Technical Note

Analysis of the Prediction of Earthquake Locations in Anatolia and Adjacent Regions of 1974 in Connection with the 2023 Türkiye-Syria Great Earthquakes

Alexander I. Gorshkov[1*] and Olga V. Novikova[2]

1. DSci, Ph.D., Institute of Earthquake Prediction Theory and Mathematical Geophysics, Moscow, Russia, *Corresponding Author; email: gorshkov@mitp.ru
2. Ph.D., Institute of Earthquake Prediction Theory and Mathematical Geophysics, Moscow, Russia

Received: 31/08/2023
Revised: 27/11/2023
Accepted: 18/12/2023

ABSTRACT

On February 6, 2023, two devastating earthquakes occurred in the southeast of Türkiye with an interval of 9 hours, which also affected the territory of Syria. The position of the epicenters of these earthquakes is discussed in connection with the forecast of M6.5+ earthquake locations for the territory of Anatolia and adjacent regions, obtained in 1974 by Gelfand et al., based on morphostructural zoning data employing the Cora-3 pattern recognition algorithm. It has been established that the epicenters of the earthquakes of February 6, 2023 were located in the node, which in 1974 was identified as capable of M6.5+. Since 1974, 36 M6.5+ events have been observed in the study region. The spatial distribution of these events is analyzed in relation to the seismogenic nodes recognized in 1974. It was found that the epicenters of 32 such events are located in the nodes recognized as dangerous for M6.5+ in 1974.

Keywords:
Türkiye earthquake of 2023; Pattern recognition; Cora-3 algorithm; Seismogenic nodes

1. Introduction

On February 6, 2023 at 01:17 UTC (04:17 local time), an earthquake of Mw7.8 occurred in southeastern Türkiye, followed by a second shock 9 hours later at a distance of 37 km west-northwest of the first with Mw 7.5. The Geophysical Survey of the Russian Academy of Sciences determined MS 8.0 and 7.8 for these events, respectively. The intensity in the epicentral zone of both events reached XII according to the modified Mercalli scale (MMI). Catastrophic destruction spread to vast territories of Türkiye and north-western Syria, with a total area of about 350,000 km^2. These earthquakes killed more than 54 thousand people in Türkiye, and about 8.5 thousand people in Syria.

Earthquakes occurred at the junction of the Anatolian, African and Arabian plates in the zone of the East Anatolian fault system. Although mag-nitudes greater than 6 were not observed in this area in the last century, according to historical data, this area is characterized by high seismic activity: in the period of the 16th-90th centuries, events with magnitudes from 6.6 to 7.4 were recorded here (Ambraseys, 1989). Some recent studies also point to the high seismic potential of the East Anatolian Fault. In particular, for its individual segments, Aktug et al. (2016) based on GPS data revealed a significant slip deficit, which suggests the possibility of earthquakes with Mw 7.4-7.7.

For the first time, a forecast of earthquake locations for the territory of Türkiye and adjacent regions within the framework of a unified methodology was developed by a group of Soviet researchers led by Gelfand et al. (1973) and Gelfand et al. (1974). The forecast was based on the hypothesis that strong earthquakes are associated with disjunctive nodes that form at the intersections of morphostructural lineaments. The location of the nodes formed around the intersections of morphostructural lineaments was determined within the Balkans, the Aegean Sea, Anatolia and Transcaucasia by the method of formalized morphostructural zoning (Alekseevskaya, 1977; Ranzman, 1979). It was found that the instrumental epicenters of M6.5+ earthquakes known in the region for the period 1900-1974 located near some nodes with characteristic features. The purpose of the study was to determine the possibility of M6.5+ earthquakes in other nodes of the region, where such events were not known at that time. The problem was solved using the Cora-3 pattern recognition algorithm (Bongard, 1967), adapted by Gelfand et al. (1973) and Gelfand et al. (1974) to search for high seismicity criteria. As a result, capable nodes where the M6.5+ events are possible have been identified in Anatolia and adjacent regions.

In this paper, we check the results obtained in (Gelfand et al., 1974) by comparing the locations of the M6.5+ earthquakes that occurred after 1974 with the recognized seiedmogenic nodes for this magnitude threshold.

2. Methodology

Gelfand et al. (1973) and Gelfand et al. (1974) developed an approach that was first developed and applied to identify highly seismic nodes within the mountain-folded regions of the Pamir and Tien Shan. The methodology is based on the application of pattern recognition algorithms to morphostructural zoning data. The method of morphostructural zoning (MSZ) focused on the analysis of the present-day topography enables to divide the study area into a hierarchical system of crustal blocks delimited by zones of morphostructural lineaments, at the intersections of which morphostructural nodes are formed (Alekseevskaya, 1977; Ranzman, 1979). The epicenters of strong earthquakes turned out to be confined to the nodes. This fact was first empirically established during the study of the Pamirs and the Tien Shan (Gelfand, 1973) and subsequently received confirmation in many seismically active regions of the world, where morphostructural zoning and recognition of the places of possible occurrence of strong earthquakes were carried out. Reviews of studies on the application of this methodology are given in (Gorshkov, 2010; Soloviev, 2014; Gorshkov & Novikova, 2018; Gorshkov & Soloviev, 2021).

The studying objects in the methodology are morphostructural nodes. Their position on the Earth surface is delineated by MSZ (Alekseevskaya, 1977; Ranzman, 1979; Gorshkov, 2010; Gorshkov & Soloviev, 2021) that is based on the analysis of geomorphic, tectonic, geological data with a special attention to the present-day topography because the topography is a very sensitive indicator of tectonic deformation. In the MSZ, the study region is divided into a system of hierarchically ordered areas, characterized by homogeneous topography and tectonic structure. MSZ distinguishes three interrelated elements of the block-structure (1), areal elements, blocks; (2) linear zones bounding blocks, morphostructural lineaments; and (3) sites of the intersections of the lineaments, the nodes. In mountainous regions, heights and strike of large relief elements (landforms), as well as the trend of their changes, are analyzed to identify blocks and lineaments. MSZ establishes the three-level hierarchy of the block-structure. The lower third rank unit in the hierarchy is a block, an area with a similar value of the quantitative indicators of large landforms. Blocks compose the second rank units, megablocks. A common trend in changes of elevation and orientation of large landforms is characteristic for megablocks. Megablocks are integrated into first-rank units, mountain countries, characterizing by uniform physiography (mountains, plateau, plain etc) and a common type of tectonic regime (orogeny, rifting, platformal regime etc).

A morphostructural lineament is viewed as a boundary zone between areal units delineated by MSZ. The rank of the lineament depends on the rank of the area limited by the lineament:

first rank lineaments bound mountain countries, the second ones divide megablocks, the third one's limit blocks. Regarding the regional tectonic trend and predominant strike of relief, two types of boundary zones are specified, longitudinal and transverse lineaments. Longitudinal lineaments are roughly parallel to the regional trend of topography and tectonic structure; they bound large landforms and, usually, include the prominent faults. Transverse lineaments cross large landforms. On the Earth's surface, they are presented discontinuously by escarpments, by linear segments of river valleys, and by pieces of faults lying in the same strike.

Nodes are areas of some extent; they may combine more than one intersection of lineaments and have a typical linear size about 30×60 km (Ranzman, 1979; Gorshkov, 2010; Gorshkov & Soloviev, 2021). The study of nodes during fieldwork in Central Asia and Caucasus (Ranzman, 1979) has evidenced that the areas occupied by the nodes exhibit a mosaic combination of small landforms and a higher concentration of topographical alignments of various strikes with respect to the surrounding areas. These evidences suggest the higher intensity of the young deformations within a node for surrounding areas.

In Gelfand et al. (1973) and Gelfand et al. (1974), the objects of recognition were the intersections of lineaments, which the authors called disjunctive nodes. Later on, such nodes began to be defined as morphostructural ones (Ranzman, 1979). The task was to divide the set of all nodes in the region into two classes: high (*D*) - and low seismic (*N*) with respect to the threshold magnitude $M_0 = 6.5$ using the logical recognition algorithm with training Cora-3 (Gelfand et al., 1974; Bongard, 1967). To train the algorithm, two learning samples were considered: D_0 - objects (nodes) a priori belonging to class *B*, and H_0 - objects a priori belonging to class *N*. The D_0 subset included nodes that host epicenters of the M6.5+ earthquakes known in the region. The N_0 subset included nodes near which there are no observed the M6.5+ earthquakes. Naturally, it is impossible to obtain a "pure" subset of N_0, which is the learning material of class *N*. In some of these nodes, earthquakes equal or exceeding M_0 may occur. The task of recognition was to identify such nodes. The division of nodes into classes *D* and *N* was carried out on the basis of geomorphological and morphostructural parameters, uniformly defined for each node. These parameters characterize the intensity of recent tectonic movements, the complexity of the structure of the node, and the fragmentation of the earth's crust in its vicinity.

The Cora 3 recognition algorithm (Gelfand et al., 1973; Bongard, 1967; Gorshkov & Soloviev, 2021) was used for the classification of nodes. The algorithm operates with binary vectors. Therefore, the initial values of the parameters should be converted into binary vectors. The conversion is carried out by the procedures of discretization and coding (Gorshkov & Soloviev, 2021). After the conversion, the recognition algorithm carries out the classification of the objects using the training sample $W_0 = (D_0, N_0)$: $W = D \cup N$, where *D* and *N* are the vectors assigned by the algorithm to the classes *D* and *N*, respectively. At the classification stage, the algorithm counts the numbers of *D*- and **N**-traits (n_D and n_N respectively) that each node possesses and appoints it to class *D* if $n_D - n_N \geq \Delta$ or to class **N** if $n_D - n_N < \Delta$, where Δ is a parameter of the algorithm.

The quality of the final classification defined by the recognition algorithm can be evaluated by the computational control tests. A number of such tests have been developed to estimate the stability of the resultant classification (Gelfand et al., 1973; Gelfand et al., 1974; Gorshkov, 2010). The positive results of the control tests suggest that the objects of recognition are reliably subdivided into the **D** and **N** classes. Evidences about historical and paleo-earthquakes are also considered in the evaluation of the classification of the nodes. Clearly, the objective of evaluating the reliability of the recognition results obtained for the studied region may only come by prospective testing, accounting for the subsequent target earthquakes occurred after the nodes classification and publication of the results.

The mapping of the natural boundaries of the nodes is time-consuming procedure and in the practice was impossible for us in the majority of

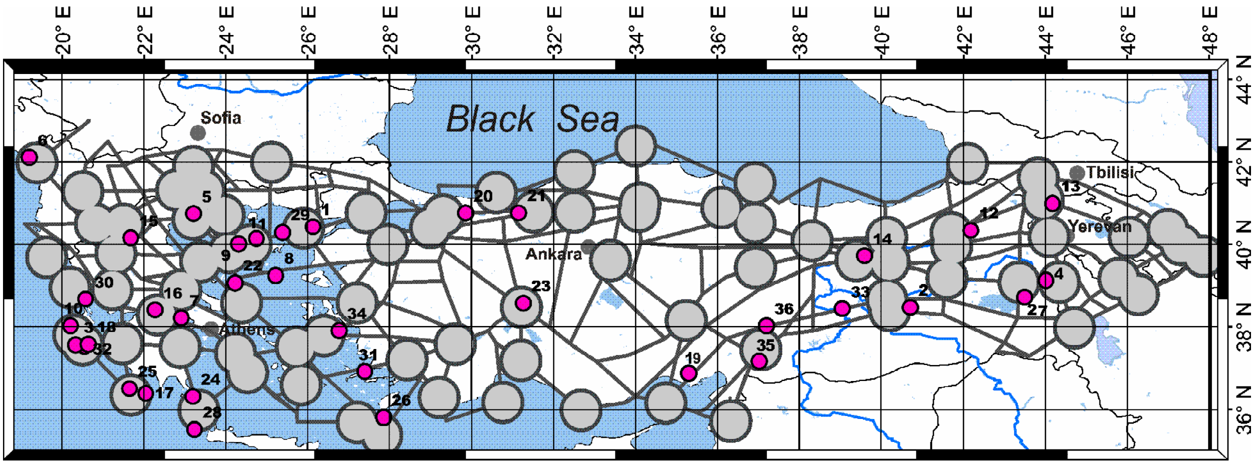

Figure 1. Map of lineaments of Anatolia and adjacent regions and recognized seismogenic nodes (D) for M6.5+. Large gray circles show D nodes. Small rose circles depict epicenters M6.5+.

the studied regions. Therefore, the nodes were defined as the circles of a certain radius, which depends on the target M_0 according to the empirical relation between magnitude and the earthquake source (Wells & Coppersmith, 1994). In our case, the target magnitude was M6.5+. Therefore, in Anatolia and adjacent regions, the nodes were defined as circles of radius $r = 40$ km with centers at the intersection points of the lineaments. With some margin, this radius is consistent with the size of the source for M6.5+.

The recognized highly seismic nodes *D* identified in (Gelfand et al., 1974) are shown in Figure (1) by circles.

3. Verification of the Results of Recognition of Seismogenic Nodes in Anatolia and Adjacent Regions

Since the publication of recognition results in 1974, according to the NEIC global earthquake database, 36 earthquakes of magnitude *M*6.5+ have occurred in Anatolia and the surrounding regions. The list of these events is presented in Table (1), and their correlation with the forecast in (Gelfand et al., 1974) is shown in Figure (1). The epicenters of 32 of them fell into seismogenic nodes *D*. At the same time, the epicenters of 15 earthquakes occurred in seismogenic nodes designated as *D** nodes, where the considered magnitudes were not known at the moment of the recognition. One event (no. 8 in Table 1 and Figure 1) occurred near the node assigned to class *N* by recognition, and three earthquakes (nos. 19, 31 and 33) occurred on the lineaments, but outside the nodes.

Thus, the comparison of the predicted the *M*6.5+ earthquake locations developed in (Gelfand et al., 1974) with actual events of such size that occurred after 1974 shows its rather high reliability. About 89% (32 earthquakes out of 36) of post-publication earthquakes occurred within *D* nodes.

The epicenters of the earthquakes on February 6, 2023 (Nos. 35 and 36 in Figure 1) occurred in a complex node, where the East Anatolian Fault abruptly changes its strike from northeast to south-southwest and continues south as a Dead Sea fault. The Cretan Arc fault is attached to the same node from the southwest. The junction of such large fault zones caused a high degree of fragmentation of the earth's crust in the vicinity of the node, which was reflected in the characteristic features of *D* nodes, which were determined by the Cora-3 algorithm. In Anatolia, characteristic features of nodes *D* are formed mainly from indicators of tectonic fragmentation: the length of the major lineament, the complexity of the node, the proximity of lineaments of the first rank, the proximity of lineaments. Features of nodes *D* contain such values of the listed parameters that indicate an increased fragmentation of the earth's crust (Gelfand et al., 1974).

Recognized *D* nodes are shown as gray circles with a radius of 40 km after (Gelfand et al., 1974). The epicenters of the post-publication *M*6.5+ earthquakes are shown as purple dots with numbers corresponding to those in Table (1).

Table 1. List of earthqukes M6.5+ for the period 1975-2023.

No of Event in Figure (1)	Date	Latitude	Longitude	Magnitude	Type of the Node
1	27.03.1975	40.42N	26.14E	6.7	**D**
2	06.09.1975	38.47N	40.72E	6.7	**D***
3	11.05.1976	37.56N	20.35E	6.7	**D**
4	24.11.1976	39.12N	44.03E	7.3	**D***
5	20.06.1978	40.74N	23.23E	6.6	**D**
6	15.04.1979	42.10N	19.21E	7.3	**D**
7	24.02.1981	38.22N	22.93E	6.8	**D***
8	19.12.1981	39.24N	25.23E	7.6	**N**
9	18.01.1982	40.00N	24.32E	7.0	**D**
10	17.01.1983	38.03N	20.23E	7.2	**D**
11	06.08.1983	40.14N	24.76E	7.3	**D**
12	30.10.1983	40.33N	42.19E	6.9	**D**
13	07.12.1988	40.99N	44.19E	7.0	**D***
14	13.03.1992	39.71N	39.60E	6.9	**D**
15	13.05.1995	40.15N	21.69E	6.8	**D***
16	15.06.1995	38.40N	22.28E	6.5	**D**
17	13.10.1997	36.38N	22.07E	6.7	**D**
18	18.11.1997	37.57N	20.66E	6.6	**D**
19	27.06.1998	36.88N	35.31E	6.6	Out of Nodes
20	17.08.1999	40.75N	29.86E	7.8	**D***
21	12.11.1999	40.76N	31.16E	7.5	**D**
22	26.07.2001	39.06N	24.24E	6.6	**D**
23	03.02.2002	38.57N	31.27E	6.5	**D***
24	08.01.2006	36.31N	23.21E	6.7	**D***
25	14.02.2008	36.50N	21.67E	6.9	**D**
26	15.07.2008	35.80N	27.86E	6.5	**D**
27	23.10.2011	38.72N	43.51E	7.3	**D**
28	12.10.2013	35.51N	23.25E	6.6	**D***
29	24.05.2014	40.29N	25.39E	6.9	**D**
30	17.11.2015	38.67N	20.60E	6.5	**D***
31	20.07.2017	38.67N	27.41E	6.6	Out of Nodes
32	25.10.2018	37.52N	20.56E	6.8	**D**
33	24.01.2020	38.43N	39.06E	6.7	Out of Nodes
34	30.10.2020	37.9N	26.78E	7.0	**D***
35	06.02.2023	37.17N	37.03E	7.8	**D***
36	06.02.2023	38.02N	37.20E	7.5	**D***

4. Conclusions

Verification of the results of recognition of places of possible occurrence of earthquakes with $M \geq 6.5$, obtained in (Gelfand et al., 1974), showed that the Turkish earthquakes on February 6, 2023 occurred in a node capable for this magnitude. An analysis of the location of all earthquakes with $M \geq 6.5$ that occurred after 1974 throughout Anatolia and adjacent regions reviled a fairly high efficiency of the 1974 forecast: about 89% of subsequent earthquakes occurred within nodes *D*. We especially note the fact that 14 earthquakes that occurred after 1974 were localized in nodes **D*** (Table 1), where events with $M \geq 6.5$ were unknown at the time of solving the recognition problem.

Validation of recognition results for Anatolia and adjacent regions, as well as data from global verification of recognition results in all previously studied regions (Gorshkov & Novikova, 2018) indicate that:

- The hypothesis about the nucleation of strong earthquakes at morphostructural nodes is generally confirmed;
- Morphostructural zoning maps, reflecting the hierarchical system of interacting blocks, are a

fairly adequate basis for identifying potential earthquake locations;

- The technique for recognizing the potential locations of strong earthquakes is sufficiently effective for identifying seismically hazardous areas.

Therefore, seismogenic nodes defined by pattern recognition provide first-order systematic information that can make a significant contribution to a reliable seismic hazard assessment. Information about potential locations of strong earthquakes can be directly used for the purposes of assessing the seismic hazard of both individual critical infrastructure facilities and included in existing seismic hazard assessment methods. Seismogenic nodes identified by pattern recognition make it possible to fill in possible gaps in the seismic history of the region under study when applying the Neo-deterministic approach to seismic hazard assessment (Panza and Bela, 2020, NDSHA) (Peresan et al., 2011).

In particular, the importance of seismogenic nodes in NDSHA applications has been demonstrated for some seismic regions including the Italian region (Peresan et al., 2011), northeastern Egypt (Gorshkov et al., 2019), Corsica-Sardinia (Brandmayr et al., 2021; Gorshkov et al., 2021), Kosovo (Brandmayr et al., 2021).

The catastrophic event in Türkiye-Syria once again highlighted the problem of effective use of the results of academic research in practical works on seismic hazard assessment and development of anti-seismic measures.

References

Aktug, B., Ozener, H., Dogru, A., et al. (2016). Slip rates and seismic potential on the East Anatolian Fault System using an improved GPS velocity field. *Journal of Geodynamics*, *94-95*, 1-12.

Alekseevskaya, M.A., Gabrielov, A.M., Gvishiani, A.D., Gelfand, I.M., & Ranzman, E.Ya. (1977). Formal morphostructural zoning of mountain territories. *J. Geophys.*, *43*, 227-233.

Ambraseys, N.N. (1989). Temporary seismic quiescence: SE Türkiye. *Geophys. J. Int.*, *96*, 311-331.

Bongard, M.M. (1967). *Problema Uznavaniya (Problem of Recognition)*. Moscow: Nauka.

Brandmayr, E., Vaccari, F., & Panza, G.F. (2021). Neo-deterministic seismic hazard assessment of Corsica-Sardinia block. Rendiconti Lincei. *Scienze Fisiche e Naturali*, https://doi.org/10.1007/s12210-021-01033-w.

Brandmayr, E., Vaccari, F., Romanelli, F., et al. (2021). Neo-deterministic seismic hazard maps of Kosovo. *Vietnam J. Earth Sci.*, *43*(4), 418-427, https://doi.org/10.15625/2615-9783/16328.

Gelfand, I.M., Guberman, Sh.A., Izvekova, M.L., Keilis-Borok, V.I., & Ranzman, E.Ya. (1973). Recognition of earthquake prone areas. I. Pamir and Tien Shan, in Vychislitel'naya seismologiya, Vyp. 6: Vychislitel'nye i statisticheskiemetody interpretatsii seismicheskikh dannykh (Computational Seismology, Vol. 6: Computational and Statistical Methods for Interpretation of Seismic Data), Keilis-Borok, V.I., Ed., Moscow: Nauka, 107-133.

Gelfand, I.M., Guberman, Sh.A., Zhidkov, M.P., Keilis-Borok, V.I., Ranzman, E.Ya., & Rotwain, I.M. (1974). Recognition of earthquake prone areas. II. Four regions in Asia Minor and SouthEast Europe, in Vychislitel'naya seismologiya, Vyp. 7: Mashinnyi analiz tsifrovykh seismicheskikh dannykh (Computational Seismology, Vol. 7: Computerized Analysis of Digital Seismic Data), Keilis Borok, V.I., Ed., Moscow: Nauka, 3-40.

Gorshkov, A.I. (2010). Raspoznavanie mest sil'nykh zemletryasenii v Al'piisko-Gimalaiskom poyase. Vychislitel'naya seismologiya, Vyp. 40 (Recognition of the Earthquake Prone Areas within the Alpine Himalaya Belt. *Computational Seismology*, *40*, Moscow: KRASAND.

Gorshkov, A., & Novikova, O. (2018). Estimating the validity of the recognition results of earthquake prone areas using the ArcMap. *Acta Geophysica*, *66*(5), 843-853, Doi:10.1007/s11600-018-0177.

Gorshkov, A., Hassan, H., & Novikova, O. (2019). Seismogenic nodes ($M \geq 5.0$) in north-east of Egypt and implication for seismic hazard assessment. *Pure Appl. Geophys.*, *176*(2), 593-610, https://doi.org/10.1007/s00024-018-2012-9.

Gorshkov, A., Panza, G.F., Soloviev, A. et al. (2021). On the seismic potential of the Corsica-Sardinia block. Rend. *Fis. Acc. Lincei.*, *32*, 715-728, https://doi.org/10.1007/s12210-021-01014-z.

Gorshkov, A., & Soloviev, A. (2021). 'Morphostructural zoning for identifying earthquake-prone areas'. In: *Earthquakes and Sustainable Infrastructure: Neodeterministic (NDSHA) Approach Guarantees* Prevention Rather Than Cure. (Eds Panza, G.F., Kossobokov, V.G., Laor, E., De Vivo, B.) Elsevier, 135-149.

Panza, G.F., & Bela, J. (2020). NDSHA: A new paradigm for reliable seismic hazard assessment. *Engineering Geology*, *275*, 105403.

Peresan, A., Zuccolo, E., Vaccari, F., Gorshkov, A., & Panza, G. (2011). Neo-deterministic seismic hazard and pattern recognition techniques: time-dependent scenarios for North-Eastern Italy. *Pure Appl. Geophys.*, *168*, 583-607, doi:10.1007/s00024-010-0166-1.

Ranzman, E.Ya. (1979). *Mesta Zemletryasenii I Morfostruktura Gornykh Stran (Locations of the Earthquakes and Morphostructure of Mountain Regions).* Moscow: Nauka.

Soloviev, A.A., Gvishiani, A.D., Gorshkov, A.I., Dobrovolsky, M.N., & Novikova, O.V. (2014). Recognition of earthquake-prone areas: methodology and analysis of the results. *Izvestiya, Physics of the Solid Earth*, *50*(2), 151-168, DOI: 10.1134/S1069351314020116.

Wells, D.L., & Coppersmith, K.J. (1994). New empirical relationships among magnitude, rupture length, rupture width, and surface displacement. *Bull. Seism. Soc. Am.*, *84*, 974-1002.