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Seismic Hazards and Risk Assessment of Badakhshan Region (Northeast Afghanistan)

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Abstract

The Badakhshan region, in the northeast of Afghanistan, has complex and intertwined geology that was created as a result of the collision of the Indian and Eurasian blocks (Thingbaijam et al. 2009; USGS). The tectonic maps of the active tectonic plates of the region are updated from time to time and new information is obtained, which is necessary to reduce the risk of earthquakes. Therefore, using the data of the EMME seismic catalog with updates (years 2011-2021) from the website of Harvard University and the International Centre for Earthquake Research (ISC) and USGS, a catalog was prepared of the epicenters of machine earthquakes from 1900-2021. Then, considering the last earthquake with a magnitude of 7.2 in 2015, coefficients a and b were calculated at the surface and depth. this amount for variable b reaches the maximum value of 0.8 in the northern half and 0.65 in the southern half. The increase in numerical values of a, and b in the central and southern half after the 2015 event has been fully evident. It is expected that in the future, the occurrence of earthquakes in the southern half of Badakhshan will increase the mentioned values. The results indicate that contrary to the direction of the main fault in North Badakhshan (north-south), the highest frequency of earthquakes >=4 at and depth of 150-70 km, earthquakes >=5 and a depth of 150-300 km, and finally earthquakes >=6 at depth 300 -150 km in the east-west direction. This area is exactly the place where the Pamir Corridor plate sinks to the west and southwest of Badakhshan due to the pressures of the Indian plate. The results of this research show that the tectonic situation of the region is subducting towards the south and the western Haunt and has caused compression and bending in the subduction zone, which has caused ruptures on scales of 1 cm to more than that. It is worth mentioning that these small faults are the continuation of the previous faults and the evolution of their lengths shows that in the extreme part of the Pamir Corridor (Ashkashim city) from east to west and south, there are ruptures in the depth of 0-150 km in the country. It shows

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three new trends: east-west, east-southwest, and central-north.

***Keywords**:* Himalayan Alpine Belt, Pamir and the Hindu Kush, Badakhshan, Afghanistan

1. Introduction

Due to the continental collision of the Hindu Kush(Shanker et al., 2007; Sippl et al., 2010,2011, 2014) and Pamir(Sycheva et al., 2021; Sychev et al., 2019) Mountain ranges (Wheeler, 2005), faulting, rifting and folding, compression and tension have both occurred in this region and provide a limited frequency tomography, based on common local and remote inverse earthquakes, for the Hindu Kush in Provide Afghanistan, where slab fracturing is underway (Li, 2018; LOU,2007; Lukk, 1995). We interpret ourselves. Due to the inward crustal drift of the Indian block, as a result, the Badakhshan Plate moves northward, during penetration into the depths along the thrust, the crust thins and stresses increase, and by nature, the lithosphere is mostly disintegrated and thinned in the horizontal direction and We will have east-west. Finally, we will have an earthquake when the Hindu Kush crust gets stuck in the depths. Most likely, the coupling of crust and mantle is related to breaking in depth. Geological signs and evidence of new construction activities include those movements and shape changes that started in the late Tertiary and continue until now. Among these types of movements and shape changes, we can mention shortening or lengthening, thickening or thinning, young bending or arching in the crust, young folding and breaking in rocks and layers of the earth, diapirism processes, young discontinuity, heterogeneity, volcanism, and young isostasy. Earthquake is considered one of the most important signs in the recognition of new construction movements in any region. Afghanistan is located in the Alpine-Himalaya earthquake zone (Yadav et al. 2012, 2013), there have been earthquakes here since ancient times, but they have been less studied. Earthquakes in Afghanistan have not spread evenly, 90-95% of earthquakes occur in the northeastern part, especially in Badakhshan, where 1070 earthquakes have been recorded in this part of the country. In Afghanistan, there are three main regions containing sedimentary rocks: 1- North Basin, 2- Southwest (Helmand River Basin), and Ketwaz Region (South East). The igneous and metamorphic masses are particularly large in the east and southeast of the country, which includes: Badakhshan, Nuristan, Laghman, Parwan, Paghman, areas around Kabul, and strips in the central and southern regions of the country. In terms of age, the Upper Paleozoic and Mesozoic formations are more widespread in Afghanistan (Benham et al., 2009). One of the prominent characteristics of the structural geology of Afghanistan is the existence of major faults and fractures that form the boundaries of different geological regions. In addition to these major trends, there are scattered structural elements throughout the country. The eastern and southern blocks are moving towards the north and are colliding obliquely with the continental mass of Asia. The last block that is joining this complex is the large continental block of India. The tilting of this continent has caused changes in construction processes, fractures, and folds. These blocks are separated from each other by seams along which ophiolites can be seen. In appearance, these are only remnants of the subducted oceanic crust, which itself indicates oceanic spaces of uncertain width. Rahman et al., 2021 prepared a catalog by collecting data from the International Seismological Center (ISC) from 1900 to 2005 and the United States Geological Survey (USGS) from 2006 to 2017. It showed that during the period before 1960, the catalogs were incomplete. Metzgar et al., 2021, installed 19 new global navigation satellite (GNSS) stations between 2014 and 2020 in the Hindu Kush (northeastern Afghanistan) and northern Pamir to extend the three profiles of the Panjshir NE fault, the Badakhshan N fault, and the Pamir thrust after the 2015 earthquake. they did They investigated the possibility of an earthquake with a magnitude of 6.4 in 2016. Waseem et al., 2019 are based on an updated and homogenized earthquake catalog consisting of 29,097 >4 events. In this research, he used the ground motion prediction model for shallow and deep earthquakes. High PGA values were obtained for the provinces of Badakhshan, Kunduz, Takhar, and Kabul, in the northeast of the country, which is located in the Hindu Kush and Pamir Mountain ranges (Bloch, 2021a: 2021b; 2022,). It also showed that the results obtained are generally consistent with the study of Zhang et al. and Kufner et al., 2021 showed that part of the subducting plate breaks during a continental collision due to traction.

2. Material and Method

In this research, all historical earthquakes and mechanical earthquakes along with the focal mechanism of earthquakes that have occurred in Badakhshan have been investigated. Historical data from reports and books. The history of Faiz Mohammad Kateb, which was not included in other catalogs, and the historical data collected from Embersys articles, as well as the seismic data of the device needed for the study, from the EMME catalog with updates (years 2011-2021) from the university website Harvard and the International Center for Earthquake Research (ISC) and other international authoritative sources, were obtained. In the earthquake department, investigations were done about the history of the region and the results showed the features of the Badakhshan earthquake. The software used in this study is EZ frisk, Global mapper, and GIS 10.2. is. At first, the device seismicity data was standardized by the relevant formulas, which means that the magnitudes approved by each organization and site were all converted to Mw magnitudes, then it was entered into the EZ frisk software for modeling. In the next step, they were converted into a map by Global mapper, GIS 10.2. Finally, while monitoring the catalog of earthquakes related to Badakhshan, the pattern of Gutenberg-Richter seismicity coefficients including a, b was determined and an attempt was made to prepare equipotential maps of these two important and key variables.

3. Location of the Study Area

Badakhshan is one of the northeastern provinces of Afghanistan, which is located in the mountainous region of Hindu Kush (Metzger et al., 2021), and Pamir Li and Wei, (1983), and between longitude 70 degrees 4 minutes 36 seconds east and latitude 36 degrees 50 minutes 16 seconds north; (Figure 1) is 1,800 meters above sea level (Kufner et al., 2018). This province is located 470 km from Kabul. The area of Badakhshan is more than 47,403 square kilometers, and the amount of Quaternary sediments is low and mostly limited to the river bed (Rahman et al. 2021). Heights are often composed of limestone, dolomite, and in some cases, a set of rocks with a high degree of metamorphism, such as gneiss. In different sources, different tectonic zones are considered for Afghanistan, but what caught the author's attention is 1: Band Amir zones, 2: Sukhab, 3: Western Badakhshan, 4: Eastern Badakhshan, and 6: Nuristan zone (Gutenberg, Beno, and Richter, 1942**)**. The geology of Badakhshan is structurally very complex and consists of sequences of narrow trends of northeast-southwest lands of continental fragments, from the Paleozoic to the Tertiary age. In terms of geological formations, rocks of Precambrian to Quaternary age can be seen in Badakhshan and different geographical places with different ages and gender. Also, the glacial sediments of the fourth era can be seen in the Hindu Kush mountains

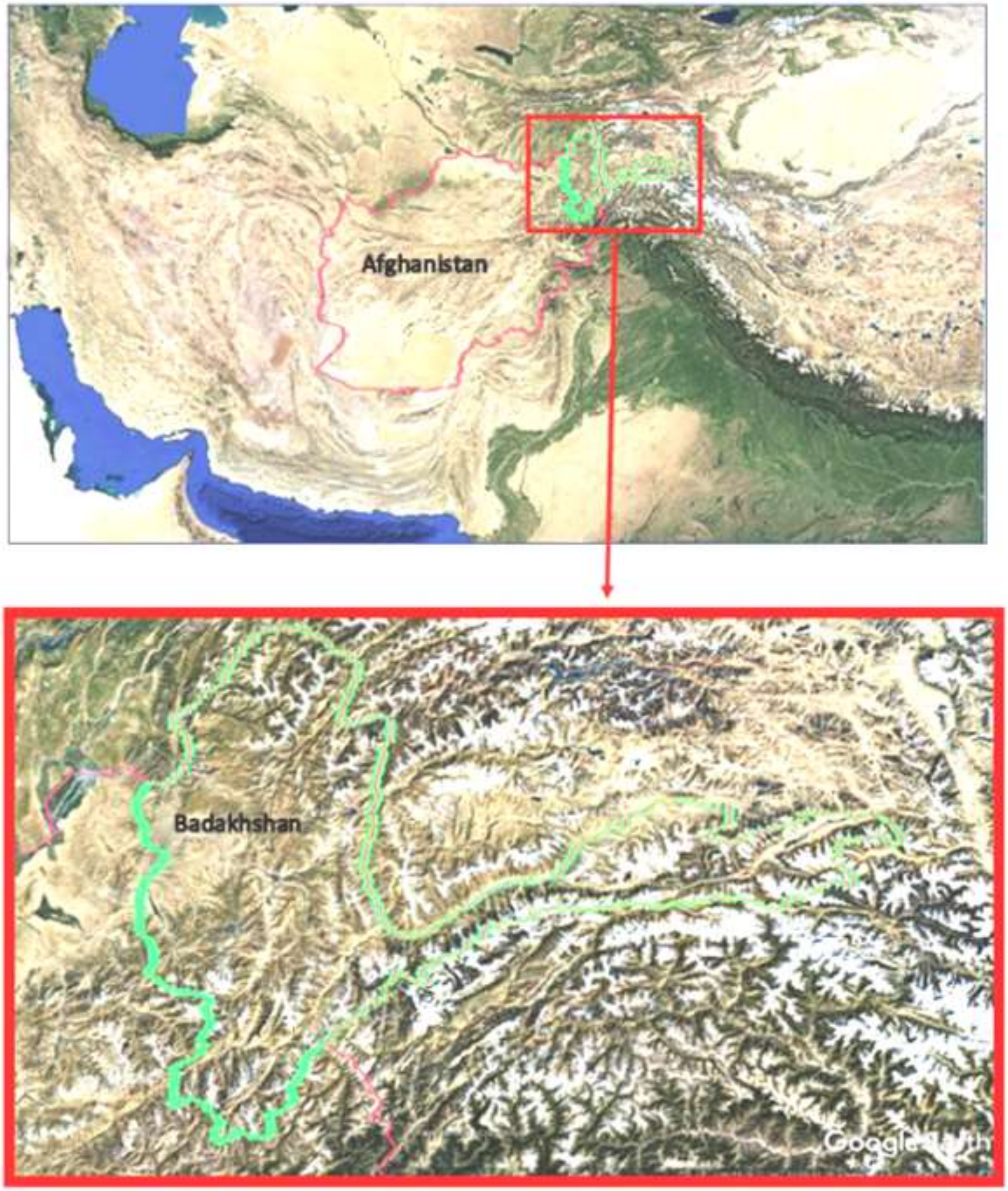

Figure 1. Geographical location of the study area research

4. Depth of the Focus of Earthquakes in the Region

According to (Figures 2, 3, and 4), an important point that can be mentioned about the Badakhshan seismic zone is the foci between the depths of 300-150 km (green trend) and the foci of the depths of 70-150 km (blue-green trend). It can be considered a seismic layer. Active alluvial cones can be seen in the Conic line of the Pamir and Hindu Kush Mountain ranges. These alluvial cones are the path of young rivers, which have been dug among the old alluvial cones due to the active tectonic influence of the region. Of course, the humid climate of the region, on the one hand, and the high rate of erosion and transport by the rivers of the region, on the other hand, have caused the transfer of Quaternary sediments to other lowland areas to form alluvial cones in those areas. Therefore, the area covered by Quaternary sediments in this region has a very low percentage.

5. Catalog of Seismicity and the Trend of Earthquakes

Most of the earthquakes that occurred after the 19th century in the study area have a small magnitude but a large distribution, which are at great depths of up to 270 kilometers. In this research, an attempt has been made to introduce earthquakes with a magnitude of M=>4. According to (Figure 2) and observing the distribution of earthquakes in the study area, we will notice the concentration of earthquake foci in the opposite direction and direction of the main fault of Chaman and North Badakhshan (north-south extension) in the Pamir-Hindu kush mountain front. The Pamir-Hindu Kush region is located in an active and earthquake-prone region (Khan, 2003). While many researchers continue in the field of producing seismic catalogs in this region, however, the interpretation of catalogs using different criteria and with different characteristics is still incomplete (Rahman et al. 2021). The written reports of the historical earthquakes of Afghanistan (Embersis) from 734 AD to today describe a catalog of more than 1300 earthquakes in Afghanistan [30], which mostly occurred in the Badakhshan region. According to the EMME catalog (1900-2011), with the 2011-2021 update, shown in the map below. According to the shape of seismicity, the region has a northeast-southwest trend, which has the highest frequency of earthquakes with a magnitude of 4 on the Richter scale.

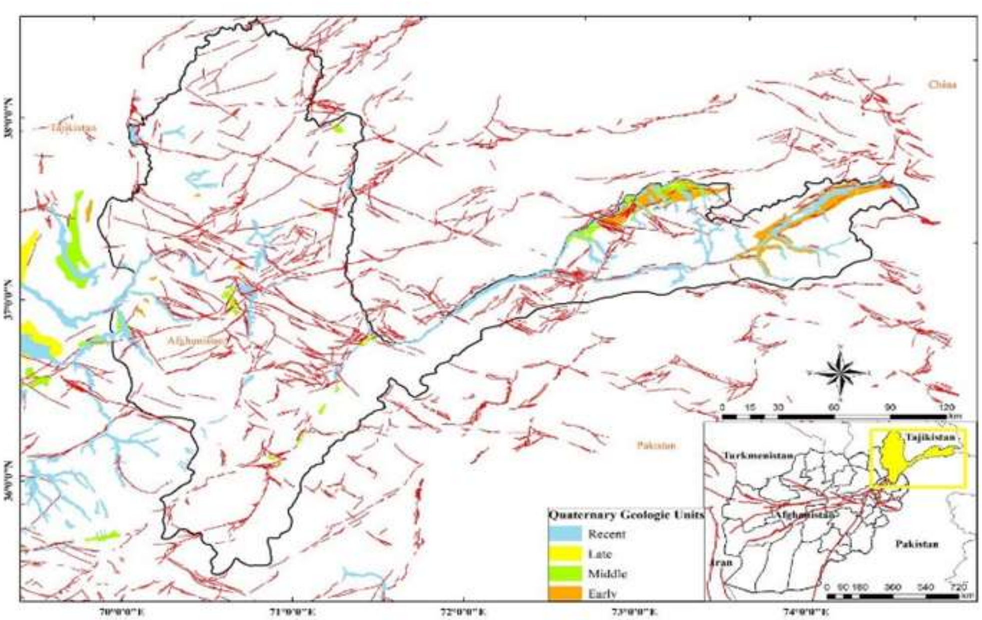

Figure 2. Division of Quaternary into four categories of early, middle, late and recent quaternary

6. Density of Earthquakes in the Region

To prepare km from the center of Badakhshan and 200 km deep in the Hindu Kush mountains), the list of earthquakes in the studied area was processed in Z Map software and the final results are shown in (Figure 4). The density of earthquakes is considered an exponential function of the number of events per square kilometer. The highest frequency of earthquakes is related to the end of the Pamir Corridor and the South Badakhshan Plateau (Hamburger,1992, Strecker, 1995; Metzger 2017,2020). The low density of earthquakes before the 1997 event is fully evident in the southeastern part of the fault. This variable reached a higher level after the 1997 event. The increase in this variable shows a clear relationship with the southeastern part of Badakhshan. Considering this pattern, it is expected that more earthquakes will occur in the southeast part in the future to establish a balance between the density of earthquakes in both the northwest and southeast parts.

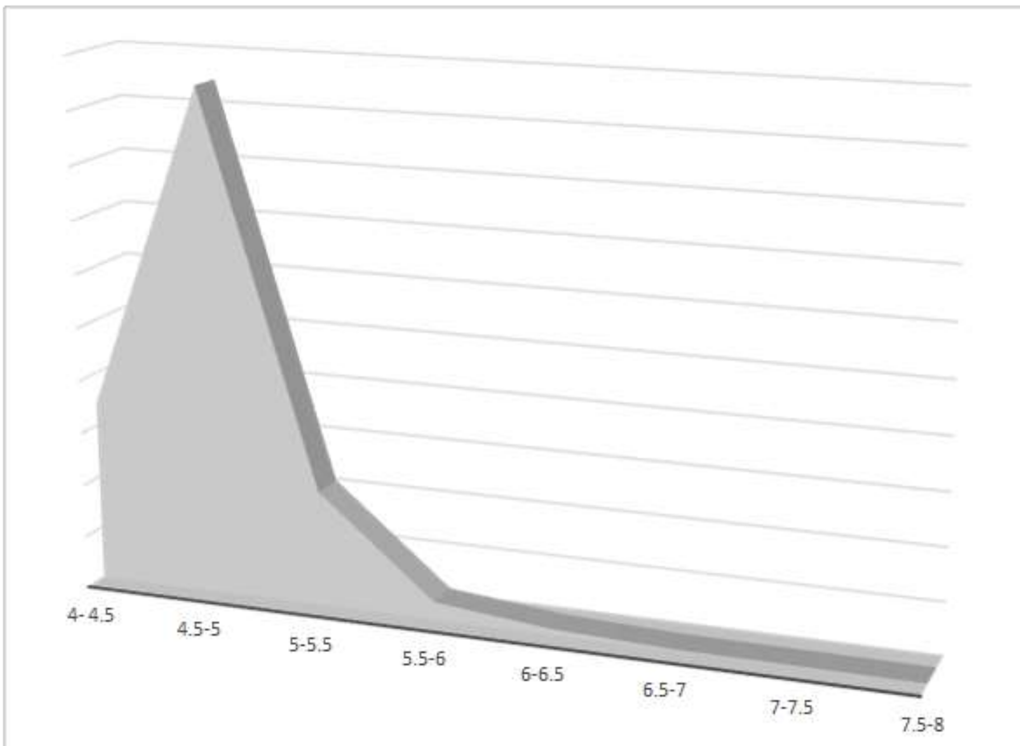

Figure 3. Frequency of fault distribution**.**

Figure 3, shows the results related to the frequency distribution of earthquakes based on their magnitude. The magnitude has been divided from 4-8 into half-Richter intervals, as the results show that the majority of earthquakes in the first two categories were 4-4.5 and 5-4.5 on the Richter scale.

The term fracture is derived from the Latin word fractus, meaning to break, and is a general term in geology that refers to the surface of discontinuity in materials and rocks that undergo deformation and along which the adhesion of materials has been lost (Twiss and Moores, 2001) since fractures occur in a variety of sizes, from less than one millimeter in length (cracks and cleavages) to several hundreds of kilometers (large faults), and express the direction and type of stress. Itself and the characteristics of stress in materials include fracture, one of the most important geological structures can be found in this way to find their mathematical and geometrical model to quantify the formation of these structures. Fracture classifications in many branches of geosciences are an important reason to pay attention to their location. Fracture patterns are used to study seismic areas. Statistical modeling is one of the methods of fracture study in geological studies. This means that in the statistical model, the lists in the statistical population of fractures (such as length, the distance between fact, rues, and their density, etc.) are calculated and analyzed. The process model is an index model including frequency values, displaying data on logarithmic charts, determining optimal curves, and their equations, which have mathematized finitionstion and sizes.

Classes	Frequency	Percent
0-10.100	29414	99.3
10.100-20.200	166	0.6
20.200-30.300	24	0.1
30.300-40.400	8	0.0
40.400-50.500	4	0.0
50.500-60.600	0	0
60.600-70.700	1	0.0
70.700-80.800	0	0
80.800-90.900	1	0.0
90.900-100.100	1	0.0
Total	29619	100.0
Mean	1.48	
Median	0.88	
Minimum	0	
Maximum	100.92	

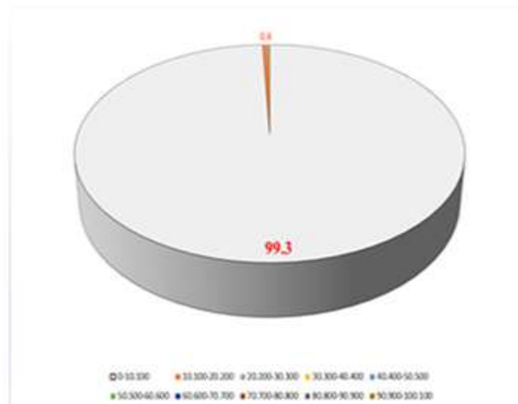

Figure 4. Fault length and thickness of Badakhshan faults

In the table above, the length of the faults is given in ten-kilometer classifications. As the information in the table shows, most of the faults are in the 1CM–10-meter floor. The total number of errors was 29,619. The average length of faults is 1.48 meters, the minimum length is 1 cm and the maximum length is 100.92 meters. As shown in the diagram, more than 99% of the faults were between 1 cm and 1 meter in length. The average length of the faults shows that the absolute majority of them have a length of less than one meter, and this means that in response to the compression of the region and the subduction towards the south and southwest, and the bending of the main reverse fault, some discontinuities have been established in the bulge of the fault, or is forming.

7. Length Analysis

In the longitudinal statistics of faults in the region, the analyses were done by examining the changes of one variable with another variable, and in the term, the changes were examined in only one dimension (**Figure 5**). Because the length of the fracture shows, therefore, in general, with the increase in the frequency of the fault, the length of the fracture decreases (Twiss and Moores, 2001). Larger fractures only participate in large events and change if the fractures The smaller one participates in few events and changes in case of anincrease in length or rotation and change in the distance between the fractures (Ackermann et al., 2001). Longitudinal distribution analysis is done to analyze the relationship between fracture length and earthquake events. In this way, the length and number of fractures indicate the number of fractures greater than 5, so the analysis of the frequency of fracture length is the appropriate way to acquire the mentioned goal (Ackermann et al., 2001). The more skewed the graph is to the right, it indicates that in the same events, smaller structures are more important than larger structures.

Ackermann et al., 2001 believe that there is no tendency to create new fractures in natural fracture systems with an increase in occurrence, but rather an attempt to evolve previous structures, and with an increase in occurrence, fractures begin to change in direction and distance between them. Finally, the length changes, and the geometry of the fault effect becomes irregular to the point where the connection and communication between the fault and the existing faults become the transmitter of the event to another place.

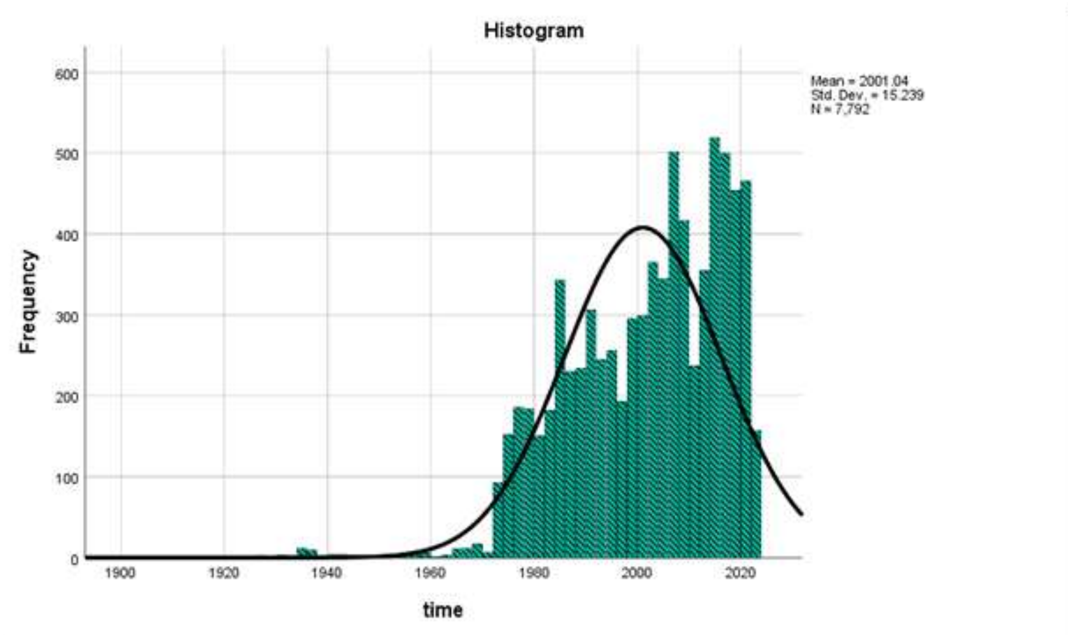

Figure 5.

Here (statistics that is used in geological sciences) the second and third dimensions of statistical analysis also enter this field and then it deals with the changes of the variable along with its location, such an analysis is called spatial analysis, in other words, geostatistical studies of changes examine a variable in different places and assigns a specific value to the desired variable in each situation(Mousavi, 2017). It displays a place in the form of a two-dimensional map. The advantage of this method is that the resulting map can be analyzed from different aspects and the changes can be compared with other types of parameters. The above figure shows the information related to the earthquakes that occurred in the Badakhshan region. As the information in the figure shows, as we approach the recent years from 1900, the number of recorded earthquakes has increased. The most important reason is the advancement of recording technologies and more accurate recording of earthquakes. It also shows the more important cause of fault activity, which causes more earthquakes. Another result that can be taken is the creation and formation of new faults and sub-faults in the region. Since the region is tectonically active, it is not out of mind to have more emerging faults in different scales. The skewness of the graph to the right means recent years and is a confirmation of the above view.

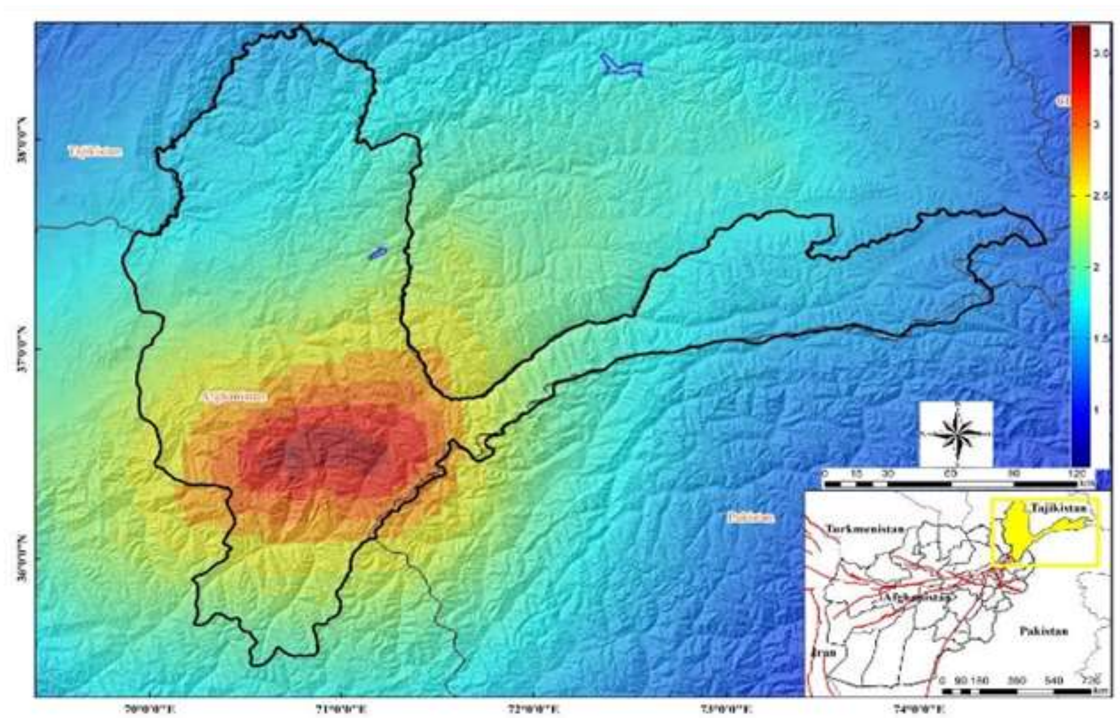

Figure 5. The density of earthquakes in the studied area

8. Seismicity Variables a and b at the Surface

Seismic coefficients a and b, which are known as Gutenberg-Richter coefficients, are key factors in determining the amount and position of stress in a region. For this purpose, the equipotential map of these two variables was drawn on the ground. If we divide Badakhshan province into two regions, north and south, this amount for variable b reaches the highest value of 0.8 in the northern half and 0.65 in the southern half. The increase in numerical values of a, and b in the central and southern half after the 2015 event is fully evident. As was said before, it is expected that in the future, the occurrence of earthquakes in the southern half of Badakhshan will increase the mentioned values.

9. Seismicity Variables a and b in Depth

While analyzing the list of earthquakes in the studied area before the 2015 event, the numerical values of a and b for the southern half of the fault are almost zero. But after the mentioned 2015 earthquake event, these values have increased to a great extent for the northern half of the fault in the shallow part. But the deeper parts in the northwest half, the shallow and deep southeast regions, have low numerical values of a and b, and for this reason, it can be predicted that the next earthquake will occur in these parts.

10. Earthquake Migration

In this section, earthquake movements on the fault plane are considered from a time point of view. This is to determine whether, over time, earthquakes have defined movements on the fault surface (Berberian, 2014) and have migrated, or whether their occurrence was completely random from a spatial point of view. The movement of the surface focus of earthquakes related to Badakhshan from 1900-2021 from southeast to southwest and west is completely known. This is important in confirming the previous seismic behavior of the fault during the events before 2015. In simpler terms, seismic migration is from the southeast to the northwest, whether over time or during a seismic event. What can be distinguished from the seismicity of Badakhshan in the last century, indicates the fact that the energy of the fault during relatively large earthquakes starts from the southeast segment. The location of the accumulation of this energy gradually moves towards the northwest and in the meantime, with the occurrence of numerous earthquakes, some parts of the energy are released and the other part continues to move. Perhaps one of the reasons for the rupture with these dimensions is the rupture of parts of the fault in previous events and the release of the fault path. If this theory is completely correct, there should be a high slip rate for Badakhshan.

11. Results and Discussion

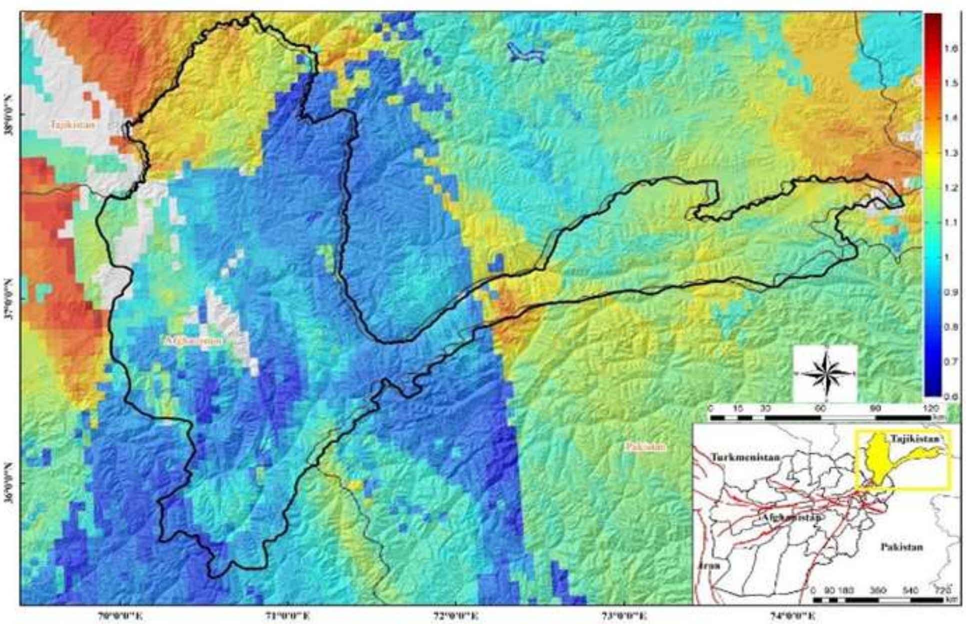

Figure 6. Scattering of seismicity coefficient b in the studied area

The recent continuous earthquakes in Afghanistan show that many areas in this country are under active tectonic stress and there is a possibility of an earthquake in any area. Checking the possibility of an earthquake in recent years has been done with earthquake risk analysis methods, but in some cases, other methods have been proposed, which are based on the changes in physical parameters before the earthquake. For example, in several types of research, it has been shown that some parameters such as local gravity (Li et al., 1983), local magnetic field (Iftaxias et al., 2002), groundwater level (Kopylova et al., 2017, Asim et al., 2017) and underground water temperature (Li et al., 1983) and soil electrical resistance change before the earthquake. In addition to this, many types of research have been conducted with the help of statistical analysis to obtain appropriate information about earthquake risks (Asim et al., 2017, Sammonds et al., 1992). One of the important seismic parameters in the field of risk analysis and estimating the probability of an earthquake is b is the Gutenberg-Richter relationship (Scholz, 1968). Parameter b is related to the stress level of the region so the value of parameter b decreases with the increase of stress in the region (Bufe, 1970; Scholz, 1968). Some believe that parameter b can be used as an indicator of stress. In a usage area (Jackson and McKenzie, 1984), since the stress level in the area changes with time, it can be said that parameter b is a function of time and changes with time. The decrease of parameter b with time can be used as an appropriate tool to analyze the risk of earthquake occurrence in a specific period (Nuannin et al., 2005). The changes of parameter b in high-tension areas, especially before the occurrence of strong earthquakes, have been checked many times. Recent research shows that this parameter decreases in high-stress areas before an earthquake occurs and this decrease continues until the occurrence of an earthquake (Scholz, 1968; Gutenberg and Richter, 1944; Sammonds et al., 1992). It is necessary to have more appropriate and complete primary information, which is so called the richness of the catalog of earthquakes (Scholz, 1968), in which all earthquake events in a region are recorded by measuring systems and the number of these events is at a desirable level. Considered the catalog complete or rich. Usually, the higher the accuracy of parameter b calculations, the more reliable the catalog is in a region and the more reliable the final results.

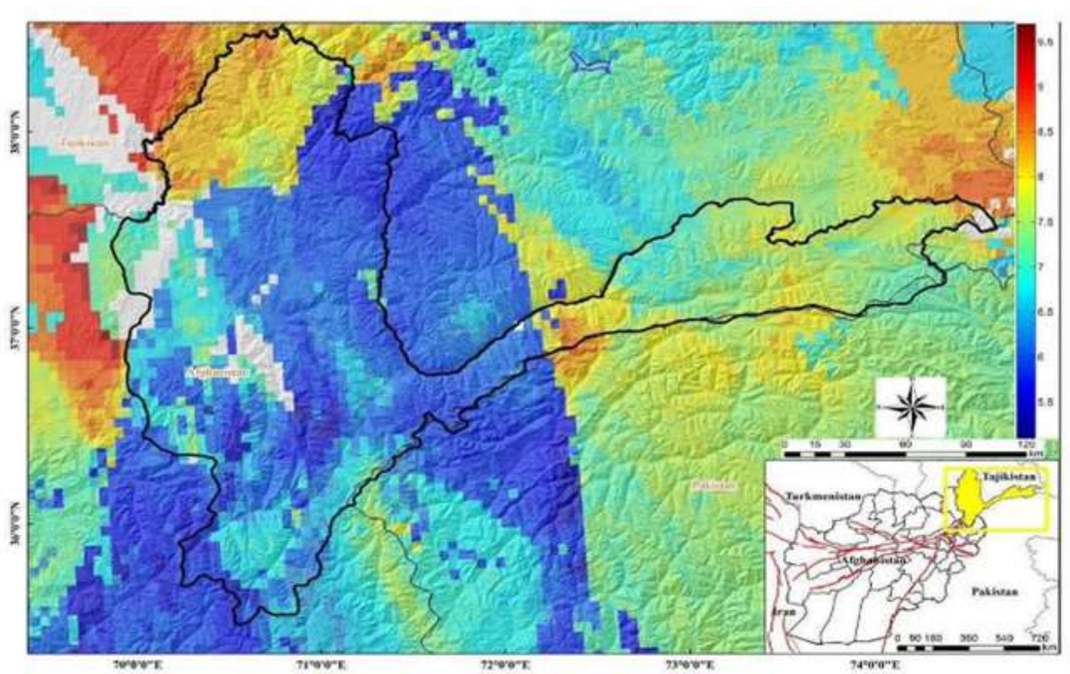

Figure 7. Scattering of seismicity coefficient in the studied area

After analysing the list of earthquakes in the studied area in Zmap software, the variable equipotential map b, a has been drawn on the ground surface (Figure 7). In two regions, one in the eastern bend of Badakhshan and the other in the eastern and western half, the numerical values of b and a are relatively high (Figures 1 and 2). This amount for variable b in the first part reaches the maximum value of 0.8 and in the second part, it reaches 0.65. Regarding variable a, these values are 5.5 and 4.5. The increase in numerical values of a, and b in the central half of the fault (Badakhshan region) after the 1997 event is fully evident. It is expected that in the future, the occurrence of earthquakes in the eastern, southeastern, southwestern, and southern parts of Badakhshan will increase the mentioned values. It should be mentioned that the increase of these two variables in the southern corner of the studied area is related to the earthquakes of the Nasdaq fault that occurred after 1997. There is a general principle about areas with active tectonics.

Such areas are prone to earthquakes. With the concept that future earthquakes can be expected in these areas. The ability to seismicity and in other words locate future earthquakes has been the main goal. But every theory, even if proven, needs to be investigated in other areas. Therefore, a great event of 2015 with a magnitude of 7.2 was taken into consideration as a validation criterion. In such a situation, first, all the analyses from 1900 to before the 2015 event were done once. The expectation is that according to the foreshadowing theory, the next earthquake will occur in one of the predicted situations. Therefore, the same analysis was done once again for the years 1900 to 2021, and this time the areas prone to future events were identified and introduced. If the 2015 event is located in one of the regions of the first part of the study, this theory can be cited in the Badakhshan region.

12. Conclusion

Earthquakes in Pamir and Badakhshan are divided in such a way that there are more than dozens of tectonic blocks and fractures in this area of 44,059 km². According to the trends of historical and systematic earthquakes from 1900-2021, three new trends have been established in low, medium, and high depths. In fact, contrary to the direction of the main fault in North Badakhshan (north-south), the highest frequency of earthquakes >=4 and a depth of 150-70 km, earthquakes >=5 and a depth of 150-300 km, and finally earthquakes >=6 at a depth of 150-300 km It occurs in the east-west direction. This area is exactly the place where the Pamir Corridor plate sinks to the west and southwest of Badakhshan due to the pressures of the Indian plate. From the first seismic risk maps (Zare, Kamranzadeh, and Farnaz, 2014) of Afghanistan, we can refer to the seismic risk zoning map, which the research of Baloch et al. 2021 also confirms this claim. Also (Schurr et al., 2014; Bai, and Zhang, 2015; Kufner, 2018) confirmed the earthquake-prone areas in the southeastern part of the region. Sippl et al., 2013 confirmed the same issue in the seismic catalog they prepared. This shows that at the end of the Pamir Corridor from east to west and south, ruptures are being created at depths of 0-150 km. The country has three new trends: east-west, east-southwest, and central-north. Earthquake movements show the migration of the focus of earthquakes. The movement of the surface focus of earthquakes related to Badakhshan from 1900-2021 from southeast to southwest and west is completely clear.

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