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Traces of Strong Earthquakes in Ruins of the Afrasiab Archeological Site (Samarkand, Uzbekistan)

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Abstract—We revealed traces of two earthquakes of the 10th and 12th centuries at six objects of the Afrasiab archaeological site. These traces include numerous ruptures and fractures that form a "flower" structure, a subsided graben, and the slopes and turns of fragments of fortress walls. The type of the deformation indicates that the epicenter of the earthquake of the 10th century was located to the west-southwest of the ancient city; the epicenter of the earthquake of the 12th century was to the south-southwest of it. The intensity of both events was VIII–IX points on the MSK-64 scale.

Keywords: Afrasiab, Samarkand, consequences of strong earthquakes, Zeravshan ridge
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INTRODUCTION

Ruins of the ancient city of Afrasiab, the capital of Sogd (Sogdiana), are located in the Zarafshan Valley on the territory of Samarkand. It was founded no later than the 8th century B.C. and was a center of industry, trade, science, and culture. The Arab geographer Ibn Haukal, who visited Samarkand in the 70s of the 10th century, described its squares, houses, streets, ponds, parks, and gardens with admiration. Unfortunately, Ibn Haukal saw destroyed houses and the ruler's palace in the citadel (Betger, 1957). There were no serious political events and enemy attacks in Samarkand in the second half of the 10th century. Therefore, the destruction of the city could be connected with some natural cataclysm, apparently, with a strong earthquake. To verify this assumption, we made archeological excavations at six objects in the citadel and inside the second wall of Afrasiab and recorded traces of two earthquakes of the Xth and XIIth centuries using archeoseismological methods.

MATERIAL AND METHODS

This work is based on the traditional method of arheoseismological research, which is thoroughly described in the monograph (Archaeoseismology, 1996), as well as in the works published in the last decade by foreign specialists, for example (Martín-González, 2018, 2021; Liritzis et al., 2019). Our group has also contributed to the development of a methodology of field research, especially in terms of the use of kinematic indicators of deformations in relation to damage and destruction of ancient building structures (Korzhenkov, Mazor, 1999; Korzhenkov et al., 2020). Field archeoseismological observations were carried out at six objects in the ruins of the ancient city of Afrasiab (Fig. 1). We described the deformations of the building structures, estimated their age, and determined the kinematic characteristics of seismic events and their intensity based on the type of destruction. Special attention has been paid to through fractures penetrating several blocks/bricks in a row, as well as to

Fig. 1. An aerial photo of Afrasiab: objects 1–2–citadel (donjon), remains of the wall of the 9th–10th centuries with traces of the earthquake of the 10th century; object 3, the southern wall of the citadel with traces of the earthquake of the first half of the 12th century; object 4, the pahsa wall to east of the citadel with traces of the earthquake of the first half of the 12th century, object 5, remains of the fourth fortress wall with traces of the earthquake of the first half of the 12th century; object 6), remains of the second fortress wall with traces of the earthquake of the 10th century.

branching fractures coming from a single fracture, because such fractures are mostly associated with earthquakes.

RESULTS AND DISCUSSION

It is difficult t to find any seismic inertial deformations in the archaeological excavation through the building structures made from pahsa. Nevertheless, we found a fragment in the wall of a submeridional trench through the second pahsa wall of Afrasiab (Fig. 2), which tilted at a significant angle and turned clockwise around a vertical axis. Such deformations occur during strong seismic movements, when the lower part of a structure moves with ground, while the upper part of the structure remains in place due to inertia forces. The visible dimensions of the deformed wall fragment are as follows: the width is 85 cm, the height is 80-85 cm, and the thickness (considering neighboring pahsa blocks) is 92–100 cm. It should be noted that we accidentally discovered the studied plane in the old excavation because a neighboring pahsa block, which was also deformed, fell out.

The strike of the rotated block is 8°–10°, and the strike of the outer (southern) facade of the second southern wall of the city is ~90°. Thus, rotation of the deformed fragment of the building structure was about 9° clockwise. The very significant tilt of the fragment at an angle of 60°–61° is impressive. It tilted along an azimuth of 278°–280° (to the west); this is where the strongest seismic movements apparently came from, resulting in such significant and complex deformation. The deformed wall is 500 to 800 years old; thus, the time of the seismic event responsible for the seismic dislocation is older. It is important to mention that earlier we described a similar tilt and rotation of a significant pahsa block, which was detected in the antechamber tower in ancient city of Kyrkhujra in the Fergana Valley. (Korzhenkov et al., 2020).

It is known that during strong earthquakes, the upper parts of high-rise buildings have a greater amplitude of vibration than the lower parts. Accordingly, the

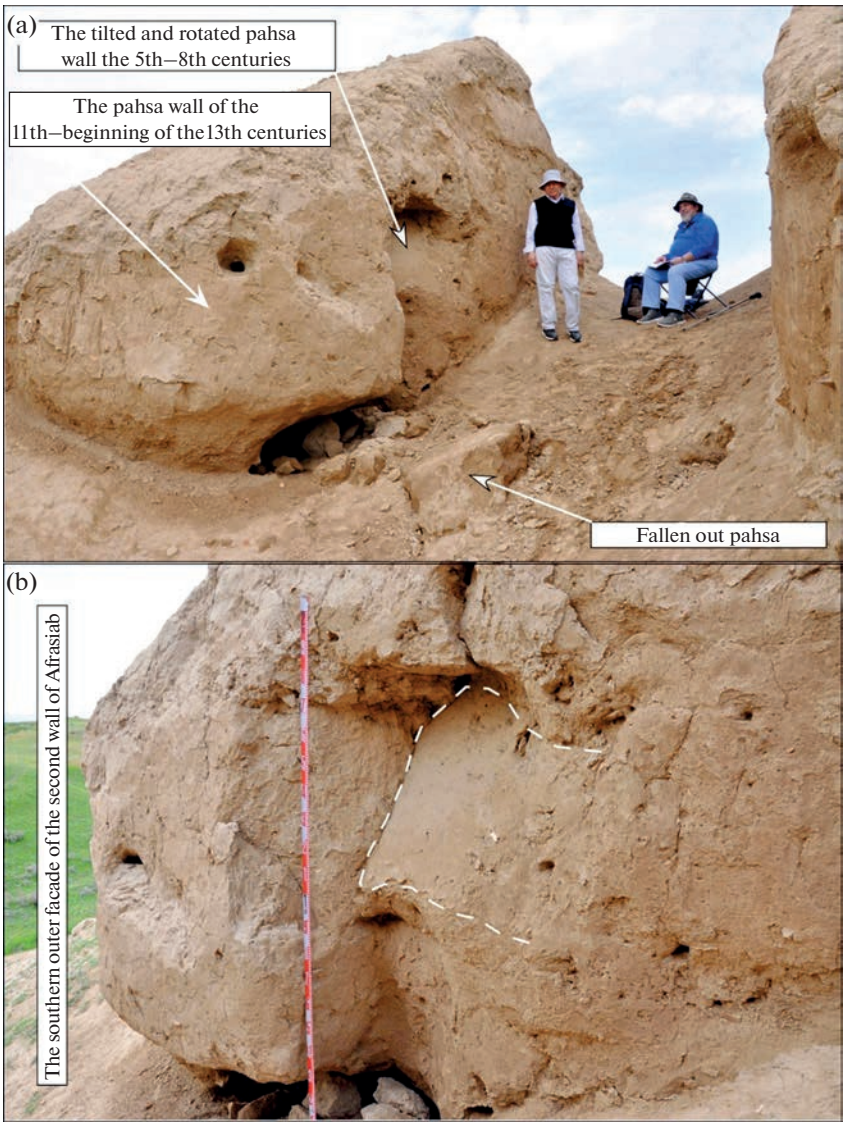

Fig. 2. The tilt and turn of pahsa in the second wall of Afrasiab (object 6 in Fig. 1). *A*, general view to the northwest, *B*, close view to the southwest. Length of measuring tape is 2 m. Photo, 2023.

degree of damage and destruction increases upwards with each floor. This is called the "skyscraper effect." However, it is not only the upper parts of skyscrapers that demonstrate the maximum damage. Natural objects, such as long ridges, also experience the maximum vibrations in their upper parts resulting in the formation of contiguous grabens. For example, during the Suusamyr earthquake in the Northern Tien-Shan in 1992 with magnitude 7.3 and intensity IX–X MSK, a stepped bilateral graben was formed in the watershed part of the Chet-Korumdy intra-fold rise (Korjenkov et al., 2004). A similar mechanism apparently acted during the formation of a small bilateral graben in the central part of the southern wall of the Afrasiab citadel.

The eastern plane crosses the pahsa layers, while the western plane separates the pahsa masonry and the "shirt," that is, the outer shell of the wall made of raw bricks. The distance between the adjacent breaks is 70 cm, the displacement along the western one is 1.5 cm. The residual height of the citadel wall rising above the adjacent shakhristan to the west is 15 m (Fig. 3). Such unilateral normal faults lead to the downward displacement and collapse of significant fragments of walls. We observed such a mechanism in one of the walls east of the square in front of the citadel. Here, the 13° pahsa wall has significant damage in its outer (western) part. The outer parts of the wall have cracked to the west, and the upper part has collapsed in the same direction (Fig. 4).

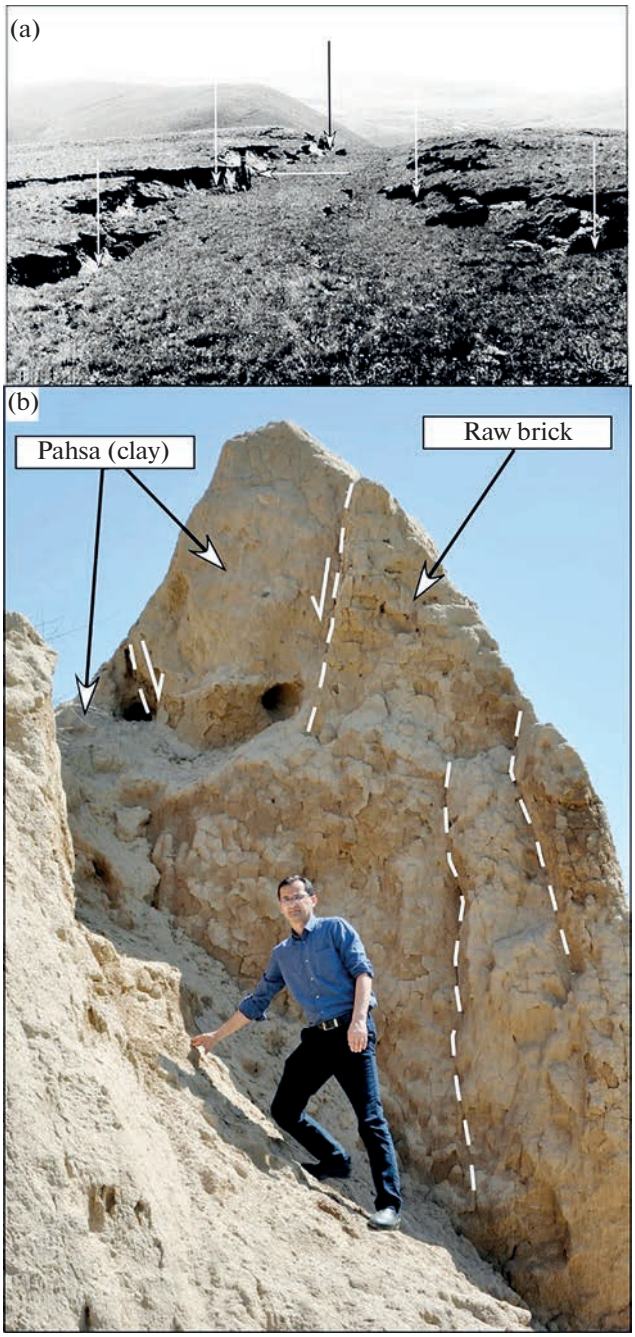

Fig. 3. Formation of bilateral grabens during seismic events. *A*, graben in the watershed part of Chet-Korumdy Ridge, formed during IX–X-ball Suusamyr earthquake 1992 in Northern Kyrgyzstan, from (Korjenkov et al., 2004) with additions. Photo of 1993. View to the east. Vertical arrows show the outcrop of normal-fault planes to the surface, horizontal arrow shows a human figure in an open fracture. *B*, graben in the southern wall of the citadel in Afrasiab with traces of the earthquake of the first half of the 12th century (object 3 in Fig. 1). View to the north. Dashed lines show ruptures, one-sided arrows show direction of displacement along them. Photo, 2022.

The branching fractures, coming out of a single rupture, are of great interest to specialists in archaeoseismology. These, so-called "flower" structures, result from shear stresses on both sides of a fracture ensemble. Most often, "flower" structures are upward branching fractures. However, some of them are factures branching downward.

For example, in the southeastern corner of the shakhristan of the Kyrkhujra on hill III, a significant part of the corner of the building structure collapsed outward during a strong earthquake (Korzhenkov et al., 2020). In the resulting outcrop, we found a structural ensemble composed of several small fractures-ruptures, that is, the "flower" structure. We also studied a similar structure in the corner formed at the junction of the northwestern city wall of Afrasiab and the eastern slope of a dry sai cutting the above-mentioned wall. The northwestern wall of the city is bounded by a ditch, through which waters of the Sieb River flow. The strike of the river and the canal is 110°. The extension of the sai is almost perpendicular, about 35°. Along the ruptures that form the "flower" structure, there is a lateral stepped extension of each plate on the first tens of centimeters according to the rule of left shift (Fig. 5).

In addition to the "abnormal" (reversed) "flower" structures, there are many

normal "flower" structures, often located next to each other. They are evidence of significant lateral shear movements parallel to a strike of the massive pahsa walls. For example, a number of "flower" structures can be seen in the trench through the western wall of the donjon (Fig. 6). The azimuth of the western facade of this wall is 170°. The strike of the trench is 80°. The azimuths of the fractures composing the mentioned "flower" structures have a submeridional trend, falling within the range of 10°–16°.

In extended archaeological trenches, a complex of both brittle deformations and plastic subvertical zones is quite common (Fig. 7). Similar fracture-ruptures are observed in the perpendicular wall attached to the south wall of the donjon of Afrasiab; they compose graben-like and "flower" structures. These brittle fractures alternate with buckling zones of the first tens of centimeters thick. It is not quite clear why brittle deformation occurs under significant stresses in some cases and plastic deformation in others. Perhaps, this can be explained by the specific features of the construction structure and the density of pahsa ramming. An interesting peculiarity was noted at the site. Our measurements of the strike of the fractures cutting the investigated wall showed a gradual increase in the values from 90° to 120°. This may indicate a gradual turning of the whole wall around the vertical axis by 30°.

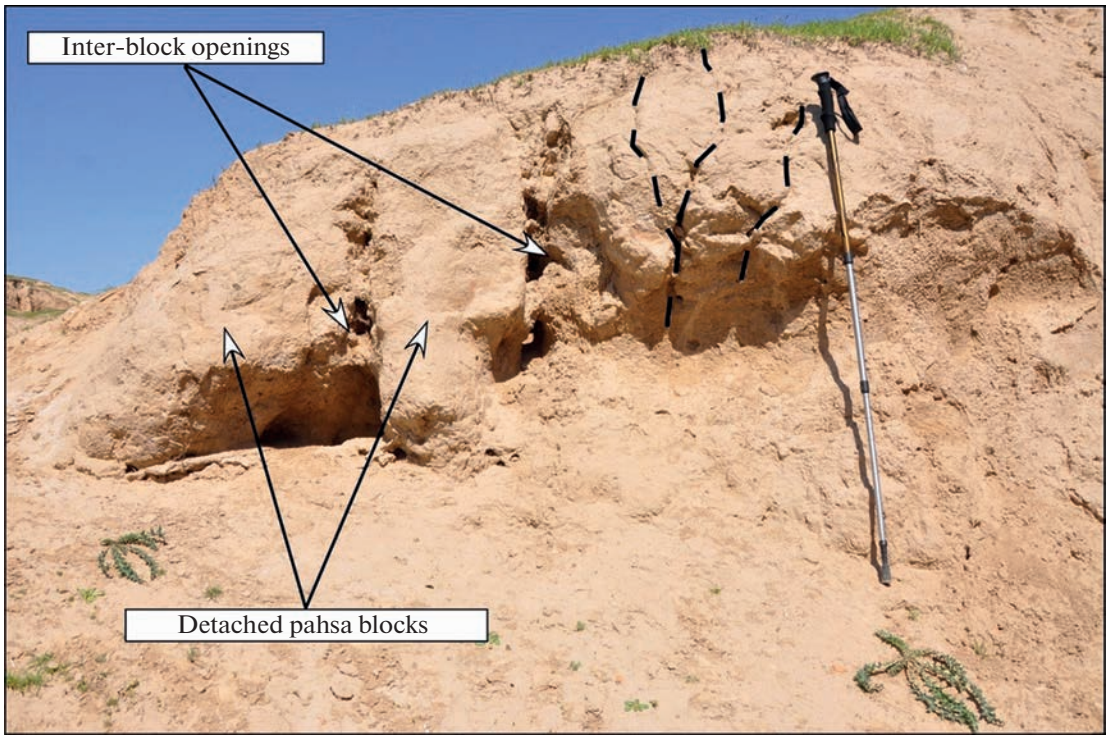

Fig. 4. Peeling and detachment of the outer parts of one of the walls to the east of the square in front of the citadel along the normal fault ruptures /fractures (shown with dashed lines) (object 4 in Fig. 1). Traces of an earthquake in the first half of the 12th century. The length of the track stick is 1.1 m. View to the north. Photo, 2022.

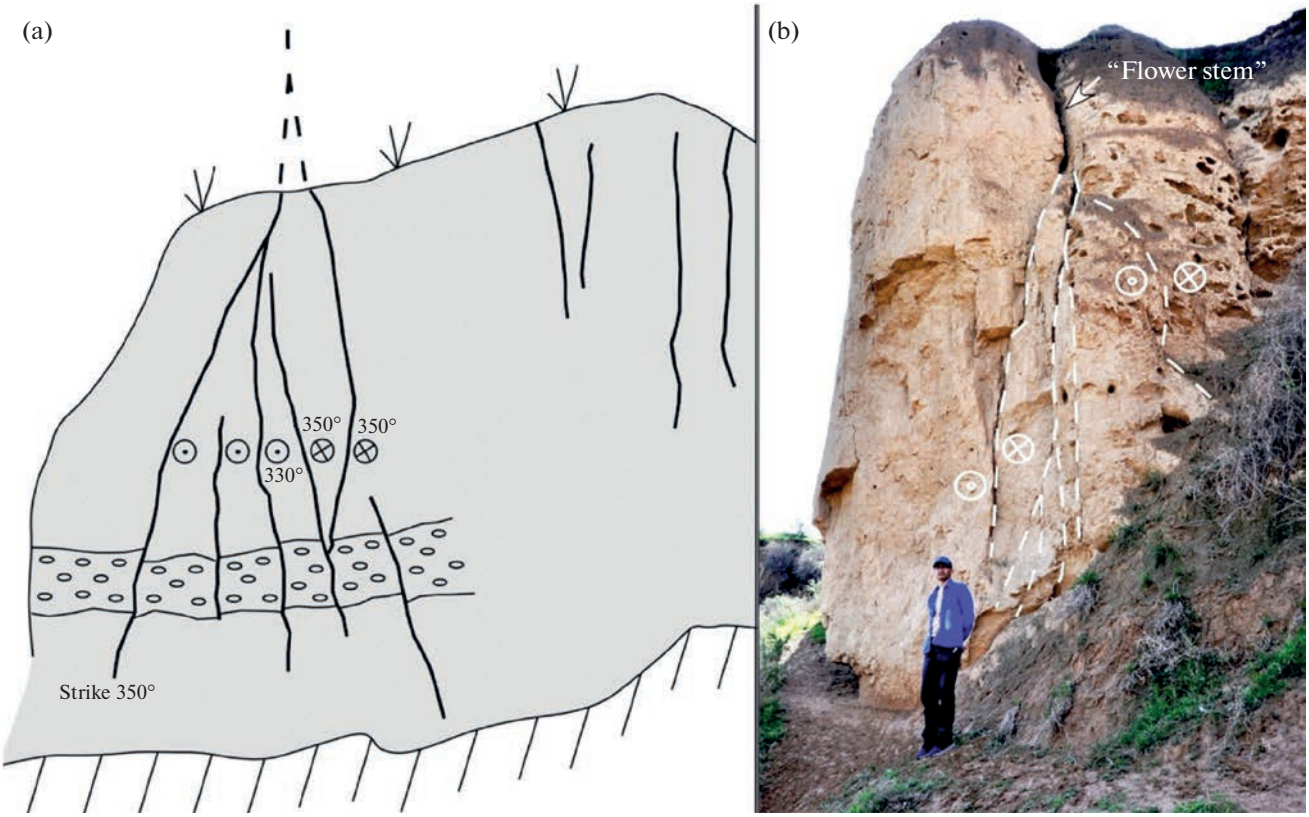

Fig. 5. The "flower" structure of fractures opening downward and indicating shear displacements along them. Circles with a dot show the movement of the block toward the viewer. Circles with crosshairs show the removal of the block. *A*, the southeastern corner of the first shahristan structure of the ancient city of Kyrkhujra. A schematic out-of-scale sketch (Korzhenkov et al., 2020). *B*, Northwest corner in the northeast part of the quarters of the city wall of Afrasiab (object 5 in Fig. 1). Remains of the fourth fortress wall with traces of the earthquake of the first half of the 12th century. Photo, 2023. View to the east.

Fig. 6. "Normal" flower structures (shown in dashed lines) in the northern wall of the trench through the western wall of the donjon (object 1 in Fig. 1). Remains of the wall of the 9th–10th centuries. Traces of the earthquake of the 10th century. Figures indicate the places where fracture strikes were measured. The length of the measuring tape is 2 m. Photo, 2023. View to the northwest.

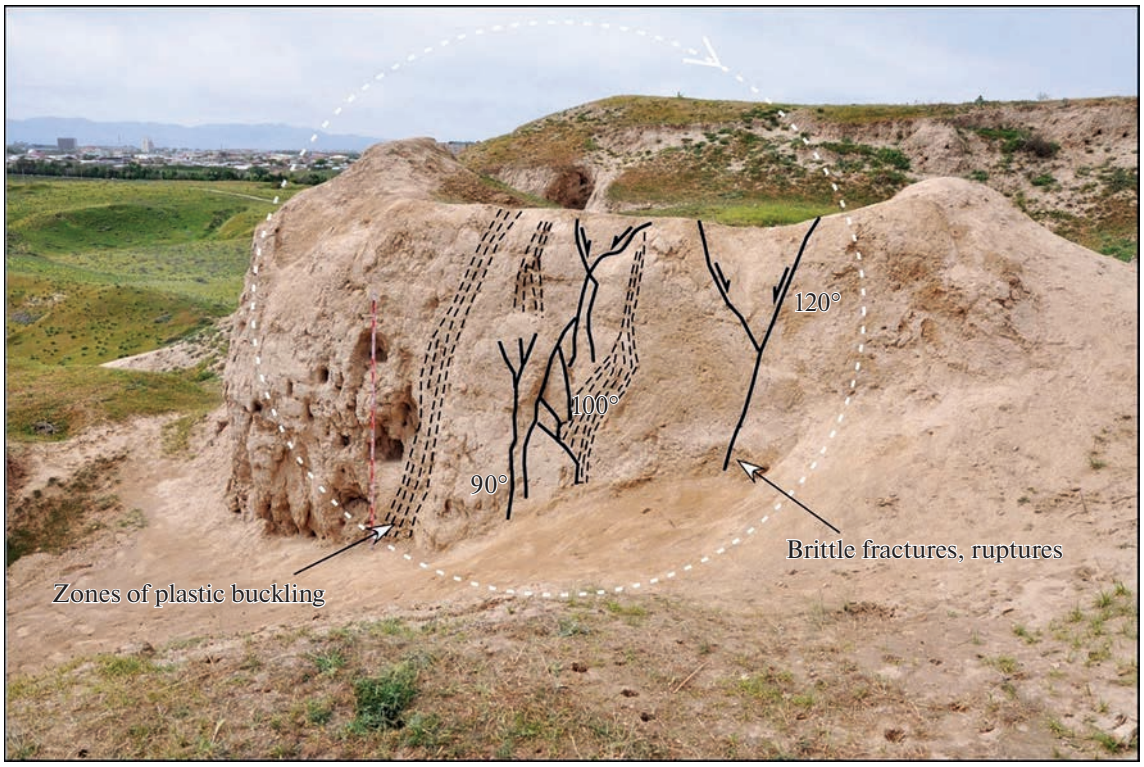

Fig. 7. A perpendicular wall (object 2 in Fig. 1). Remains of the wall of the 9th–10th centuries attached to the south wall of the donjon have brittle (bold solid lines) and plastic (dashed lines) deformations. Traces of the earthquake of the 10th century. It is possible that the whole wall gradually turned clockwise: circle is shown by dashed line. The length of the measuring tape is 2 m. Photo, 2023. View to the southwest.

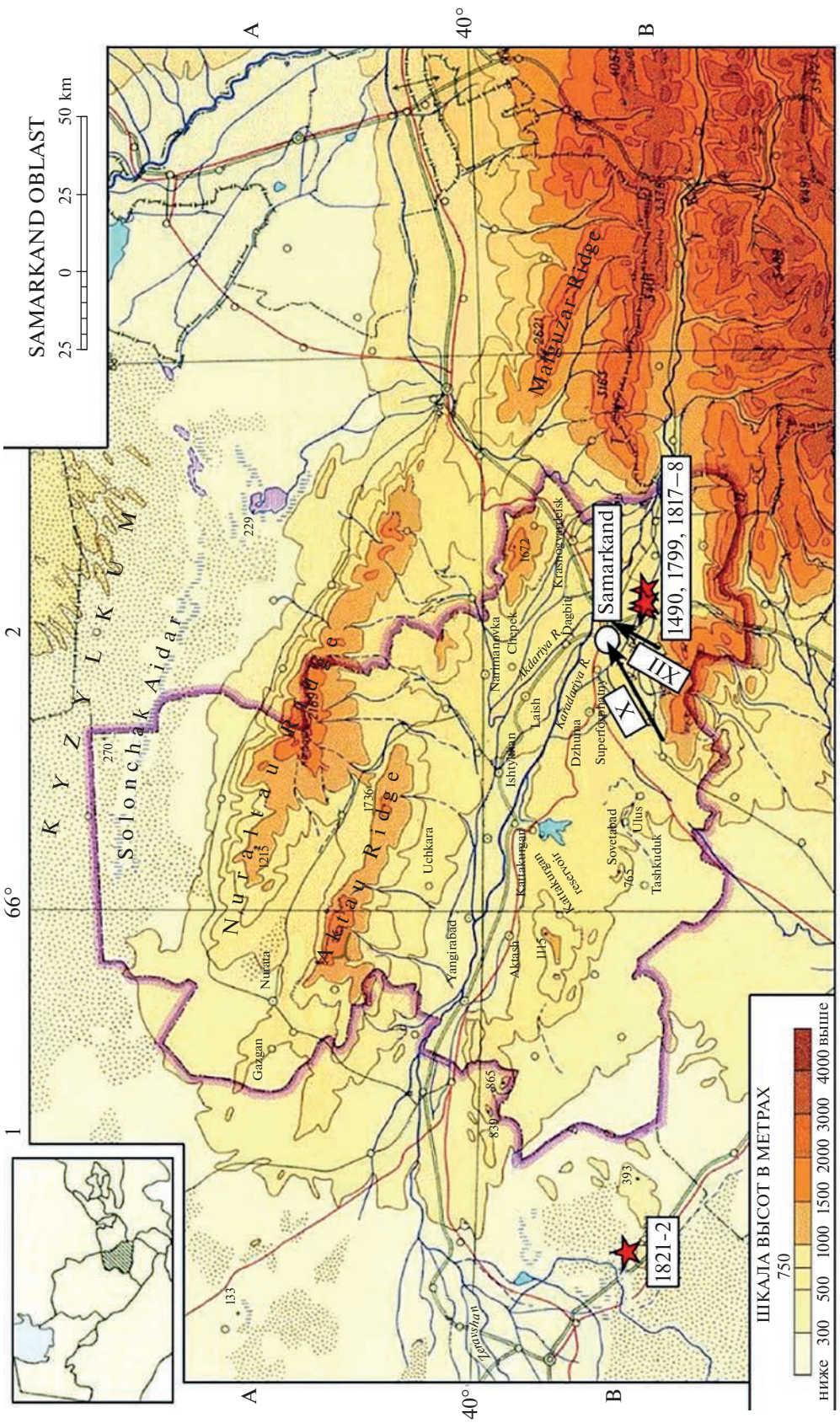

Fig. 8. A topographic map of Samarkand oblast of Uzbekistan. Stars designate epicenters of the strong known earthquakes according to (*New...*, 1977); the years of the seismic events are next to them. Arrows come from the central parts of epicentral zones of the strong earthquakes of the 10th–12th centuries.

CONCLUSIONS

Six objects of the city have traces of two earthquakes of the 10th and 12th centuries. The deformations of objects nos. 1, 2, and 6 affected the walls built before the 10th century. The damaged fragments of walls have a tilt to the west and, at the same time, rotate clockwise around the vertical axis (nos. 2, 6). This means that seismic vibrations came from the west-southwest, that is, the epicentral zone of the earthquake of the 10th century was located to the west-southwest from Afrasiab, at the location of the western lateral opening of the Zeravshan Ridge pericline. Data on deformations of walls erected before the 12th century at points nos. 3–5 indicate vibrations along the submeridional axis (no. 3), as well as delamination and collapse of the wall to the west (no. 4). These facts point to a location of the epicentral zone of the ancient earthquake to the south-southwest from Afrasiab. The migration of strong earthquake sources along the northern front of Zeravshan Ridge (mega-anticline) in the eastern direction is interesting: it occurred from its western end in the 10th century to the epicentral zone of earthquakes in 1817–1818 at a distance of 50 km (Fig. 8).

Taking into consideration the strong deformations of the most important and capitally built structures of Afrasiab, the degree of the described destruction can be estimated as I = VIII–IX according to the MSK-64 macroseismic scale.

These data allow us to extend the catalog of the strong earthquakes in the region into the depth of centuries and to estimate more reliably the recurrence and migration of the strong seismic catastrophes, as well as to again asses the seismic hazard of the region using data of archeoseismology.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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