Methodology for numerical integration of different data types for the purposes of seismic hazard assessment

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Key words: seismic hazard, data integration, matching index, Bulgaria

Abstract
Analysis of input data is a fundamental component of the seismic hazard assessment. The territory of Bulgaria, located in the seismically active region of the Balkans, gives us the opportunity to test new methods of integrating different types of data in order to refine our seismotectonic model. In recent years, a number of high-quality geological, geophysical and seismological data have been collected that are used for the purpose of seismic hazard assessment. The present paper presents an algorithm for the so-called spatial matching index, which indicates the absence or presence of potential seismic sources in the input data. The Spatial Match Index (Q) is used to assess the hazard in Bulgaria by quantifying the seismic potential of 416 square blocks of 20x20 km covering the entire territory of Bulgaria and extended by 20 km outside of the country borders. All operations are performed in GIS using their capabilities to handle different types of georeferenced spatial data. The results show that the highest seismic potential (the highest Q) was observed in 56 network elements (13% of the territory), in which all three types of data were matched. Expected are the areas near Varna, Rousse, Veliko Tarnovo, Sofia, Plovdiv, Krupnik and several other places. Partial matching, i.e. one of the features is missing, is recorded in 98 block elements. There are no signs of a seismogenic structure according to our calculations in 117 network elements, covering 28% of the studied area.

Методология за цифрово интегриране на данни от различен тип за нуждите на оценката на сеизмичния хазарт

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Ключови думи: сеизмичен хазарт, интегриране на данни, индекс за пространствено съвпадение, България

Резюме
Анализът на входните данни е основен компонент при оценката на сеизмичния хазарт. Последните проучвания ясно подчертават значението на интегрирането и обработването на различни типове гео-данни, които са свързани с възможните източници на земетресения. Територията на България, намираща се в сеизмично активния район на Балканите, ни дава възможност да изпробваме нови методи за интегриране на различни типове данни с цел прецизиране на сеизмотектонския модел на страната. През последните години бяха събрани редица висококачествени геоложки, геофизични и сеизмологични данни, които са използвани за целите на оценката на сеизмичния хазарт. Настоящата работа представя алгоритъм за генериране на т. нар, индекс на пространствено съвпадение, който показва липса или наличие на потенциални сеизмични източници във входните данни. Индексът за пространствено съвпадение (*Q*) се прилага за оценка на опасността в България чрез количествено определяне на сеизмичния потенциал на 416 квадратни блока с размери 20x20 км, разположени по цялата територия на България и външна ивица с ширина 20 км извън нея. Всички операции са извършени в ГИС, използвайки възможностите си за работа с различни видове георефериранипространствени данни. Резултатите показват, че най-високият сеизмичен потенциал (най-голямата *Q*) се наблюдава в 56 елемента на мрежата (13% от територията), в които има съвпадение и на трите изследвани типа данни. Очаквано, това са районите близо до Варна, Русе, В. Търново, София, Пловдив, Крупник и други места. Частичното съвпадение се регистрира в 98 блокови елемента, т.е. липсва една от характеристиките. Не са установени признаци за наличие на сеизмогенна структура според нашите изчисления в 117 елемента на мрежата, обхващащи 28% от изследваната площ.

Introduction

Key part of the probabilistic seismic hazard assessment is the identification of regional or local seismotectonic domains that, based on geologic, geophysical, and seismological information, may be interpreted to have relatively consistent spatial and temporal variations in historical seismicity.
Previous studies of the seismic hazard assessment for the territory of Bulgaria relied mainly on a visual correlation

of the lineaments obtained from different type of data. Ek. Bončhev et al. (1982) performed a complex analysis of the existing seismological, geological, geophysical and geodetic information using big team of experts (more than 15 persons) who independently traced the lines on the separate maps and after a visual inspection determined the position of the complex lineaments. The outlined seismogenic lineaments were ranked to a certain level of confidence according to predefined criteria and accepted for the final map compilation. For the seismic hazard assessment accomplished in 2009, Solakov et al. (2008) elaborated a seismotectonic map through digital juxtaposition of geological, geophysical and seismological data using direct visual evaluation of their coincidence.
For the purposes of this study we use the spatial distribution of active faults and geophysical lineaments, and seismological data. We process and integrate the available data sets in GIS and asses the seismogenic potential of the Bulgarian territory calculating a specially developed matching index thus avoiding subjective evaluation of a visual comparison and the danger of gaps.

Data

To perform quantitative spatial analysis investigating the seismotectonic characteristics of the studied region we divide the territory of Bulgaria into square blocks of size 20x20 km. The grid of these elements is extended by 20 km outside of the country borders so that to allow coverage of data from the nearest border region that have an impact on the seismic hazard as well. An input database is compiled using the following three independent data sets: geological (Fig. 1), geophysical (Fig. 2) and seismological (Fig. 3).

Geology

The first key dataset which is used in the present study is the spatial distribution of active faults (AF) on the territory of Bulgaria. Data (Fig. 1) are modified from the map of active faults that is presented in Solakov et al., 2008.
The faults are classified into three categories depending on their characteristics and degree of knowledge: active, potentially active and possibly active (with unverified activity). In the category of active faults are those for which there are clear evidences of the Late Pleistocene or Holocene activity. To the category of potentially active faults are referred those marked on the base of indirect information fragments or lines that can be activated in the contemporary tectonic regime. As possibly active, with unproven activity are identified faults or lineaments with scarce data on their ruptured origin and Late Pleistocene or Holocene activity.
Because we use a conservative hazard assessment approach in the analysis, all classes of active faults described above are included in the study. The length and coordinates of the outlined faults (Fig. 1) are specified in a data set table. A number of 136 structures with length larger than 5 km are included. The length of the longest fault is 68 km (near Plovdiv), while the average length of structures is 18 km. The dominant fault strike is in NW – SE direction.

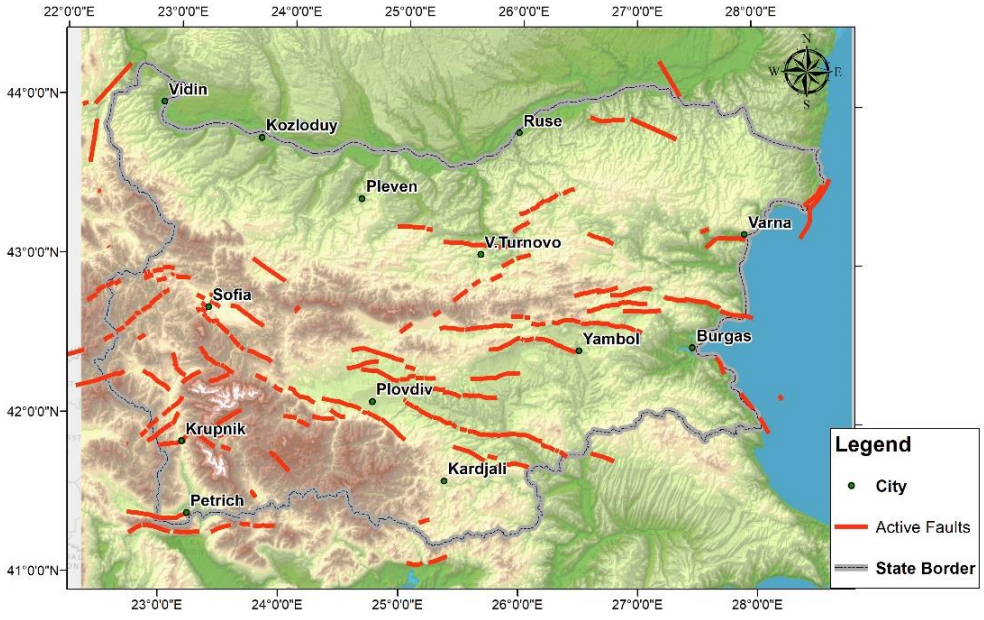


Fig. 1 Map of the geological data (active faults - AF) used for calculation of the spatial matching index and identification of seismogenic domains (modified from Solakov et al., 2008).

Geophysics

As more suitable for detection of fault-like features we use the first order derivatives of anomalous gravity field and in particular the modulus of the total horizontal gravity gradient (THG) in cooperation with the vertical gradient. Their linear spatial distributions reflect the presence of faults, horst or graben structures, block borders, etc. (Blakely and Simpson, 1986). THG we calculate from the Bouguer anomalous field map of regional scale for the Bulgarian territory. The horizontal derivatives along two orthogonal axes are calculated and geometrically summed in points of a grid with a 3 km cell size over the entire territory (Stavrev et al., 2009).

The map of THG lineaments indicates the axes of pronounced gravity transitions by the lines of maximum gradient values. The most intensive among them are marked by long black lines (Fig. 2). The amplitude, length and coordinates of the gradient anomalies are specified in a data set table. The number of gravity transitions is more than 110. The longest transition is 42 km of size (to the northeast of Sofia), and the average length of the transitions found is about 19 km. The dominant orientation of their strikes is in WNW – ESE direction following the main lineaments of the known structures of the lithosphere in Bulgaria.

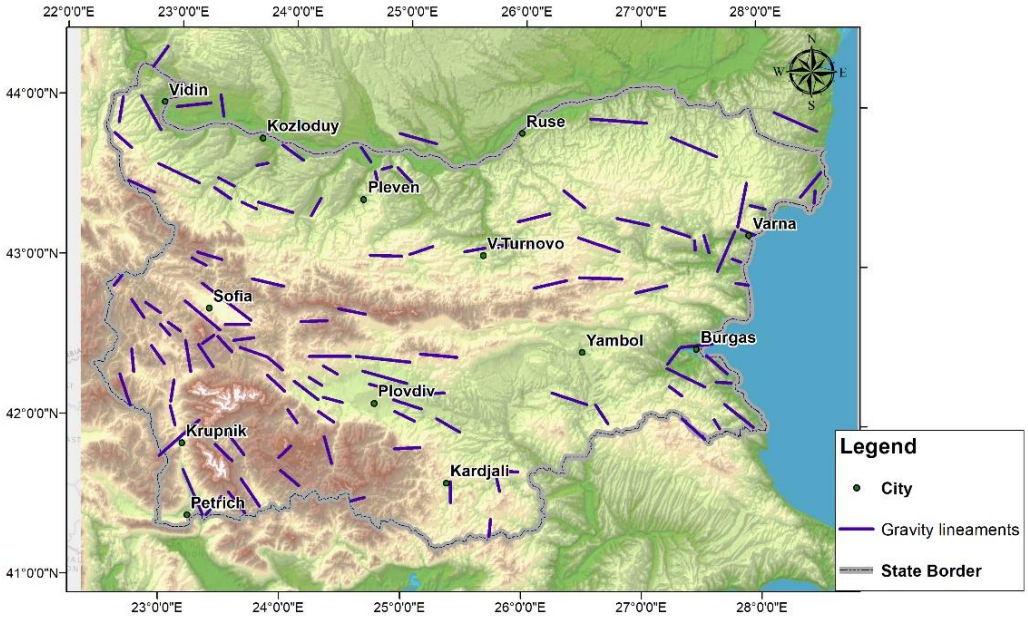


Fig. 2 Map of the geophysical data (total horizontal gravity gradient lines –GL) used for calculation of the spatial matching index and identification of seismogenic domains (modified from Stavrev et al., 2009).

Seismology

The last but not the least, an earthquake catalogue containing 755 shallow earthquakes with a magnitude $M_W > 3.0$ occurred in the territory under consideration (Fig. 3) is used as the third dataset. Earthquakes cover the period from the 1st century BC up to year 2016 and are based on available historical documents and information from the sources described in (Solakov et al., 2009).

To insure homogeneity in energy domain and compatibility of seismological information magnitude estimates are converted to the most widely used in the recent years scale - seismic moment magnitude (M_W).

The de-clustered and homogenized catalogue was also studied for the completeness using the Stepp's test (1971), which is essential for the reliable evaluation of the seismic statistical parameters used in probabilistic seismic hazard assessment.

The described information is organized in a dataset where each earthquake is specified with space-temporal parameters (date, time, longitude, latitude, depth) and magnitude. The dataset contains 755 events occurred in and near Bulgaria with the largest magnitude Mw=7.6 (the 1904 earthquake occurred near Krupnik).

The parameter used in the present analysis is the logarithm of the seismic moment M_0 calculated from the moment magnitude scale using the equation (Hanks and Kanamori,1979):

$$M_w = \frac{2}{3}\log M_0 - 10.7 \qquad (1)$$

were M_w is the moment magnitude from the seismological dataset described above.

The seismic moment M_0 is a scalar value depending on the area of fault rupture, the average amount of slip (displacement), and the shear modulus of the rocks involved in the earthquake. M_0 thus has dimensions of torque, measured in Newton meters and is in the basis of the moment - magnitude scale introduced by Hiroo Kanamori, which is often used to compare the size of earthquakes.

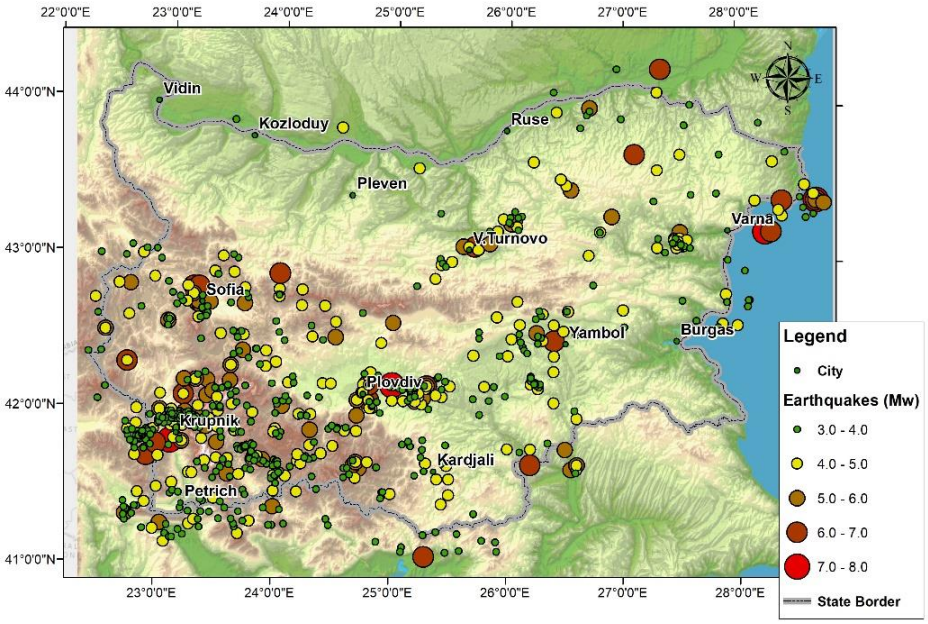


Fig. 3 Map of the seismological data (earthquake epicenters) used for calculation of the spatial matching index and identification of seismogenic domains (modified from Solakov et al, 2009).

Method

The considered territory is gridded with a step of 20 km. As a result 416 square blocks are obtained each of them containing geological, geophysical and seismological data showing the presence or absence of a potential seismogenic features.

The technique which we applied in this study consists in calculating the proposed spatial matching index assessing the manifestation or absence of any of the two V_1 and V_2 features set in the input data of each element of the spatial square blocks grid. The spatial matching index, marked by the symbol Q, for a given element of the network's number i is estimated using the formula:

$$Q_i(V_1, V_2) = \left[\frac{V_1 + V_2}{\sqrt{V_1^2 + V_2^2 + 1}} \right]_i, \quad i = 1,2,3,\dots,k, \qquad (2)$$

where variables V may be different geological, geophysical or seismological characteristics derived from the available information and prescribed as non-negative numbers for the square elements (k = 416) of the used grid.

The matching index Q has strictly defined boundaries in which is assessed the existence or not of a match in the spatial manifestation of any two features (characteristics) V_1 and V_2 having the same or different units of measure:

The matching index Q boundaries used in the analysis are as follows:

- if $V_1 > 0$ and $V_2 > 0$, then Q is within the limits [1.0; $\sqrt{2}$), and the grid element with number i, is marked by "existence" of both characteristics
- if $V_1 = 0$ and $V_2 = 0$, then $Q = 0$, the grid element is marked by a "zero value matching" or "missing" for both characteristics;
- if $V_1 > 0$ and $V_2 = 0$, or $V_1 = 0$ and $V_2 > 0$, i.e. only one of the two features has an expression larger than 0 in the network element, then the Q value falls within the range (0; 1), with the assessment of "non-match" in the manifestation of the two characteristics.

As is seen in Fig. 4 the maximum values of Q are obtained when $V_1 = V_2$, which means that as close are the compared parameters as high the matching index will be.

Above methodology is applied using ArcGIS on the three key datasets: active faults, lineaments of the total horizontal gravity gradient and catalogue of earthquakes (epicenter's distribution). For each element of the grid were calculated the sum of the active faults' length ($\sum AF$), sum of the gravity lineaments ($\sum GL$), and logarithm of the aggregated seismic moment ($lg \sum M_0$).

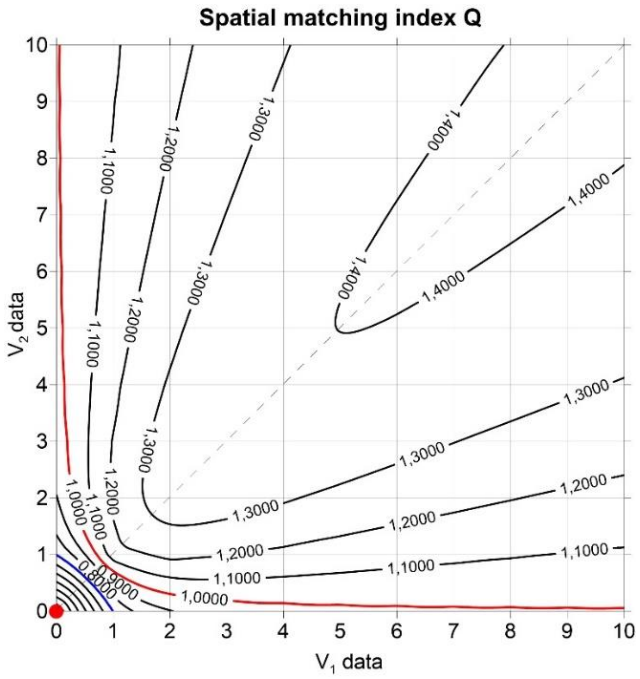


Fig. 4 Diagram of the isolines of the spatial matching index Q (Eq. 2) showing the function properties. The matching boundary values (Q = 1 and Q = 0) are marked in red.

Three mutual matching indices $Q_{AF\text{-}GL}$, $Q_{AF\text{-}lgM}$, $Q_{GL\text{-}lgM}$ are calculated between the geological and geophysical data, geological and seismological data and geophysical and seismological data respectively using Eq. 2.

Results

Results about the juxtaposition of the three independent data sets (geological, geophysical and seismological) obtained from the calculation of a spatial matching index are shown in Figs. 5-7. With the lightest color are marked areas without any indications of presence of a seismogenic structure while the darkest one correspond to a match of both variables indicating a larger probability for an earthquake source existence.

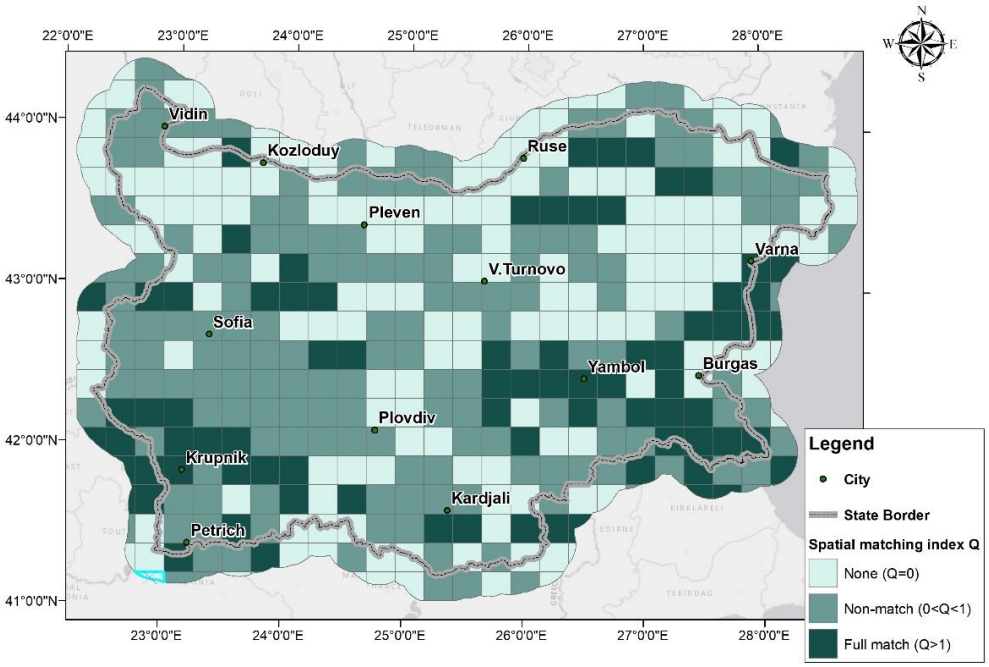


Fig. 5 Map of the calculated spatial matching index Q in 416 square elements covering the entire territory of Bulgaria and showing the coincidence of geological and geophysical data indication for presence of a seismogenic structure.

The case of non-match means that information for structure existence is coming from only one of the three data sets. Most such cells are observed in the northwestern Bulgaria due to the presence of gravity lineaments reflating the block borders of the Moesian platform tectonic units and its coupling with the West Balkan (Dachev, 1988).

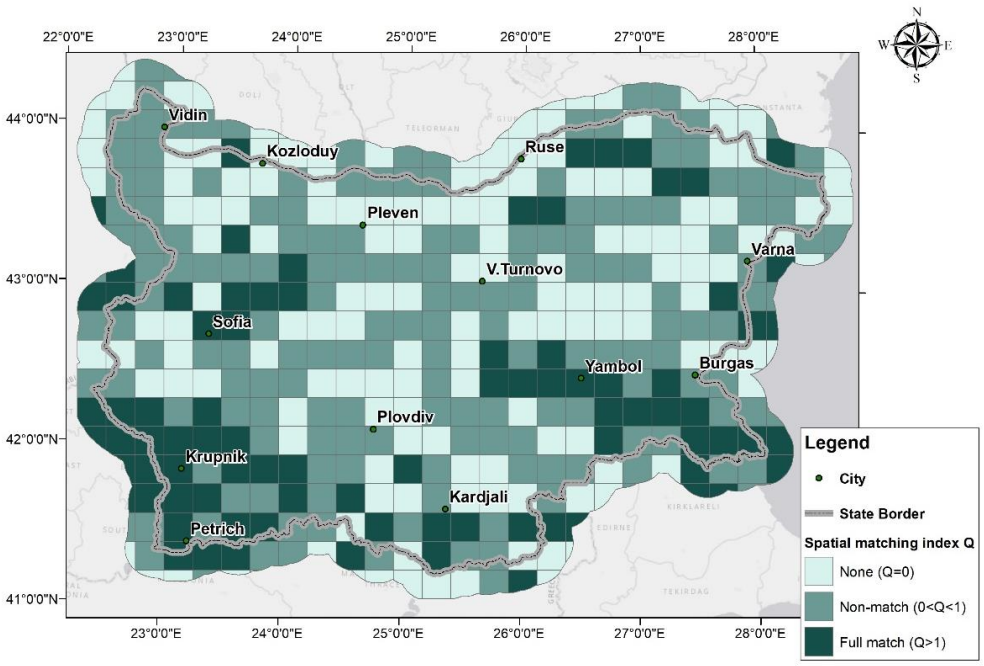


Fig. 6 Map of the calculated spatial matching index *Q* in 416 square elements covering the entire territory of Bulgaria and showing the coincidence of geophysical and seismological data indication for presence of a seismogenic structure.

The lack of earthquakes and observed faults confirms the tectonic stability of those structures today. Similar is the case southwest of the Burgas region. Due to the number of effusive and intrusive magmatic bodies embedded in the upper crustal section (Trifonova et al., 2012), a lot of corresponding gravity lineaments are delineated while information about earthquakes and active faults is missing.

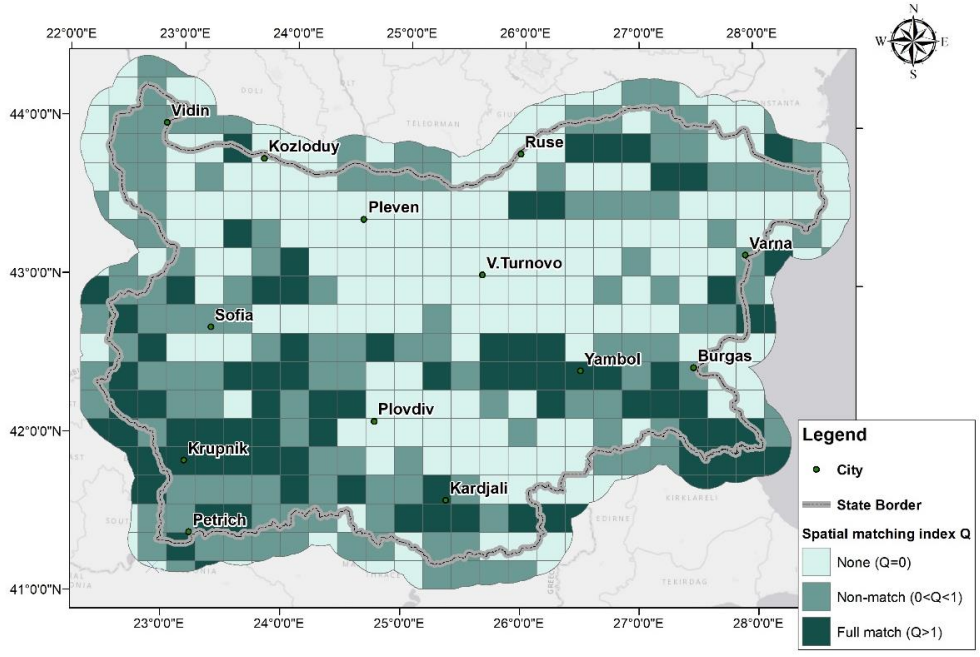


Fig. 7 Map of the calculated spatial matching index *Q* in 416 square elements covering the entire territory of Bulgaria and showing the coincidence of geological and seismological data indication for presence of a seismogenic structure.

Matching elements of the investigated grid represents areas where both indicators are observed. As such, very clearly stand out the region north-east of Plovdiv (between Stara Zagora and Yambol) and the sub-parallel strip north-west and south of Burgas.
The first one is connected with the densely positioned fault structures and plenty of earthquake epicenters (see Fig.3), while the second are result of the presence of faults and gravity lineaments marking the large plutonic bodies with high density and ultra-basic composition located there (Dobrev et al., 1990).
In the north-eastern part of the territory the mosaic pattern of the calculated index is related to large transposed blocks inside the North-Bulgarian arc and neighboring depressions. Block borders are mainly of fault type and respectively a number of epicenters are also spread around.
The most impressing in Figs. 5-7 are the Upper Thrace basin region and the entire territory of southwestern Bulgaria. The zone near Plovdiv contains the most intensive gravity gradient anomalies, active faults and well grouped earthquake epicenters. One orientation of the lineaments dominates - along Maritsa River outlining the deep Maritsa dislocations, as well as the set of faults in the heterogeneous basement depression.
Complicated border faults of the West and Central Srednogorie units (zones according to Dabovsky et al. 2002), neotectonic structures of the Sofia complex graben and the fault zones along the Struma and Mesta Rivers form the region with the observed matching index in the all three maps. Gravity lineaments are caused mainly by plutons and basic intrusions fed from that magma conducting fractures. Geological dataset also contains a great number of dislocations marked as active or potentially active faults which combined with the high epicenter density result in dark-colored elements in Figs. 5-7.
The peculiarities of the applied methodology, namely the interpretation in a network of square elements 20x20 km in size, partly hinders the accurate identification of the areas with the highest seismic potential, sometimes expanding them too much (as for example south of Sofia). Nevertheless, the used approach clearly outlines the areas with the highest earthquake capacity and prevents from omissions, errors and subjective assessments.

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