Research Paper

Tectonic Setting and Seismicity of the Badakhshan Region, Afghanistan

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ABSTRACT

The plate tectonics of Northeast Afghanistan are complex with diffuse and sparse seismicity in the broad plate deformation zones embedded by a number of micro-plates in the Badakhshan. Geothermal techniques in this area provide an important tool for investigating plate tectonic kinematics and identifying the approximate plate tectonic geometries. In this paper, we have processed seismic centers data (1909-2022) collected by EMME and USGS catalogs and geothermal data by Landsat 8 satellite images. Modeling of tectonic lines by geothermal energy and seismicity trends are studied. We find that the deformation in Northeast Asia can be well described by several blocks, independent of the Eurasian plate motion. Landsat images showed the important geothermal lines with medium and low importance. Tectonic micro-zones were defined by placing lines of high importance and medium importance together. According to the trend of seismicity centers concentrated from east to west of the Badakhshan region, the result shows the continuation of east-west fractures. This east-west trend in the center of Badakhshan is located exactly in the fracture and the edge of the micro-zone plate with medium importance. The transformation of medium-importance fractures into high-importance fractures in the geographical center of Badakhshan can cause more important earthquakes in the region

Keywords:
Slip tendency; Enhanced geothermal systems; Seismicity; Badakhshan

1. Introduction

Any plate has a growth process from small to large. The micro-blocks or micro-plates are sometimes the precursors of large plates [1]. Afghanistan is located on the border of the Indian, Eurasian and Arabian plates and therefore is located in a seismic zone. Based on an updated and homogeneous earthquake catalog consisting of 29,097 larger than 4.0 earthquakes for Earth, it is used for shallow earthquakes. The Pamir at the northwestern tip of the Indo-Asia contact zone (Figure 1) is a seismically active orogen that produces M6-7 magnitude earthquakes approximately once every 10 years. During the last 50 years, they have mainly occurred along the northern perimeter of the Pamirs . focus earthquakes at the boundary between the Pamir and Hindu Kush mountains including the Hindu Kush mega source. Reconstruction of the Late Cretaceous-Paleogene basin between the Northern and Central Pamirs allows connecting of anomalously high seismicity with the deformation of the subduction

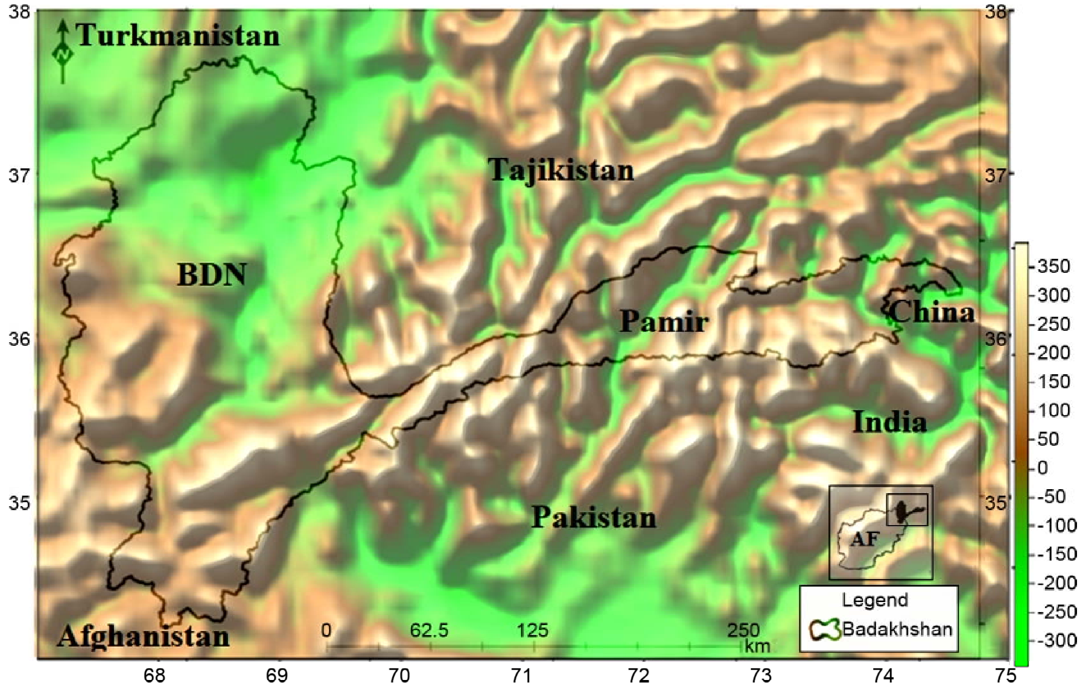

Figure 1. "BDN" stands for Badakhshan and "AF" stands for Afghanistan.

plate (slab) of the oceanic lithosphere in this basin during its submersion into the mantle. In this sense, the Vrancea zone in the Carpathians is an analog of the Hindu Kush Mega source. The concentration of mantle earthquakes of the intermediate type with hypocenter depths up to 300 km and magnitudes up to 8 and greater within a small mega-source region at the boundary of tectonic zones in the Hindu Kush, Central, and Southwestern Pamirs have 90% of strong earthquakes in the Pamir-Hindu Kush zone and 95% of released energy are concentrated territory of 200 × 120 km. In the western region, mantle earthquakes are sharply interrupted at 69°30 E. The zone of mantle earthquakes approximately 350 km long with hypocenter depths up to 200 km is extended to the northeast of the mega source already on the territory of the Pamirs. Thus, the belt of mantle seismicity with a total length of up to 500 km is pronounced. The Hindu Kush source is confined to its southwestern part [2]. The Pamir Mountains, in Central Asia, are the result of the northward subsidence of the Indian continent into Eurasia. On average, the Pamir Plateau is 3,000 m higher than the adjacent Tajikistan depression to the west. We present a set of high-precision point-positioning data that show in great detail how the upper Pamir crust subducts into the lower Tajik depression. This westward transfer occurs in shallow, low-friction sedimentary layers that reach the surface at the beginning of the Tian Shan Mountains further north. These sediments accommodate a total slip of about 2 cm, which is very high for continent-continent plate boundaries. In addition, our data observed a few centimeters of slip on the Gate fault, most likely triggered by a large earthquake 200 km away. Such phenomena have rarely been observed so far. At the northwestern tip of the India-Asia collision zone, the Pamir foothills overcome the Tajik Depression and the Tarim Basin and collide with the Tien Shan. Currently, the northern edge of the Pamirs shows a local shortening rate of 13-19 mm/year. While the eastern Pamir and the Tarim Basin move northward in roughly the same block, the north-south shortening decreases westward along the Pamir Front toward the Tajik Depression. In the northeastern depression of Tajikistan, the wedge-shaped crust of Peter I is compressed between the dextral faults of Vakhsh and the sinistral-Farouz-Darvaz faults. Global Navigation Satellite shows that there are many geothermal areas in Badakhshan. Geothermal resources are found in a wide variety of geological regimes from limestone to shale, volcanic rock, and granite. Nevertheless, most usages of geothermal resources have been found in volcanic rocks, though the substantial issue is that the existence of tectonic elements and high heat flow is more important than rock type [3-4], which are divided into three types based on the distribution of Quaternary faults, high-temperature hot springs, and Quaternary sedimentary basins. Most of them are developed in Quaternary faults zones and in Tertiary neotectonics districts. Subduction zones generate the largest earthquakes and are the main source of Great earthquakes [3]. Knowing and investigating the trends of fractures in the future can determine the focal position of earthquakes and their importance, regulate urban constructions and identify geothermal energy sources. Badakhshan Province is one of the seismicity provinces in Afghanistan, located in the farthest north-eastern part of the country between Tajikistan, northern Pakistan, and China, and covers an area of 44,059 sq.km. The province contains 22-28 districts, over 1,200 villages, and approximately 938,000 people. Faizabad serves as the provincial capital. The population of the province has a multiethnic rural make [4].

1.1. Tectonic Setting and Seismicity of the Region

Reconstruction of the Late Cretaceous- Paleogene basin between the Northern and Central Pamirs allows connecting of anomalously high seismicity with the deformation of the subduction plate (slab) of the oceanic lithosphere in this basin during its submersion into the mantle. In this sense, the Vrancea zone in the Carpathians is an analog of the Hindu Kush Mega source. The concentration of mantle earthquakes of the intermediate type with hypocenter depths up to 300 km and magnitudes up to 8 and greater within a small mega-source region at the boundary of tectonic zones in the Hindu Kush, Central, and Southwestern Pamirs have 90% of strong earthquakes in the Pamir-Hindu Kush zone and 95% of released energy are concentrated territories of 200 × 120 km. In the western region, mantle earthquakes are sharply interrupted at 69°30 E. The zone of mantle earthquakes approximately 350 km long with hypocenter depths up to 200 km is extended to the northeast of the mega source already on the territory of the Pamirs. Thus, the belt of mantle seismicity with a total length of up to 500 km is pronounced. The Hindu Kush source is confined to its southwestern part [2]. The Pamir Mountains, in Central Asia, are the result of the northward subsidence of the Indian continent into Eurasia. On average, the Pamir Plateau is 3,000 m higher than the adjacent Tajikistan depression to the west. We present a set of high-precision point-positioning data that show in great detail how the upper Pamir crust subducts into the lower Tajik depression. This westward transfer occurs in shallow, low-friction sedimentary layers that reach the surface at the beginning of the Tian Shan Mountains farther north. These sediments accommodate a total slip of about 2 cm, which is very high for continent-continent plate boundaries. In addition, our data observed a few centimeters of slip on the Gate fault, most likely triggered by a large earthquake 200 km away. Such phenomena have rarely been observed so far. At the northwestern tip of the India-Asia collision zone, the Pamir foothills overcome the Tajik Depression and the Tarim Basin and collide with the Tien Shan. Currently, the northern edge of the Pamirs shows a local shortening rate of 13-19 mm/year. While the eastern Pamir and the Tarim Basin move northward in roughly the same block, the north-south shortening decreases westward along the Pamir Front toward the Tajik Depression.

2. Materials and Methods

In addition to using books and written sources, Landsat 8 satellite image data was used in this research, and Google Earth images were processed in Envi 5.1 software for comparison and to apply edge detection techniques. Arc map 10.4.1 was used to extract lines and draw the output map. The extraction of faults in the area is the main goal and an important step in the analysis of the tectonic geomorphology situation in order to achieve a better result, along with the geothermal energy method of some lines by the method of linear interpolation of large and focal depth of earthquakes from the earthquake catalog that in this research from USGS and M catalog were added to the collection of lines.

3. Results and Discussion

In the following, we will discuss the results related to micro-plate tectonics on geothermal energy and the interpolation of large earthquakes and epicenters.

3.1. Micro-Plate Tectonics

Deformation can be well described by the number of blocks [5]. The specification is divided into 14 sections. As shown in the map (Figure 2), zones 1-7 have a slope towards the south and southwest of the region, which confirms the subduction zone. Contrary to that, zones 9-14 have south-north runes, which is evidence of subsidence in the east of the region and, by nature, includes uplift to the north. In this map, the zones of the Pamir and Badakhshan regions are depicted. This tectonic map of the region is evidence of subduction to the south and southwest of Badakhshan.

3.2. Seismicity in Afghanistan

Western Himalayas, Afghanistan, is a highly active region located at the triple junction between the Arabian, Eurasian, and Indian plates. Devastating earthquakes in the last century have Friday significant casualties in Badakhshan, northeastern Afghanistan, and surrounding areas. Therefore, it is necessary to develop an understanding of the spatial distribution of seismicity and potential earthquake sources throughout the region. This is important for calculating seismic hazards. A critical input in design codes is a requirement to initiate testing for high earthquake hazard mitigation. The development of seismic source areas for seismic analysis is guided by geologic and tectonic seismic inputs. Despite many advances in the field of seismic hazard in recent decades, how seismic information helps define the source of earthquakes, in many parts of the world including Badakhshan and its surrounding areas, can be a subject driven by expert judgment. While little research is being done to map and identify active faults in Badakhshan, knowledge about the seismogenic properties of active faults is still incomplete in many areas. As a result, seismicity, both historical and instrumental, remains the primary guide to Badakhshan seismic sources (Figure 3).

Modeling of progressive failure leads to associated seismicity is reported. Associated seismic events due to progressive failure led toa collapse in brittle rocks. The heterogeneity of topographic parameters can simulate the nonlinear behavior using the linear method, (2) reduction for failed

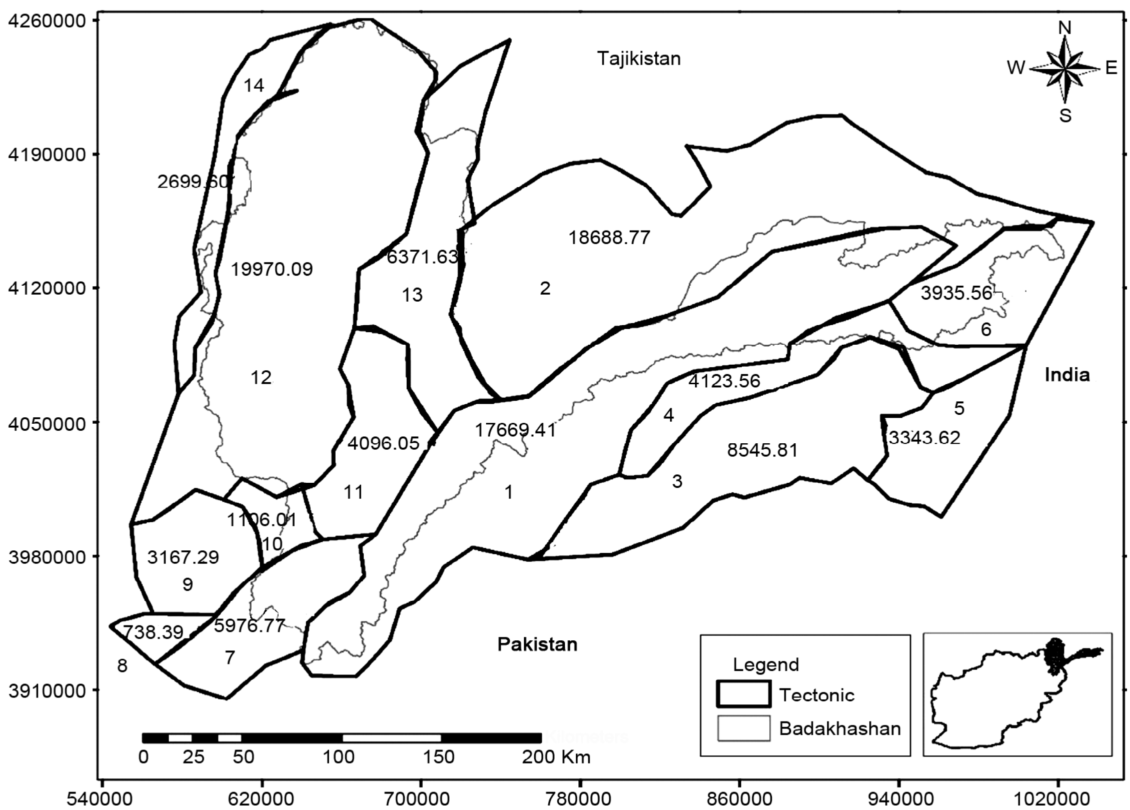

Figure 2. The zones of Pamir and Badakhshan regions are depicted. This tectonic map of the region is evidence of subduction to the south and southwest of Badakhshan.

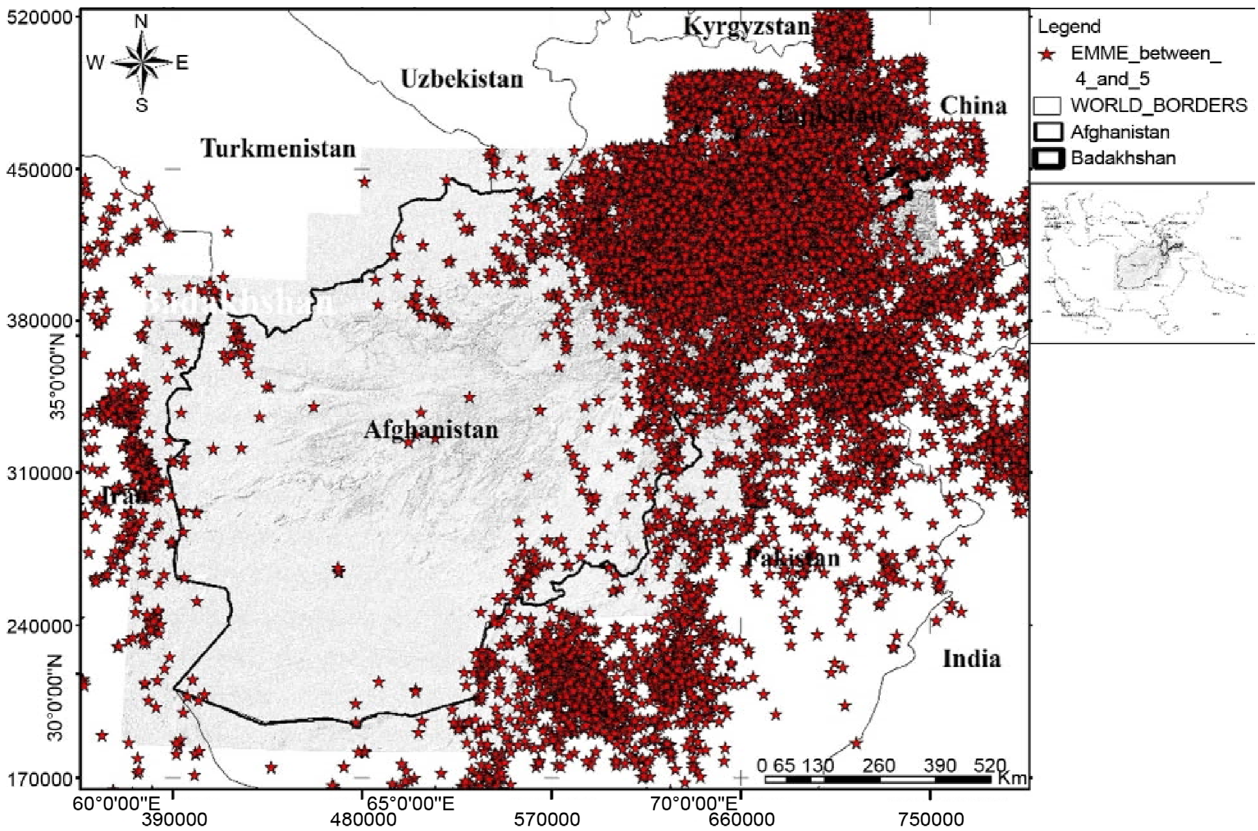

Figure 3. Seismicity of Afghanistan. In this map, each red dot represents an earthquake event. The catalog of earthquake events from 1909-2022, which are known as mechanical earthquakes, is from the USGS. Since earthquakes greater than and equal to 4 are more important, a catalog of magnitude 4 to 8 has been prepared on this map. As the map shows, the Badakhshan region in northeastern Afghanistan has the most earthquakes.

elements, discontinuous mechanics problems, and (3) by recording the event rate of failed elements, the seismicity associated with progressive failure in the rock. The simulation of the fault initiation process shows that some important phenomena such as microfracture coalescence, nucleation and growth of crack clusters, fault initiation and development, elastic rebound, dilation, bulge, and seismic behavior can be simulated.

The information related to the activities of the Pamir Plateau and Badakhshan Faults, Afghanistan, has been reviewed according to the geological studies and modeling conducted in the past few years. Reports evaluate the timing of recent ruptures, the previous four seasons, and the size of single-event displacements. There is a high probability of rupture of the southern part of Badakhshan in the coming years. Badakhshan is characterized by a complex tectonic history in which compressional and tensile deformation are superimposed. In such regions, characterized by low active tensile strain rates, seismic surface ruptures are rare and often the subject of much debate, leading to difficult correlations between "geological" faults (i.e., faults that can be mapped at the surface). Geothermal maps and high-resolution seismic data for the Badakhshan region allow us to compare and confirm the existence of geometric and kinematic correspondence between geomorphology and micro fault joins. Geology of Quaternary faults and activated structures in the geothermal map view, the distribution of earthquakes reflects the pattern of small connection of faults. In the cross-sectional view, there is a geometric relationship between the mapped normal faults and the post-seismic levels used to image the fault geometry at depth. A comparison of striated fault planes and focal aftershock mechanism solutions shows strong kinematic stability. This study shows that the Quaternary tectonic sedimentary evolution and the current geological and geomorphological situation of the Badakhshan region can be interpreted as the result of frequent and extensional earthquakes, similar to the events of 1900-2022. Our data also suggest that Badakhshan sequence mainshocks nucleate near intersections between normal faults and pre-existing compressional/ compressional structures, acting as lateral barriers to rupture propagation and thereby limiting fault size (Figures 4 and 5).

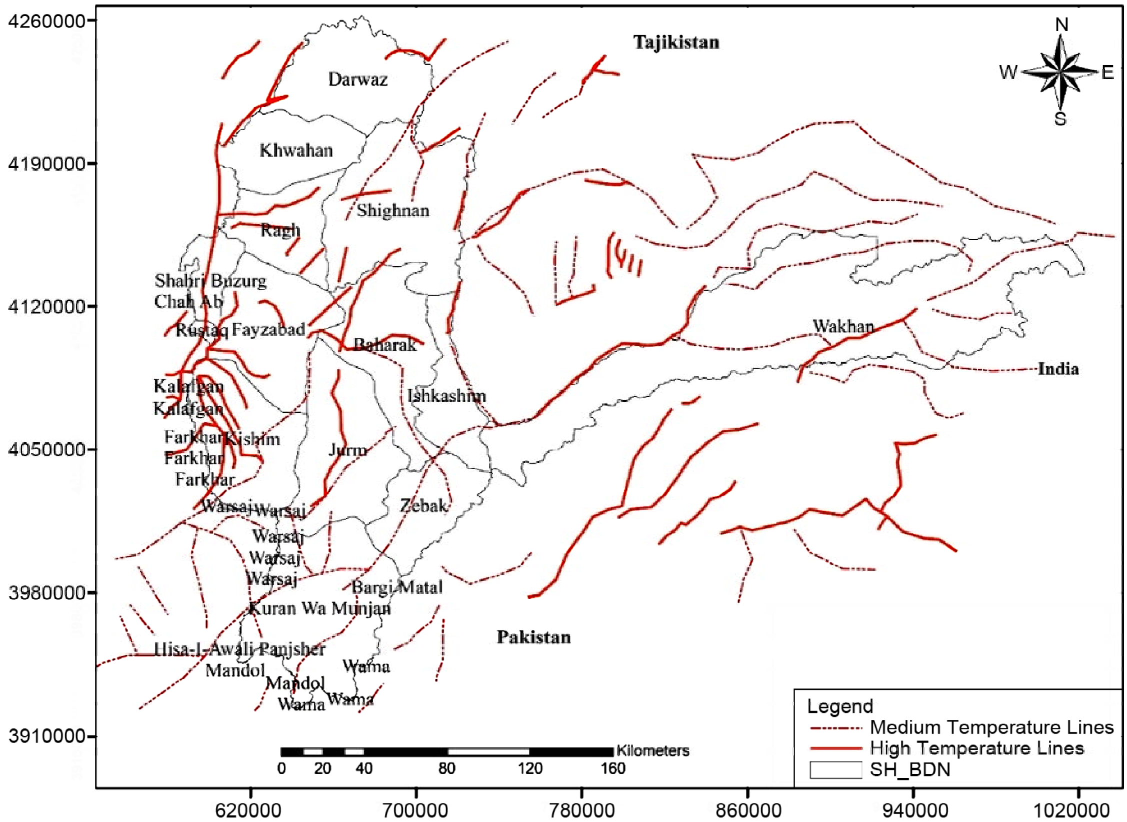

Figure 4. Areas and lines with high and medium temperatures.

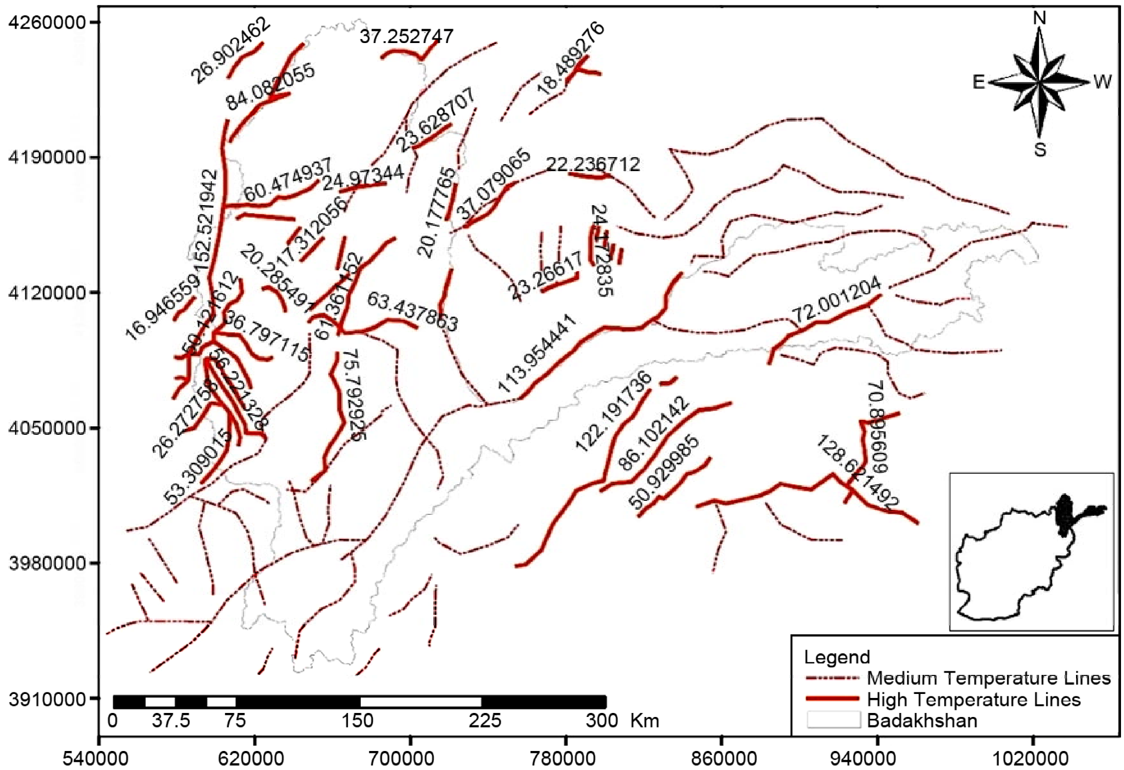

Figure 5. Main fault. During the last decade, seismic phases have been created to update the tables [6]. The new tables are specifically designed for ease of use with depth interpolation calculations and large precision in depth and range. The new iasp91 travel time tables are derived from a radial stratification surface model constructed so that the timing of major seismic phases matches the timing of events reported at the International Seismological Center (USGS) for the period 1909-2022.

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 [8], because the length of the fracture shows, in general, with the increase in the frequency of the fault, the length of the fracture decreases [8]. Larger fractures cause widespread events, and smaller fractures cause slightly smaller events [9]. 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 [10-11] so that, in analysis, 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. [9] 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 become 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 6).

Since the delay-time tables are stored as a function of slowness for each travel time branch, they are interpolated using a special tau line that takes care of squared initial singularities in the handful of travel time curves at certain critical slowness. With this representation, wherever the depth of the source is specified, it is straight-forward to find the travel time explicitly for a given focal length. The computational feed is no higher than a normal table, but there is more accuracy in constructing the travel time for the source at the desired depth. Another advantage over standard tables is that the same method can be used for each phase. Thus, for a given source depth, I can quickly

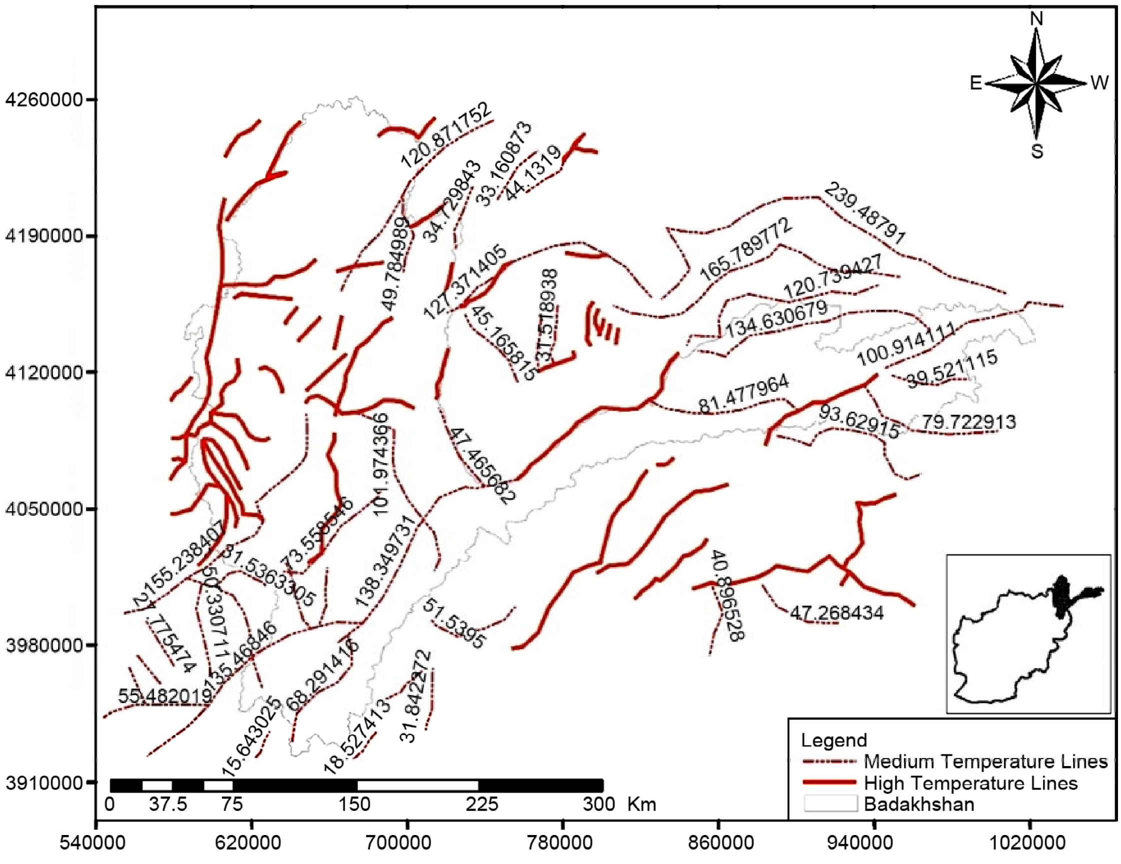

Figure 6. Sub main fault. During the last decade, seismic phases have been created to update the tables [6]. The new tables are specifically designed for ease of use with depth interpolation calculations and large precision in depth and range. The new IASP91 travel time tables are derived from a radial stratification surface model constructed so that the timing of major seismic phases matches the timing of events reported at the International Seismological Center (USGS) for the period 1998-2022.

generate a list of travel locations and derivatives associated with the phases of mainshocks that can be specified at a focal distance (Figures 7 and 8).

Any plate has a growth process from small to large. The micro-blocks or micro-plates are sometimes the precursors of large plates [12]. Slip analysis is used to evaluate the reactivation potential of shear and dilatation fractures in a deep geothermal reservoir in the northeastern Afghanistan basin (Badakhshan), based on the assumption that slip-on faults are proportional to shear stress. It is applied normally. The page is controlled. Weak in the situ stress field of reservoir rocks, consisting of Lower Permian sandstones

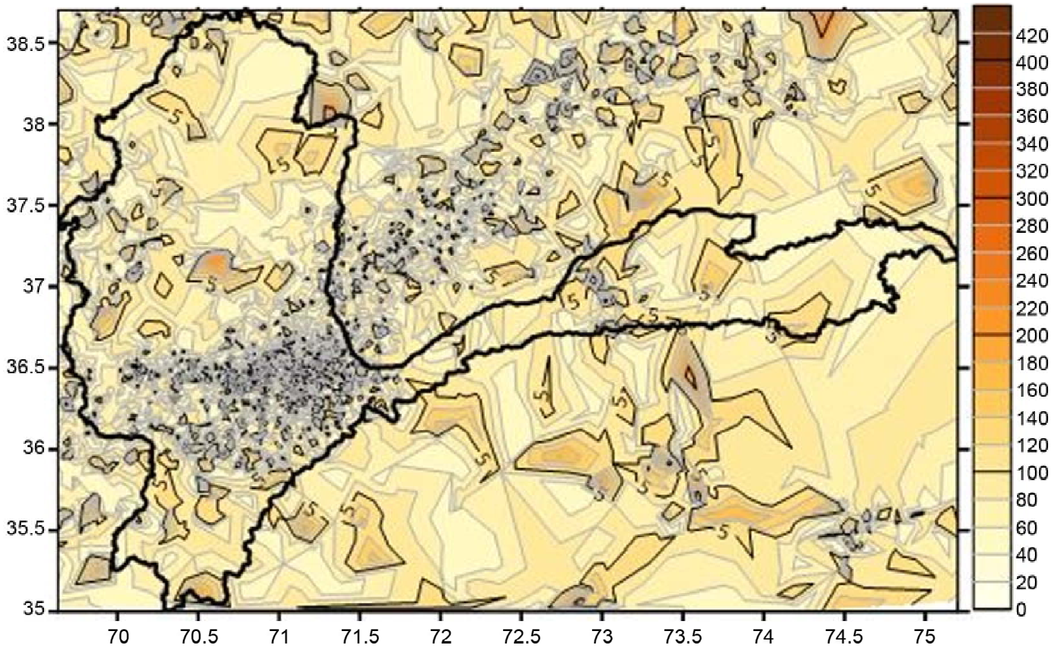

Figure 7. Linear Magnitude Linear Depth Using linear interpolation, the following pattern was observed in the study area. which indicates the existence of a distinct east-west linear pattern in the center of Esan Badakhshan. The focal Magnitude density of earthquakes continues as an east-west pattern in Badakhshan, Afghanistan, and with a lower density as a linear pattern from east Badakhshan to the northeast and east.

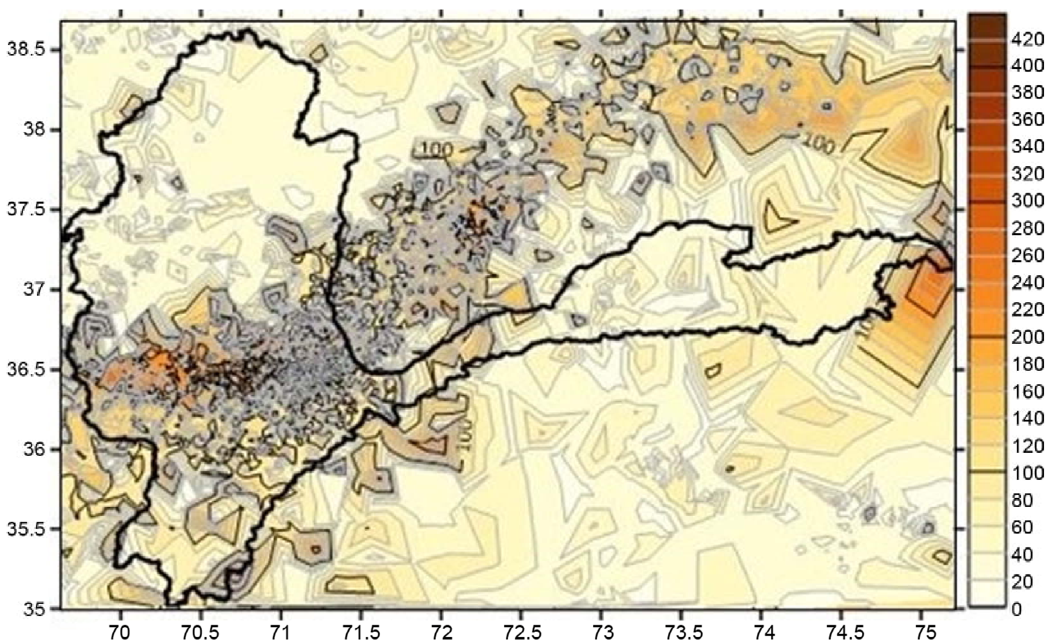

Figure 8. Linear Depth using linear interpolation, the following pattern was observed in the study area. which indicates the existence of a distinct east-west linear pattern in the center of Esan Badakhshan. The focal depth density of earthquakes continues as an east-west pattern in Badakhshan, Afghanistan, and with a lower density as a linear pattern from east Badakhshan to the northeast and east.

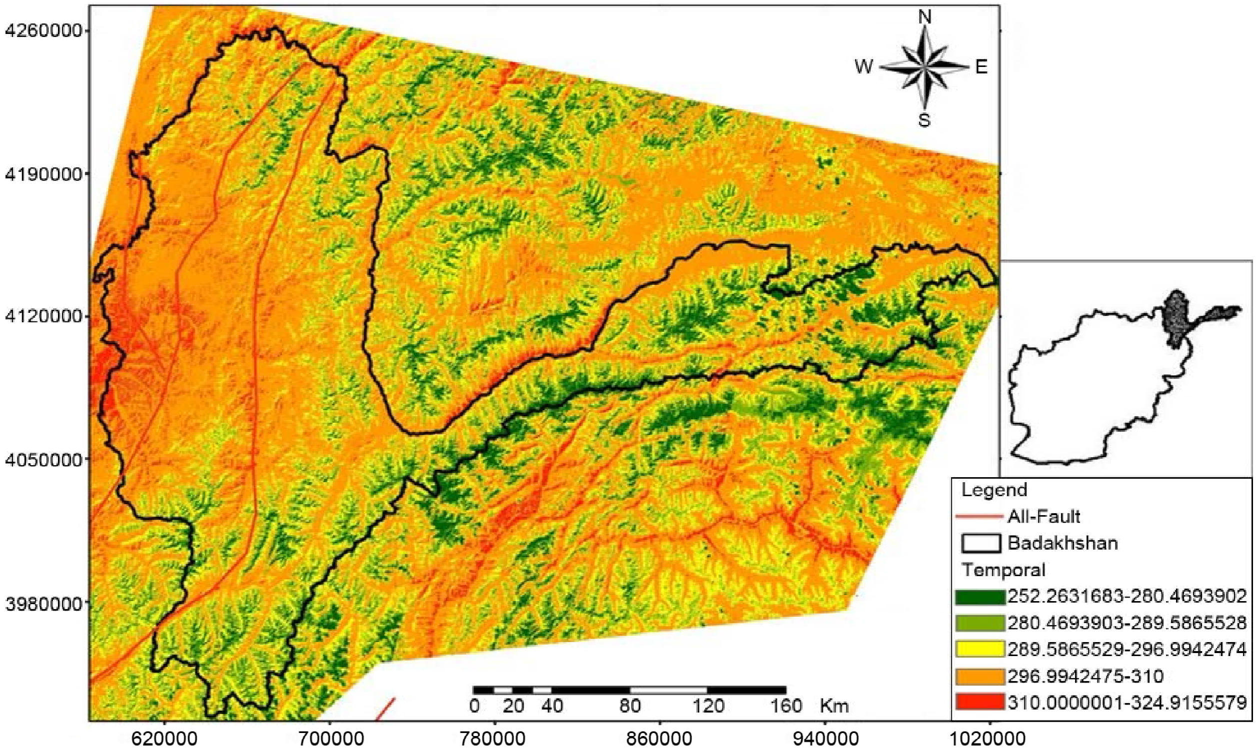

Figure 9. Geothermal relationship and fault trends. active geothermal systems permit to obtain of key parameters to define a conceptual model of the area under exploration.

and volcanic, were moved by hydraulic fracturing. Microseismic activity is surprisingly low. Slip analysis shows that there is a critical stress reservoir in the sandstones. Rock failure occurs first with excess pore pressure. Slip failure is more likely than tensile failure in igneous rocks because high normal stresses prevent tensile failure. Source features suggest slip rather than extension along probable NS failure planes. This shows that slip analysis is a suitable method that can be used to treat modified stress conditions (Figure 9).

Qualitative and quantitative analyses of known geothermal resources and geoscience evidential features are one of the most important steps in geothermal exploration which are useful in defining a conceptual model of geothermal prospectively [12-14]. The high-quality databases for Badakhshan seismicity and an extensive compilation of thermal measurements in Badakhshan are used to quantify the concept of temperature as a fundamental parameter for determining the thickness of the seismogenic zone. The base of this zone, below which only a small percentage of crustal earthquakes occur, is termed the "cutout depth," and it is at or near the brittle-ductile transition in the crust. Based on deformation studies, this transition should be temperature, strain rate, lithology, and stress-state dependent. In this study, qualitative comparisons between the heat flow in Badakhshan and earthquake hypocentral distributions show first that, as expected, earthquake cutout depths are direct related to heat flow. Second, the epicentral distributions tend to scattered and chaotic thermal transitions. This correlation is probably related to stress concentrations in these locations. Faults tend to go around it into areas of higher heat flow where the seismogenic zone is thinner and the crust may be weaker, and it is pushed toward (and under). Third, to quantitatively compare the data sets, temperatures for the seismicity cutout depth in Badakhshan were calculated using the steady-state, 1D heat conduction equation, with the variables based on published values for heat flow, heat generation, and thermal conductivity. The differences in these cutout temperatures suggest that additional factors, such as strain rate, stress regime, and/or lithology, may contribute to the seismicity cutout depth. Detailed characterization of the heat flow and earthquake synergy in this manner furthers the understanding of the earthquake process and can aid in the estimation of the maximum depth of rupture for great earthquakes, particularly in areas of low seismicity, thus reducing uncertainties in hazard calculations.

4. Conclusion

The activity of recent small and medium scale 4-5 earthquakes in it has increased with the east-west trend, and according to geothermal modeling, more and stronger rupture is predicted in the future. The upper geothermal lines indicate the thinning of the crust and the creation of fractures, which are the same as the current faults, and the medium geothermal lines are progressing in continuation of the previous failures. Finally, the geothermal zones in the west of the region indicate low topography. In order to confirm these statements, the interpolation of the magnitudes and epicenters of the existing probes, especially the east-west, has been determined.

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