Methods and results of long-term strong earthquakes forecast in the Uzbekistan territory

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Abstract. An approach to evaluate the current seismological situation in the Uzbekistan territory is presented. This approach is based on the regularities of seismic processes in strong-earthquake focal areas and the manifestation peculiarities of strong earthquakes in seismically active zones. At the first stage, within seismically active zones, areas with a high seismic activity matching the strong earthquake level were identified during the historical and instrumental observation periods. Considering the low variability in the direction of seismotectonic processes over tens and hundreds of years, which determines the modern stress state of seismically active structures, these areas were considered the most likely areas to experience strong earthquakes over the next few decades. Tectonophysical validation of the division of seismically active zones into areas with different potential hazards of strong earthquakes was carried out within the framework of cataclastic analysis method of rupture dislocations (CAM). At the second stage, temporal fluctuations in seismic regime parameters within the selected areas were studied. Based on the number of current anomalous features identified, the areas were ranked according to the occurrence probability of strong earthquakes over the next few years.

1. Introduction
The Uzbekistan territory is characterized by a complex tectonic structure and a high level of seismic activity. Both the historical and instrumental observation periods are marked by numerous earthquakes with a magnitude of $M \geq 7.0$ and a shaking intensity at the epicentre of $I \geq 9$ on the MSK-64 scale. Therefore, the problem of the seismic safety of the population and industrial and civil construction objects is very relevant. Among the anti-seismic measures aimed at reducing the consequences of natural elements, along with the development of maps of seismic zones of different scales, active work on earthquake prediction is carried out in the Republic of Uzbekistan. To date, many algorithms for long-term prediction of strong earthquakes based on the analysis of seismic regime parameter temporal fluctuations prior to strong earthquakes have been developed for various seismically active regions. However, each of these algorithms must be adapted to the regional peculiarities of the seismicity of the territory for application purposes. An approach to determine areas likely to experience seismic activity in the territory of Uzbekistan, which has been developed in real time over the last few years, is presented in the article. Analysis of existing long-term forecast maps developed...
in 2015 and then updated in 2017 within the framework of the outlined approach verifies their high informative value. An overwhelming number of strong earthquakes \( (M \geq 5.0) \) will likely occur in areas where the occurrence probability is estimated as high and very high.

2. **Source data and methods of analysis**

Figure 1 shows a map of earthquake epicentres in the study area constructed in accordance with a regional catalogue compiled at the Institute of Seismology, Academy of Sciences of the Republic of Uzbekistan. The energy class of earthquakes \( K \) was adopted as a basic characteristic of earthquake classification by size up to 2003 based on the regional catalogue [1]. The relationship between the earthquake energy class \( K \) and magnitude \( M_b \) considered hereafter was determined on the basis of [2] Central Asian earthquakes. The distribution of earthquake epicentres by area is very uneven (Fig. 1). To the east of the West Tian Shan lineament, which is the border between the Tian Shan mountain structures and the plain territory of the Turan plate, the seismic activity at both the level of weak and moderate seismic events (the blue circles on the map) and at the level of strong earthquakes (red circles) is very high, and the seismic activity to the west of this lineament is low. The increased density of strong-earthquake epicentres in western Uzbekistan is characterized by the regions of Gazli and Bukhara. Several strong earthquakes were observed in the area of Central Kyzylkum.

**Figure 1.** Map of earthquake epicentres in the study area with indications of the seismically active zones and areas with high concentrations of strong-earthquake epicentres during the historical and instrumental observation periods.

The overwhelming majority of strong earthquakes occurs in rather narrow extended seismically active zones, the direction of which coincides with the strike of large deep faults in the Earth crust. On the basis of seismological and seismotectonic data [3, 4], ten seismically active zones are distinguished within the investigated territory (Fig. 1): Tashkent (1), South Fergana (2), East Fergana (3), Angren (4), North Fergana (5), South Uzbekistan (6), Amudarya (7), Gazli-Karataq fragment of the South Tien Shan seismactive zone (8), North Tamdjin (9) and Talas-Fergana (10).

Analysis of the spatial location of the epicentres of strong earthquakes \( (M \geq 4.7, K \geq 12.6) \), which have occurred in the territory of Uzbekistan since historical time, revealed that they are not evenly
distributed across the above seismically active zones but are concentrated in the form of clusters in areas with linear dimensions from 50–80 km. These clusters are shown on the map of the epicentres (Fig. 1) as ellipses of different sizes. Comparing the constructed maps of strong-earthquake epicentres between the different time intervals (before 1900 and since the instrumental observation period), one can note that the identified areas are quite stable in regard to their configuration. Considering the low variability in the direction of seismotectonic processes over tens and hundreds of years, which determines the modern stress state of seismically active structures, these areas of intense crustal crushing are the most likely to experience strong earthquakes over the next few decades.

The physical nature of the concentration of strong earthquakes in compact regions may be related to the fact that the locations of rupture cessation during past earthquake events are additional stress concentration areas. Therefore, subsequent movements, with increasing tectonic stresses in seismically active zones, are the easiest to realize in these areas [5, 6].

Tectonophysical interpretation of the division of fault zones into segments characterized by different potential hazards of large-scale fractures is achieved within the framework of the cataclastic analysis method of rupture dislocations [7]. This is based on the study of the relative values of the maximum shear stresses and the effective confining pressure (the difference between the pressure in rock and the fluid pressure in the fracture-pore space: \( p^* = p - p_{fl} \), where \( p = -(\sigma_1 + \sigma_2 + \sigma_3)/3 \)).

3. Results and discussion
Reconstruction of the natural stress state of the Earth crust in the territory of Uzbekistan by CAM algorithms was carried out on the basis of the compiled catalogue of the focal mechanisms of earthquakes. As a result of the performed inversion of parameter averaging at different area detail levels and various magnitude scales of the considered earthquakes, the azimuthal and dip angles of the axes of the principal stresses, Lode - Nadai coefficient, geodynamic type of the stress state, and relative (normalized to the rock cohesion strength of rock massifs) values of the maximum shear stresses and effective confining pressure were determined [8].

**Figure 2.** Projections onto the horizontal plane of the principal stress axes.

Figure 2 shows projections of the principal stresses onto the horizontal plane based on the reconstruction results performed at the generalized detail level (using a 0.2×0.2° grid, with a minimum uniform sample size consisting of five determinations of earthquake focal mechanisms in each domain.
and variations in the radius of the circular region to form uniform samples ranging from 15 to 60 km in size). The same Figure shows the active crustal faults according to [9].

The dip angle of the minimum-compression axis $\sigma_2$ varies greatly among the different sections of the study area, ranging from a vertical dip in the territory of southern Uzbekistan and certain sections of the Bespan and South Fergana faults to an almost horizontal dip in the Alai valley behind the mountain range of the same name. The variations in the dip angle of the principal compression stress axis $\sigma_3$ within the study area are significantly lower. In most of the territory, this axis is near-horizontal. In most cases, the strike of the maximum-compression axis is practically perpendicular to the strike of the structures. This feature does not apply in the southeastern part of the Talas-Fergana fault, where the directions of the $\sigma_3$ axis and the fault practically coincide.

In the territory of the Turan Platform (western Uzbekistan) and within the transition zone from the orogen to the platform (Tashkent region), the prevailing direction of the maximum-compression axis $\sigma_3$ is the southeastern direction. In the orogenic part of the study area (eastern Uzbekistan), the direction is near-meridional.

Analysis of the area distribution of the Lode-Nadai coefficient indicated that in the entire study area, the domains are predominantly characterized by a state close to the simple shear state ($-0.2 < \mu_\sigma < 0.2$), and the predominant geodynamic type of the stress state of the crust is the horizontal compression mode [8].

![Figure 3](image).

**Figure 3.** Area distribution of effective pressure normalized to cohesion strength ($p*/\tau_f$) for the reconstruction performed for earthquakes with a depth $H > 10$ km with a minimum uniform sample size $N \geq 6$ and a maximum circular area radius to form a uniform sample $R \leq 30$ km.

An important result of the analysis of the inversions is the established significant differences in the stress state parameters for different deep layers of the Earth's crust [8]. Thus, for the seismic active layer below 10 km, within which the strongest ($M \geq 5.0$) earthquakes occur, areas with different values of relative values of effective pressure $p*/\tau_f$ ($p*$ values normalized to the cohesion strength of rock massifs $\tau_f$) are well structured and alternate between itself (Fig. 3). In studies [7, 8, 10, 11, etc.] strong earthquakes, as a rule, occur in areas with low values of effective confining pressure and maximum shear stresses. Such areas are characterized by reduced values of frictional forces on the ruptures, which creates favorable conditions for large-scale fracture. As shown in Fig. 3, in the territory of eastern Uzbekistan, the extended areas within the South Fergana and North Fergana faults and the
same-named flexural fracture zones are characterized by reduced values of effective pressure $p^*/\tau_f$. In the western part of Uzbekistan, lower $p^*/\tau_f$ values are noted in the Gazli origin zone. Thus, alternation within seismic active zones of connected area formations with reduced values of effective confining pressure $p^*/\tau_f$ corresponds well enough with the previously noted features of area grouping in compact areas of epicenters of strong earthquakes, which occurred during historical and instrumental time periods. Further investigation of the current seismological situation within the seismically active zones was conducted by analyzing a set of prognostic parameters of the seismic regime, which characterize the kinetics of the focal area fracturing process as the main moment of rupture is approached [6, 12]. For this purpose, we calculated the average long-term values of the seismic regime parameters at each point within the seismically active zones and identified areas where significant anomalies currently occur. The following seismic regime parameters of prognostic value were considered [4–6, 12]:

- the total number of representative earthquakes and the number of earthquakes of different energy levels occurring at each point within the seismically active zones per time unit to identify areas of seismic activation and seismic quiescence and areas where the effects of the so-called ring activity are currently observed [5];
- the temporal variation in the repeatability graph angular coefficient $b$ (parameter $\gamma$ in Gutenberg-Richter dependence-based earthquake energy classification by the magnitude or parameter $b$ in magnitude-based classification) [4, 6, 12];
- the joint behaviour of seismic activity and parameter $\gamma$;
- parameters characterizing the degree of seismic event grouping in time and space [13];
- the energy characteristics of the seismic regime, which are described with a logarithmic function of the released seismic energy, Benioff plots, and area of discontinuities formed during seismic deformation, proportional to the released energy to a power of $2/3$ [6, 12].

![Figure 4](image)

**Figure 4.** Examples of the manifestation of the seismic quiescence precursor before certain past strong earthquakes in the Tashkent seismically active zone.

In regard to the different prognostic parameters of the seismic regime, the sizes of the circular areas in which they were calculated and the threshold values, deviation from which was interpreted as a manifestation of anomalies, were selected on the basis of retrospective analysis of the dynamics of the seismic processes in the focal zones of past strong earthquakes. Figures 4–5 show examples of seismic quiescence and variation in the repeatability graph angular coefficient (parameter $\gamma$) precursors.
observed before certain strong earthquakes in the Uzbekistan territory. In terms of seismic quiescence, it is necessary to consider a variety of forms of this precursor [6].

Spatial-temporal diagrams of seismic process development in three source regions located within the limits of the Tashkent seismically active zone, as shown in Figure 4, clearly show the seismic events described in [6], which differ from the main strike by a magnitude ranging from 2–2.5 (3–4 energy classes in the energy classification of earthquakes by the magnitude), as reported in [6].

Figure 5. Examples of the manifestation of the variation in the repeatability graph angular coefficient (parameter $\gamma$) precursor before certain past earthquakes in the territory of Uzbekistan.

Figure 6. Map of the areas likely to experience seismic activation over the coming years based on the set of seismic regime prognostic parameters.
Based on the above analysis of the set of prognostic features, considering seismological data ending in December 2019, a map of areas likely to experience seismic activation over the coming years was constructed and submitted to the Ministry of Emergency Situations of Uzbekistan (Figure 6). According to the number of anomalies detected, four gradations were introduced to characterize the potential risk level in each focal zone at the current time: low, low, high, and very high.

4. Conclusion
The main results of the study can be summarized as follows:
Within the seismically active zones of the Uzbekistan territory, there are areas with a high seismic activity matching the level of strong earthquakes during both the historical and instrumental observation periods. According to the results of the reconstruction of the natural stress state by CAM algorithms, it was found that these areas are characterized by relatively low values of the maximum shear stresses and the effective confining pressure. Decreased values of the friction forces on ruptures in these regions create favorable conditions for large-scale destruction. Therefore, these areas should be considered potentially dangerous in regard to the occurrence of strong earthquakes over the next few decades. Analysis of the temporal changes in the set of prognostic parameters of the seismic regime in these areas allowed these areas to be ranked according to the occurrence probability of strong earthquakes over the coming years.

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