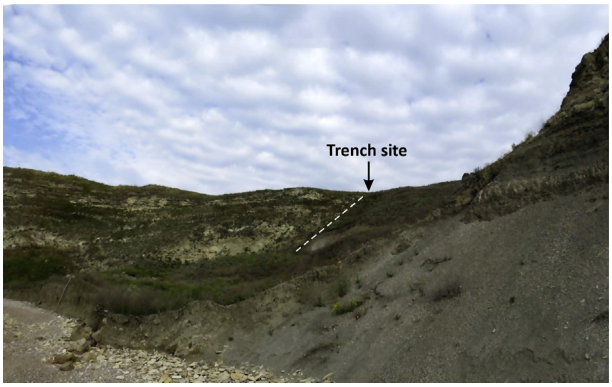

Fig. 7. The on-site photo showing the fault east of the Kytaia city wall.

The main characteristic of the loose sediments is that different fault walls show different sediment sequences. In the western wall, the layer of mature black (chernozemic) soil lies on weathered bedrocks (carbonate flysch). In the eastern wall, the black soils are overlain by a cultural layer that contains a ceramic fragment (dated to the 3rd century AD). Both the black soils and the cultural layer are cut by the fault and do not extent further. Among the diverging ruptures, there are 3 inclined lenses composed of the soil humus of different ages mixed with silty loams, bedrock clays and crushed limestone fragments. The lenses are torn by the ruptures, but do not show strong vertical displacements. Today, an accumulation of such material is possible only on the cliff slope covered by limestone fragments, scarce vegetation and thin soils, i.e., about 3 m from the trench site.

The relationship between the loose sediment layers suggests that the main displacements were horizontal. This is evident from the fact that different facies adjoin each other along the ruptures without significant vertical displacement, but with a pronounced change in thickness. For example, we can see that humus-bearing coarse fragmental deposits, which are typical of the cliff slope, adjoin mature soils with the cultural layer that accumulated on the flat ground a few meters away from the cliff edge. It can be assumed that these sediments were brought together by the displacements of the western wall to the north, i.e., the dextral strike-slip motion (see Fig. 9 for the trench layout).

The layers are displaced along the diverging ruptures over different lengths. Their thicknesses change abruptly between the ruptures. It appears that the displacements were caused by different events, and after each event a lens of humus-bearing coarse fragmental material started to form. There are three such lenses. Thus it can be inferred that there were at least three events (or movements) over the time of the black soil formation, with a total offset of 3 m or above. Considering that the cultural layer is displaced, it suggests that the last event took place in the 3rd century AD or soon thereafter.

Topographically, this fault is confined to the axial part of a NW-trending hill. Onshore, both the hill and fault are limited in size. The hill is 5 m high, up to 35 m wide and 300 m long. Its height decreases gradually away from the coast. The fold with thrust faults west of Kytaia shows a similar morphotectonic setting. These structures may be accompanied by a major fault zone that goes along the seacoast, where the South Kerch (Pravdinsky) active fault is demonstrated to locate based on geophysical data [42].

5. Conclusions

Our research results allow us to make the following conclusions:

1) Deformations in building structures within the ancient city of Kytaia (the tilted, displaced and rotated wall fragments and through-wall cracks) are seismic in origin.
2) The structure characters and deformation patterns indicate that strong earthquakes shook the city several times.

The evidence of the first earthquake (after the 3rd century BC) is that the northern defense line of the city was additionally reinforced — based on the pottery fragments of the 4th to 3rd centuries BC found in the stonework.

The second earthquake occurred before the reconstruction of the eastern city wall, which was reinforced with an additional

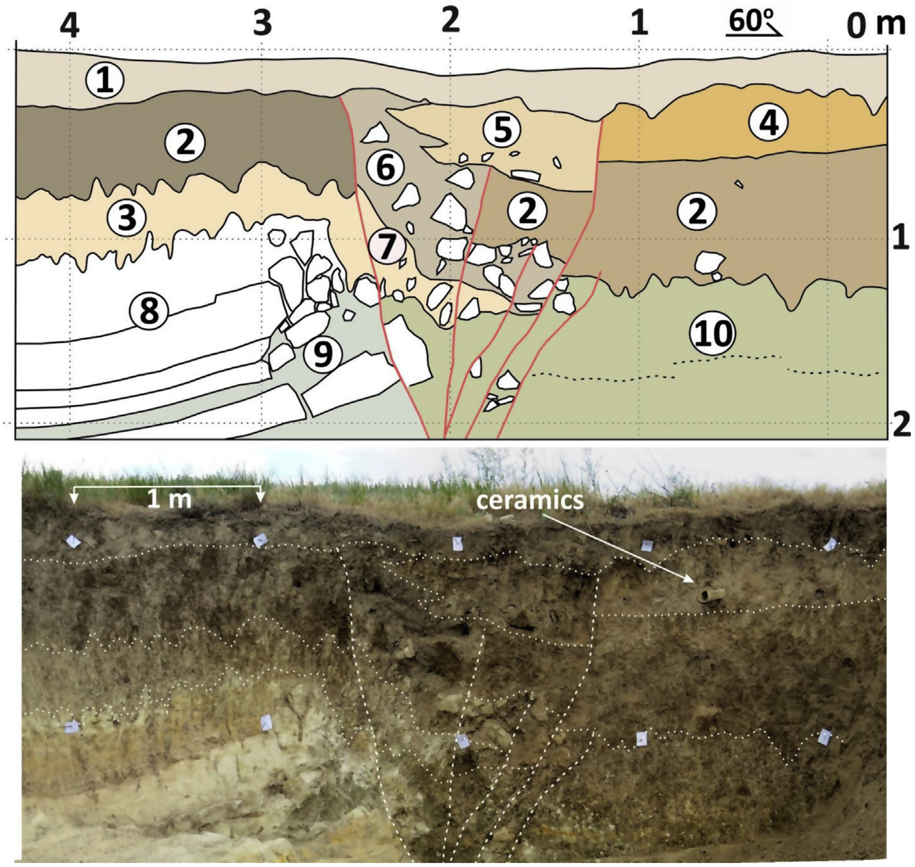

Fig. 8. The drawing (top) and on-site photo (bottom) of the trench in the fault zone west of Kytaia. 1 – modern silty soil; 2 – black/chernozemic soil (humus horizon); 3 – weathered humous clay (lower soil horizon); 4 – fine sand with ceramics (cultural layer); 5 – silty loam; 6 – redeposited, unconsolidated black soil with limestone fragments; 7 – redeposited humous clay with limestone fragments; 8 – detrital limestone (weathered to sand-size particles at the top); 9 – dark-green clay; 10 – dark-grey and greenish clay with thin interbeds of detrital sand (dashed line).

Fig. 9. The on-site photo showing the trench layout in the fault zone east of Kytaia.

protective layer dated to the middle or second half of the 1st century BC. Fragments of the tombstones dated to the 4th to 3rd centuries BC were also used in the stonework. This could be due to the 63 BC earthquake.

The city walls may also contain traces of the third strong earthquake, after which the tower walls were fortified with additional protective layers in the end of the 3rd century AD.

3) The unsystematic distribution of seismic damage patterns in the Kytaia walls suggests that the epicenters of the ancient earthquakes were very close to the city and that the vertical component was predominant.
4) In the east of Kytaia, there is a tectonic fault/rupture showing the evidence of one-time displacements during the Late Holocene time. The latest displacement is dated to the 3rd century AD or very shortly thereafter. This fault splays from a major fault zone that goes along the seacoast, where the South Kerch (Pravdinsky) active fault locates based on the indication from geophysical data.
5) The intensity of the ancient earthquakes is estimated to be ≥ 9 on the MSK-64 scale.
6) The above data are recommended to be used in the development of a new Seismic Map of Crimea.

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