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Seismicity study of the western side of Pehcevo-Kresna faulting system

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Abstract: The destructive 1904 earthquake with estimated magnitude 7.8 which occurred on the Pehcevo-Kresna faulting system along Macedonian-Bulgarian border, has been considered as the strongest instrumentally recorded earthquake in the Balkan region and also in Europe.
Seismicity analysis with the updated earthquake catalogue were performed on the western side of its faulting system in order to detect possible continuation and segmentation. Two parts were considered, one polygon containing the fault structure near the Pehcevo area and another towards Kocani area.

Gutenberg-Richter relationship was applied to compare the variation of the "a" and "b" coefficients in the two selected polygons, for the de-clustered set of earthquakes from the last century and magnitudes 2.7 and above. The results show very small difference between their normalised values for both cases, which indicate relative similar seismic regime westward of the 1904 main shock area as defined by the macroseismic intensity maps.
The findings of this study may affect the seismotectonic models presently used for that section of the faults and help in the earthquake hazard assessment on regional and wider scale.

Keywords: Earthquakes, faults, epicentral map, Gutenberg-Richter relationship, regional seismicity.

1. Introduction

On 4th of April 1904, a destructive earthquake with estimated magnitude 7.8, preceded by a large foreshock 23 min earlier, struck the south region of the Balkan peninsula. The epicentral area was in a mountainous Pehcevo-Kresna area which was then part of the Ottoman empire and today falls on the country border between Bulgaria and the Republic of North Macedonia. Beside these two, strong shaking was felt in present-day countries of Serbia, Greece, Hungary, Romania, SW Russia and Turkey, at distances of more than 500 km (Hadzievski, 1976), compiled the macroseismic map of the main even as presented on Figure 1.

The main event has long been considered as the largest shallow earthquake ever recorded instrumentally in Europe. Various estimates of its parameters have been assigned, based on the recording stations used in combination with the felt reports. The fault and the fault break as a possible source for the earthquakes has not been clearly identified until now, due to the tectonic style and the deformation rates in the region.

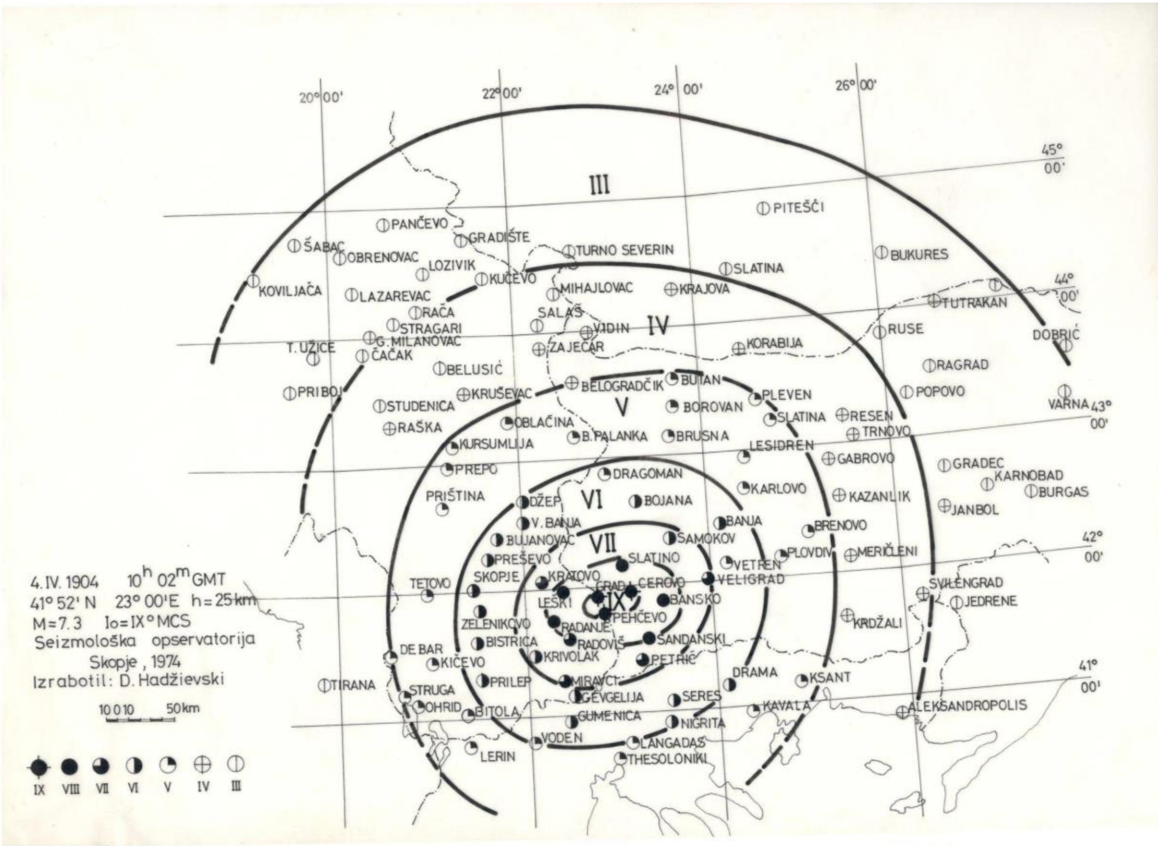

Fig. 1 – Reproduced macroseismic map of Pehcevo-Kresna earthquake on 4th of April 1904

Here, we tried to re-evaluate some of the seismicity parameters on the western part of the Pehcevo – Kresna faulting system. In order to detect a possible westward continuation and segmentation of the faults, we selected two polygons covering the Pehcevo and Kocani area. The results of our analysis with novel methods within both polygons were compared using the latest seismotectonic data, as described in the following section.

2. Seismotectonic characteristics of Pehcevo – Kresna source zone

Balkan Peninsula, has a lengthy history of catastrophic earthquakes and is one of the most seismic active areas in Europe. The territory of Macedonia, located in the south part of the Balkan Peninsula is also characterized by high seismic activity with many strong earthquakes. As part of the southern periphery of Eurasian plate segment, the Macedonian territory has been exposed to the ongoing continental collisional process due to dynamic pressure caused by the Dinarides-Hellenides mountain belt from west and Carpatho-Balkanides from east.

Epicentral areas belong to the three main seismic zones, West-Macedonian, Vardar and East-Macedonian seismic zone. The geological characteristics of the Republic of North Macedonia have a complex geology of many geological formations from different ages. (Arsovski and Petkovski, 1975; Dumurdžanov et al., 2004, 2008).

Earthquakes on 4th of April 1904 are the strongest recorded on the continental part of the Balkan Peninsula. They are generated in seismogene zone Pehcevo-Kresna as a part of Struma seismic zone, on the eastern border of the Republic of North Macedonia with Bulgaria (Pekevski, 2006).

The strongest earthquake, has the maximum magnitude of M=7.8 and epicentral intensity I=X (MCS). The major event was preceded by strong foreshock with magnitude M=7.3, I_0=IX (MCS) and many aftershocks with magnitude M_L=4.8 also on 4th of April 1904. It caused extensive damage and the geological effects included, landslides, rockfalls, liquefaction of the ground, changes in water and stream flow, and surface faulting. But the reappraisal of instrumental data as well as macroseismic effects yielded a smaller value M_s=7.2 (Ambraseys, 2001).

The biggest density of seismic events exists around and north from the Kroupnik fault, oriented approximately in west-east direction. To the east of the source zone, the seismic activity spreads to the town of Razlog, and to the west it is connected with faults along the southwestern board of the Delcevo graben. The seismic activity in the central part of the Krupnik source, where a complicated tectonic knot takes place under the Simitli graben, expresses a high seismic potential. The influence of the Kroupnik fault is clearly expressed to the north from its morphotectonic manifestation; this is connected with its northwards dipping (Meyer et al., 2002; Pekevski et al., 2006).

The Pehcevo-Kresna seismogene zone is considered to have accumulated seismic energy within a longer time period. The seismic energy accumulated during the permanent pressure of the Rhodopian massif from the northeast toward southeast is releasing continuously. The compression in that area resulting from the action of forces in opposite directions is reflected through the creation of several tectonic knots intersecting the Struma zone with many faults.

The neotectonic block structures as are the Rila and Pirin mountain massif in Bulgaria, as well as Osogovo and Plackovica-Ograzden in North Macedonia and other mountains rise for 4-6 mm/per annum. On the other hand the depressions in-between them experience relative subsidence. From the geological, geomorphological, geodetic and photogeological data, it has been defined that horizontal motion is taking place to the left and right along the main systems of conjucted faults (Petkovski, PhD diss., 1992).

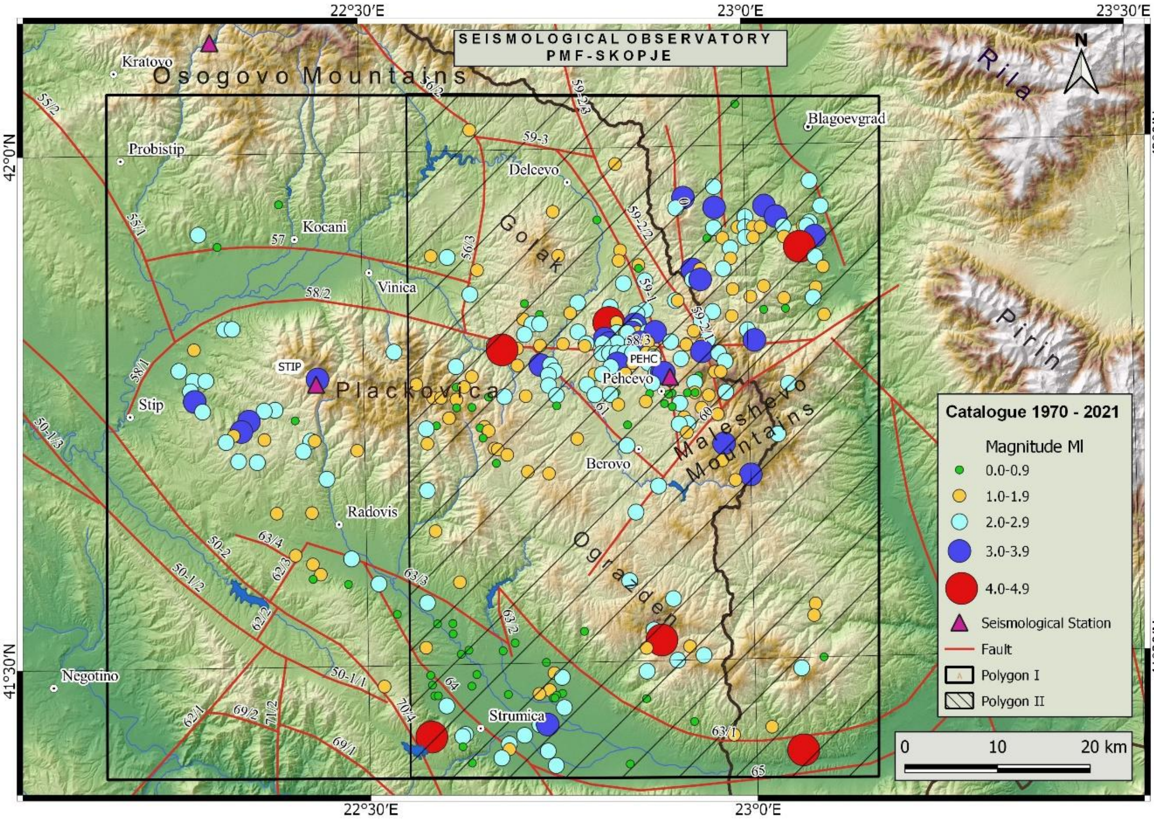

Fig. 2 – Seismotectonic map of the study region

3. Data and methodology

Using the data by the Seismological Observatory of the Republic of North Macedonia (SORM) recorded for the period of 1970-2021 (UNDP/UNESCO, 1974a, 1974b, 1974c), two areas of interest were defined according to regional seismotectonics (Fig. 2). The first one - between the latitudes of 22.4-23.1^{o}E and the longitudes of 41.4-42.0^{o}N (polygon I) and the second one between the latitudes of 22.15-23.1^{0}E and the longitudes of 41.4-42.0^{o}N (polygon II).

Then, a complete and homogenous catalogue of earthquake data was prepared to apply the Gutenberg-Richter relation (1) between the number of earthquakes (N) and their magnitudes (M),

$$LogN = a - bM \tag{1}$$

to obtain the values of the coefficients a and b.

The catalogue provided does not have magnitude scale variations as a result of the usage of uniform scale. Additionally, the original scale was converted into the moment magnitude scale M_w (Stejskal, Pekevski et al. 2010).

$$M_w = 0.9203 * M_L + 0.3987 \tag{2}$$

The most significant issue that may affect the values of a and b was detected to be the magnitude of completeness (M_C), due to the insufficient number of stations and their detectability in selected areas (Sinadinovski and M^{c}Cue, 2001). In our case, the limited data availability results in selection of only 340 earthquakes.

M_C was determined using the maximum value of the first derivative of the frequency-magnitude curve and a value of 2.7 was assigned. The dataset was de-clustered by the Gardner and Knopoff method included in the ZMAP software (Wiemer, 2001). Based on that method just 42 events were detected as fore- and aftershocks of the main events. The values of coefficients *a* and *b* were calculated using ZMAP software and were further verified by in-house calculated values using the least-square method. Also, for both areas of interest a grid of 0.05^ox0.05^o squares were assigned for coefficients' calculation.

Ultimately, an energy diagram was made, showing the normalized (by average annual amount) released energy by the events for a 10 years period and was smoothed with sliding window in increments of 2 years.

4. Results and discussion

4.1. Frequency magnitude relationship

The frequency-magnitude occurrence relationship helps to characterize the activity in each polygon. The occurrence rate of events in a given region, the random magnitude and spatial distribution of epicentres given the occurrence in time can be used to model the temporal and spatial randomness. The rate of recurrence of earthquakes on a seismic source is assumed to follow the Gutenberg-Richter relation giving in equation (1).

In this paper, from the calculation results (Fig. 3 and Fig. 4) can be seen the seismicity index values for *a* and *b* in different polygons. The calculation shows that the polygon II (Pehcevo – Kresna) is characterized by a higher value of *a* and *b*, which indicates that the seismicity in the period under consideration is more pronounced than the one in the polygon I (Kocani).

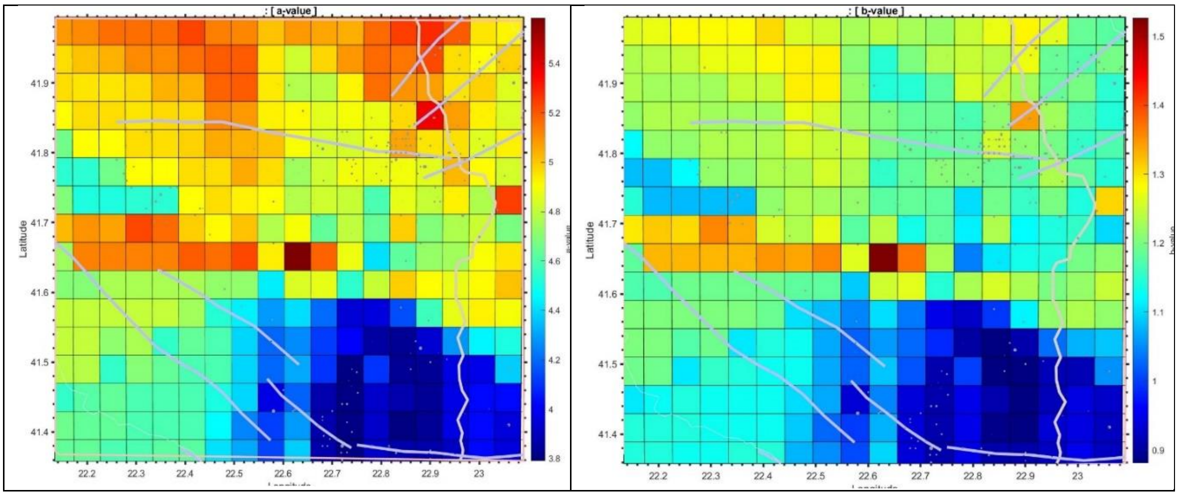

Fig. 3 – Values of coefficient a (left) and b (right) for the polygon I

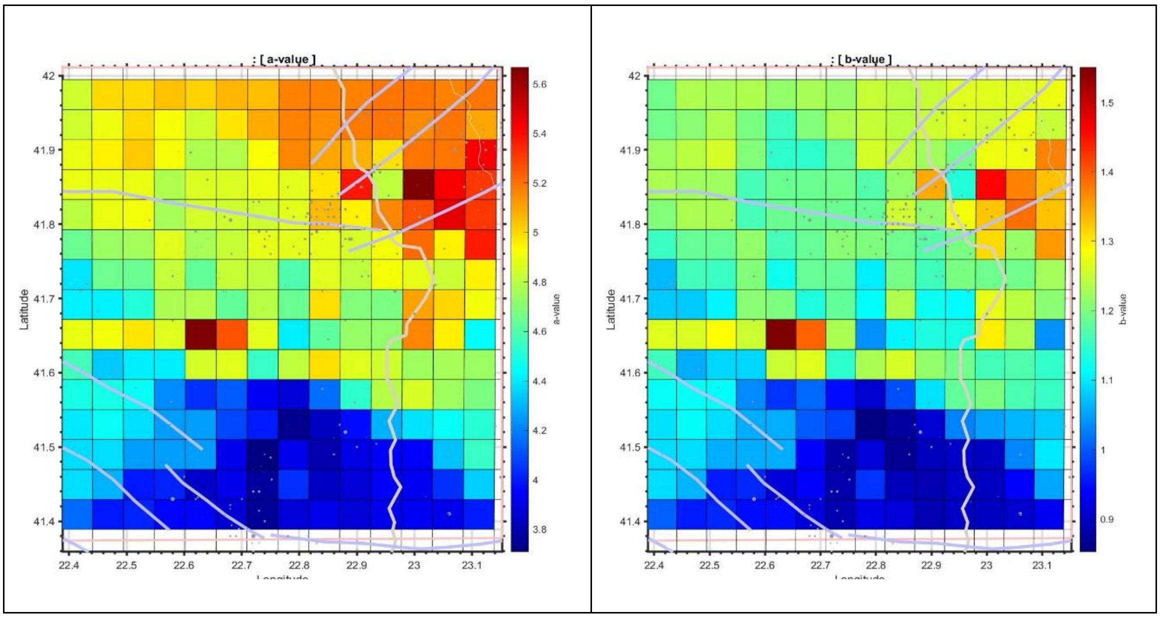

Fig. 4 – Values of coefficient a (left) and b (right) for the polygon II (Pehcevo – Kresna)

The value *a* is a parameter usually connected with seismicity of the considered area and the value *b* is a tectonic parameter showing the characteristics of the medium with reference to stress or the local crust condition. Figures 3 and 4 (left and right) show that the value *a* vary from 3.8 to 5.6 and value *b*, vary from 0.9 to 1.5. Their variation and the fitting coefficient *R* are given in Table 1.

Table 1. Values of the coefficients a, b and r for the polygons I and II

Poligon I (Kocani)			Poligon II (Pehcevo – Kresna)		
a	*b*	*R*	*a*	*b*	*R*
3.83847	-0.79293	-0.94036	4.0730	-0.7559	-0.91968

From our analysis of the coefficients' values displayed in Table 1, it can be concluded that there is no significant difference of *a* and *b* for the calculated value of magnitude of completeness M_C=2.7, which is shown by the high *R*-values.

This indicates that the polygon II (Pehcevo-Kresna) is categorized as high stress concentration area, especially in the eastern part of the area under observation. In that area is located Krupnik fault, which is oriented approximately in west-east direction as a part of Pehcevo – Kresna faulting system, characterized by high seismicity.

From the calculation value of *a* and *b*, it can be concluded that relatively similar seismic regime exists westward of the 1904 main shock area as shown by pleistoseismo line (Fig. 1). The differences in the values of *a* and *b* can specify the probability of earthquakes occurrence and variation in each part of the study area.

4.2. Energy release

Figure 5 describes energy release for the averaged seismicity period normalized on 10 years interval, when moving window was applied in increments of 2 years. We observed that after approximately 20 years of relative quiescence (1989-2009) the region enters a period of accelerated seismicity. Latest studies indicate that earthquakes on faults are sometimes preceded by phases of *accelerated seismic release* characterized by cumulative Benioff strain, following the power law of time-to-failure for different segments.

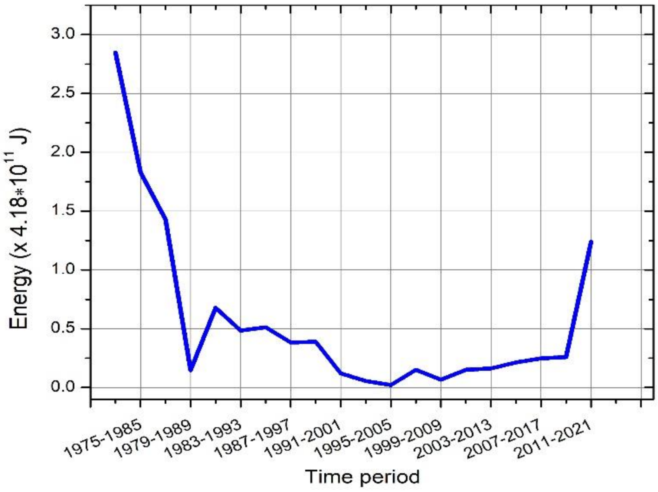

Fig. 5 - Energy release in the study area normalized on 10 years interval

According to the map of the maximum expected intensities for return period of 100 years (Jordanovski et al., 1998), the region can experience an intensity of VIII (MSK-64), which might be equivalent to an event of magnitude M=5.6±0.3 every 100 years. Hence, the released energy of the earthquakes E i.e. the seismic potential can be calculated from their magnitude, using the formula (3) (www.usgs.gov):

$$\log E = 5.24 + 1.44\ M \tag{3}$$

Figure 6 displays the time-dependent Benioff stress release diagram by (3) for the Kocani - Pehcevo region in the period 1970 until the end of 2021, where energy is represented in units of *ergs*.

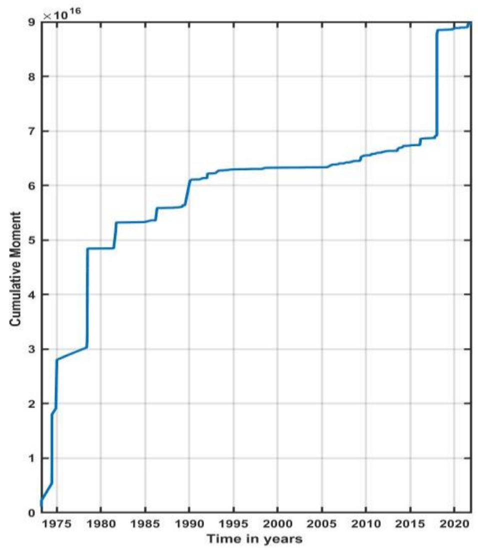

Fig. 6 - Time-dependent Benioff stress release diagram for the Kocani - Pehcevo region

Based on the diagram, it can be noticed that the accumulated stress in the volume was released in roughly three stages, each lasting about a year. Using the general formulas for size of the earthquakes and the surface of the related fault for the catalogue events distributed in average hypocentral depth of around 15-20 km, it can be concluded that the most of the seismic activity in the study region, is concentrated in the relatively old shallow crust.

5. Summary

In this study, we tried to evaluate some of the seismicity parameters on the western part of the Pehcevo – Kresna faulting system (Fig. 1). For this purpose, we selected two polygons based on geology and seismotectonic data of the area. Seismicity parameters *a* and *b* are estimated from Gutenberg-Richter relationship using the moment magnitudes above 2.7 from the de-clustered earthquake catalogue from the last century.

The main question of our analysis was whether is possible continuation and segmentation of the original fault expression. Since the results for *a* and *b* show very small difference between their normalised values for both polygons, it can be concluded that relatively similar seismic regime exists westward of the 1904 main shock area, as defined by macroseismic data.

Through the released energy graph for the averaged seismicity period normalized on 10 years interval, when moving window was applied in increments of 2 years, we observed that after 20 years of relative quiescence the region enters a period of accelerated seismicity.

Since it was noticed that the accumulated stress in the volume was released in roughly three stages, we used the general formulas for size of the earthquakes and their surfaced fault areas. For the average hypocentral depth of around 15-20 km, it can be concluded that the most of the seismic activity in the study region, is concentrated in the relatively old shallow crust.

Because the current value of the released energy is less than the 1970's cycles, it can be speculated that the region has potential to experience larger earthquakes in foreseeable future. The results of this study may affect the seismotectonic models presently used for that section of the faults and help in the earthquake hazard assessment on regional and wider scale.

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