

# Seismotectonic Investigation of the Herat Fault System, Western Afghanistan

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## ABSTRACT

The western region of Afghanistan, particularly around the Herat (Harirud) fault system, is highly seismically active. This study investigates the tectonic earthquake potential of the Herat region using seismicity parameters and fractal analysis. Seismic data were collected from international catalogs and analyzed to determine the b-value and fractal dimension (D-value) of earthquake distribution. Remote sensing, GIS, and statistical methods were applied to identify fault structures and assess stress regimes. Results show that the Herat fault and its subsidiary faults exhibit high fractal dimensions, reflecting dense faulting and elevated seismic activity. Areas such as Pashtun Zarghoon, Farsi, Zagah, and Obbeh are identified as high-stress zones with potential for future earthquakes. The b-value analysis indicates lower values along the Herat and Siakhobulak faults, corresponding to regions of higher stress accumulation and rupture probability. Stress inversion analysis confirms a convergent regime influenced by the ongoing collision between the Indian and Eurasian plates. These findings highlight the central role of the Herat fault system in regional seismicity and emphasize the need to update earthquake hazard maps for western Afghanistan. Understanding the relationship between fractal dimensions, b-values, and stress fields can contribute to better earthquake risk assessment and

support safer construction practices in the region.

**Keywords:** Herat fault, seismicity, fractal analysis, earthquake hazard, stress regime.

## 1. INTRODUCTION

Earthquakes are among the most destructive natural hazards in Afghanistan due to its location within the active Alpine-Himalayan orogenic belt. The collision of the Indian, Arabian, and Eurasian plates has created a complex tectonic environment with frequent seismic activity. In particular, the Herat (Harirud) fault system represents one of the most significant active faults in western Afghanistan, where repeated earthquakes have caused severe damage throughout history [1,2].

In recent decades, fractal analysis has been widely applied to seismotectonic studies in regions such as Turkey, Japan, and India, providing insights into the spatial complexity of fault systems and their relationship with earthquake occurrence [3-7]. The fractal dimension (D-value) and the frequency-magnitude distribution parameter (b-value) are important tools for understanding fault dynamics, seismic clustering, and regional stress distribution [8-9].

Despite the high seismic potential of the Herat region, comprehensive studies using these parameters remain limited. This study applies seismicity parameters and fractal analysis to investigate the seismotectonic

characteristics of the Herat fault system. The objective is to identify high-stress zones, assess earthquake recurrence potential, and contribute to improved earthquake hazard assessment for western Afghanistan's.

## 2. LITERATURE REVIEW

Fractal and statistical approaches have been extensively applied to seismotectonic studies worldwide. Early research demonstrated that earthquake distributions exhibit self-similar properties across different scales [6]. Hirata and subsequent studies in Turkey and Japan confirmed correlations between the Gutenberg–Richter b-value and the fractal dimension of seismicity [3-5]. Nanjo and Nagahama further established the usefulness of fractal methods in identifying spatial patterns of aftershocks and active faults [4].

In India, Singh et al. and Kumar Pal applied fractal techniques to characterize fault dynamics, demonstrating their potential in seismic hazard assessment [8,10]. Similar applications in Turkey highlighted the relationship between low b-values, high fractal dimensions, and increased earthquake risk [6,7].

Despite these global advancements, the application of fractal and b-value analysis to Afghanistan's tectonic setting remains limited. Previous works have focused mainly on general seismic hazard assessments and tectonic mapping [1,2], leaving a research gap in quantitative evaluation of seismic clustering and stress fields in western Afghanistan. This study addresses that gap by applying fractal and statistical methods to the Herat fault system.

## 3. MATERIALS & METHODS

### 3.1 Data Collection

Seismic data for Herat and surrounding regions were obtained from the International Seismological Centre (ISC) and the United States Geological Survey (USGS) catalogs. Historical earthquake records were also incorporated based on documented events [1,2]. Geological and tectonic information

was derived from maps prepared by the U.S. Geological Survey and earlier studies on the Harirud fault system [11,12].

### 3.2 Remote Sensing and GIS Analysis

Satellite images, including Landsat ETM-8 and ASTER 15 m, were processed using ENVI 5.6 and ER Mapper software. Structural features such as fractures and faults were extracted and mapped in ArcGIS 10.7, following approaches used in tectonic geomorphology and structural mapping [4,13].

### 3.3 Fractal Analysis

The fractal dimension (D-value) was calculated using the box-counting method, which has been widely applied in structural geology and seismology [14,15]. This approach evaluates the spatial distribution of linear structures (faults, drainage networks) and point structures (earthquake epicenters).

### 3.4 Seismicity Parameter (b-value)

#### Calculation

The b-value, representing the slope of the Gutenberg–Richter frequency–magnitude distribution, was estimated using ZMAP software [8]. Previous studies confirm that b-values provide insight into stress accumulation and rupture potential [6,10].

### 3.5 Stress Field Determination

The focal mechanisms of earthquakes with magnitude  $\geq 4$  (recorded between 1900 and 2023) was analyzed to determine the orientation of the maximum horizontal stress (Shmax). Stress inversion techniques were applied following the Wallace–Bott hypothesis and related approaches [16,17].

## 4. STATISTICAL ANALYSIS

Statistical analyses were performed to assess the relationship between fractal dimensions (D-values) and seismicity parameters (b-values). Correlation coefficients were calculated to quantify the relationship between fault complexity and stress conditions. The Stress Regime Index

(R') was used to classify the tectonic regime: values of 0–1 correspond to normal faulting, 1–2 to strike-slip, and 2–3 to thrust faulting regimes.

All analyses were conducted using ArcGIS 10.7, ZMAP, and specialized stress inversion software.

## 5. RESULT

### 5.1 Faults in Herat Region

The Herat fault, also known as the Harirud fault, extends over 1100 km and represents one of the most active strike-slip systems in Afghanistan. It is associated with several subsidiary faults, including the Kajroud, Qarghanaw, and Siakhobulak faults [11,12,18]. Remote sensing and GIS analyses confirm the structural complexity of this system, with numerous subsidiary fractures forming a wide deformation zone as shown in Figure 1.

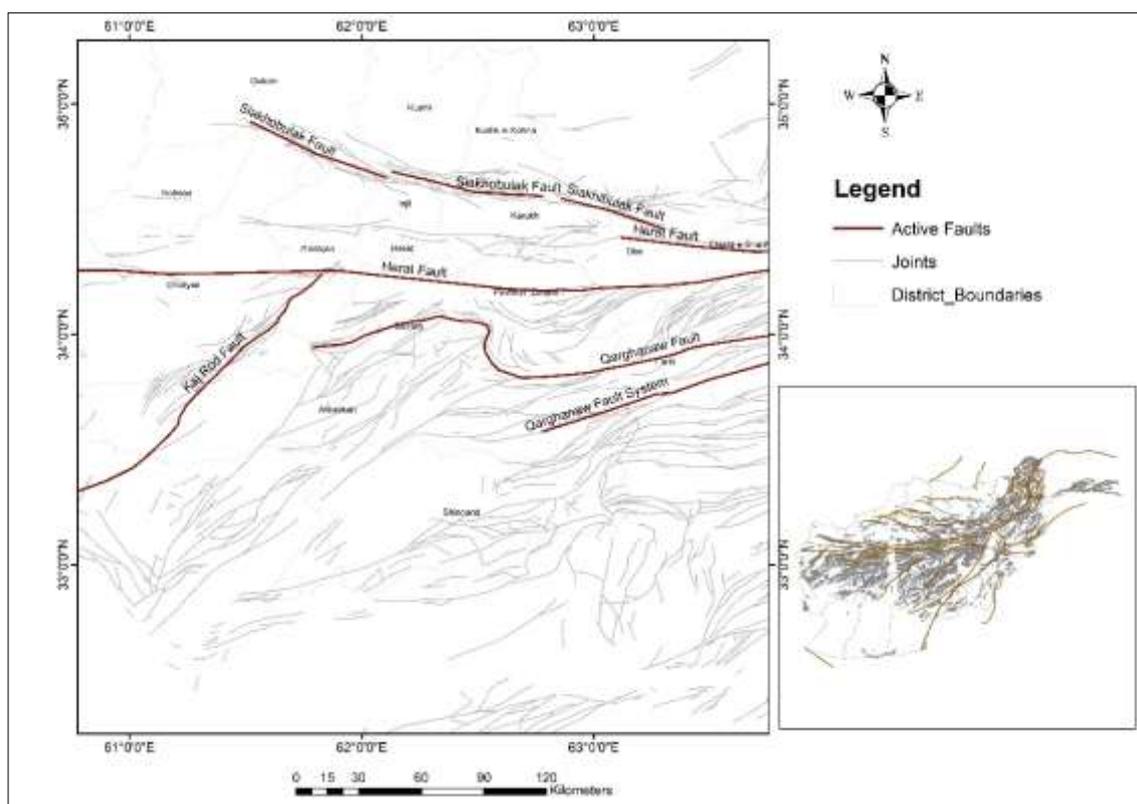


Figure 1: Herat Fault System map.

### 5.2 Historical Earthquakes

Documented earthquakes in Herat date back to 849 AD, with significant destructive events reported in 1102, 1364, 1908, and 1931 [17,19-21]. These events caused widespread damage, including the collapse of historical monuments such as the Gawhar Shad Mosque minarets. Instrumental records show at least 40 earthquakes within 80 km of the 2023 Zende Jan epicenter [1,2], highlighting the region's long-standing seismic activity as shown in Figure 2.

### 5.3 Fractal Dimensions of Faults

Fractal analysis of the Herat fault system reveals variations across different zones [14,15,22]. The highest D-values were observed in zones 16 (1.8133), 11 (1.54), and 10 (1.60), indicating areas of dense faulting and high tectonic activity. Lower D-values (<1.0) were recorded in peripheral zones, suggesting reduced deformation as shown in Table 1 and Figure 3.

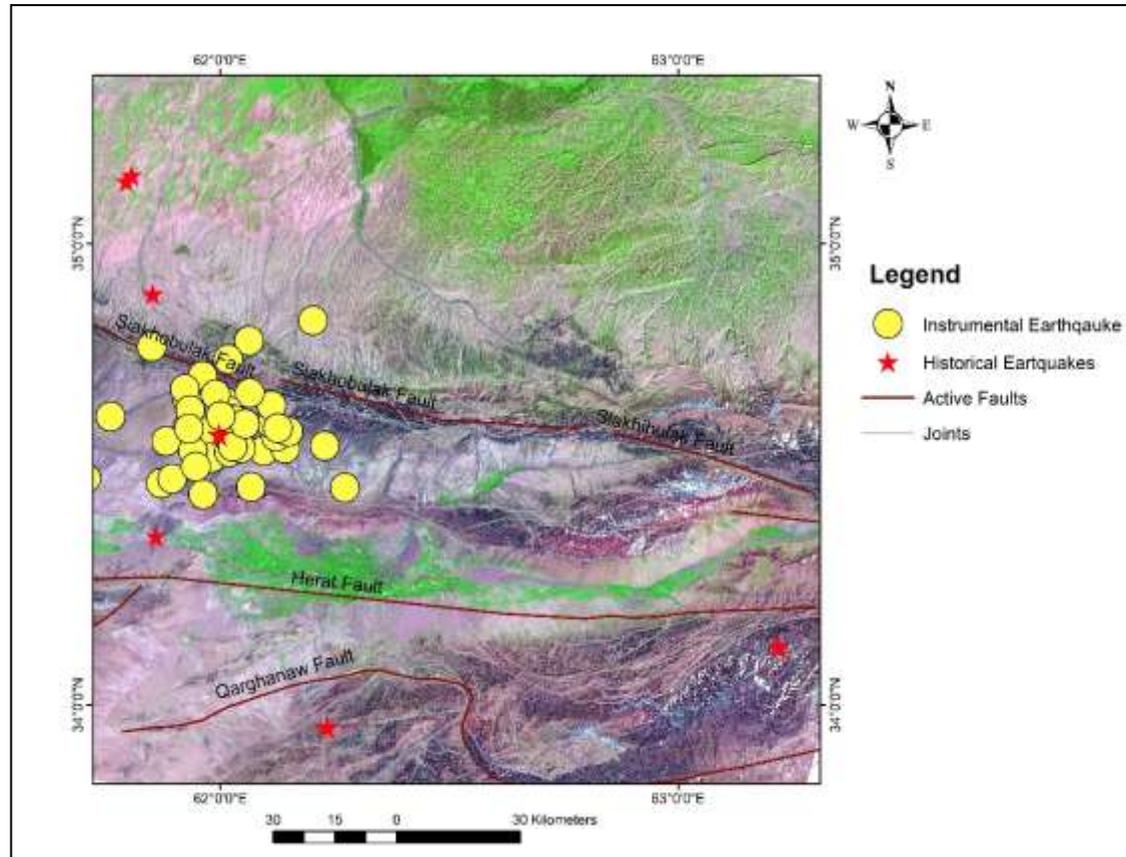


Figure 2: Historical & instrumental earthquakes map.

Table 1: Fractal analysis of active faults.

S(km)	1/S	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16
90	0.011111	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
45	0.022222	4	1	3	2	3	4	3	3	4	4	4	2	2	1	2	4
22.5	0.044444	6	1	6	3	7	14	9	6	10	14	13	7	5	1	2	10
11.25	0.088889	11	3	10	4	11	30	21	14	23	41	32	19	10	1	4	16
5.625	0.176991	22	6	19	5	19	51	34	27	42	80	73	44	16	2	8	30

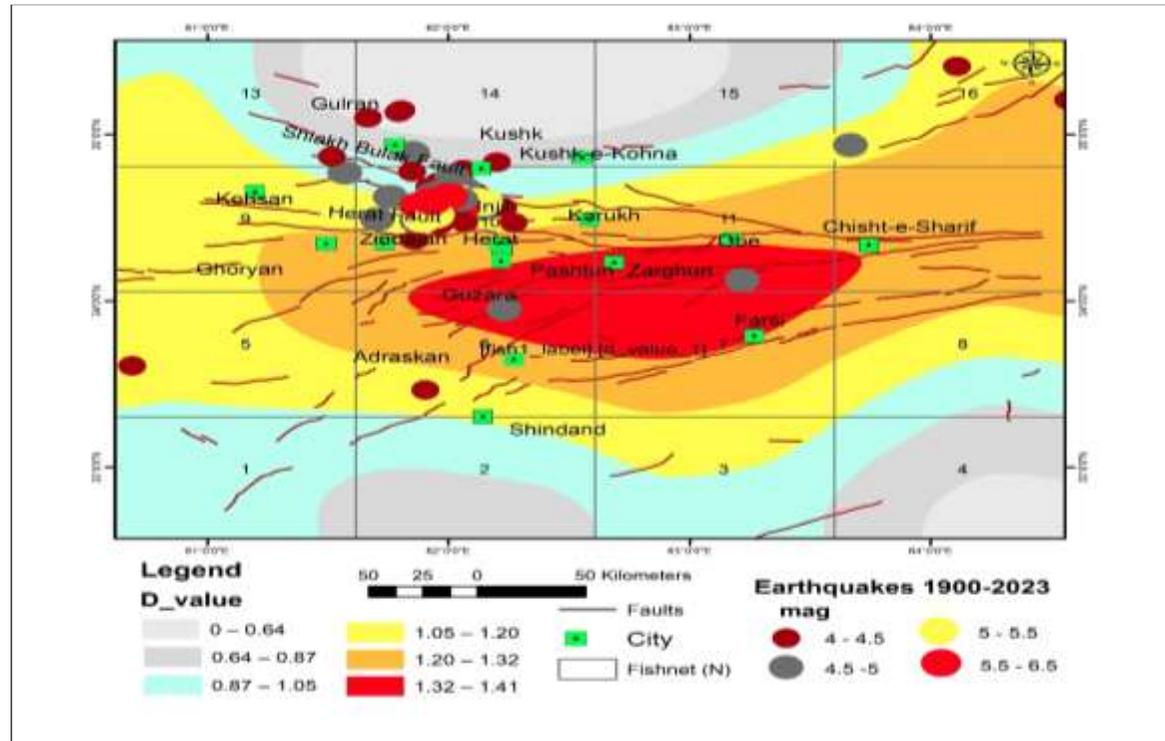


Figure 3: Fault fractal zoning map.

#### 5.4 Fractal Dimensions of Drainage Networks

The drainage network analysis shows relatively high D-values in the central zones (e.g., D7 = 1.796, D11 = 1.735), consistent with tectonic

influence on landscape development. In contrast, lower values (e.g., D9 = 1.0886) in the northern and western areas reflect higher elevation and active uplift [14,15] as shown in Table 2 and Figure 4.

Table 2: Fractal analysis of drainage networks.

s(km)	1/s	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16
90	0.011111	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
45	0.022222	4	4	4	4	0	3	4	4	3	4	4	4	4	4	4	4
22.5	0.044444	10	11	9	15	0	8	16	16	6	13	16	16	10	11	14	15
11.25	0.088889	18	23	20	46	0	22	55	49	9	38	48	44	20	28	32	49
5.625	0.176991	35	52	27	107	0	56	135	103	25	110	117	101	40	58	82	107

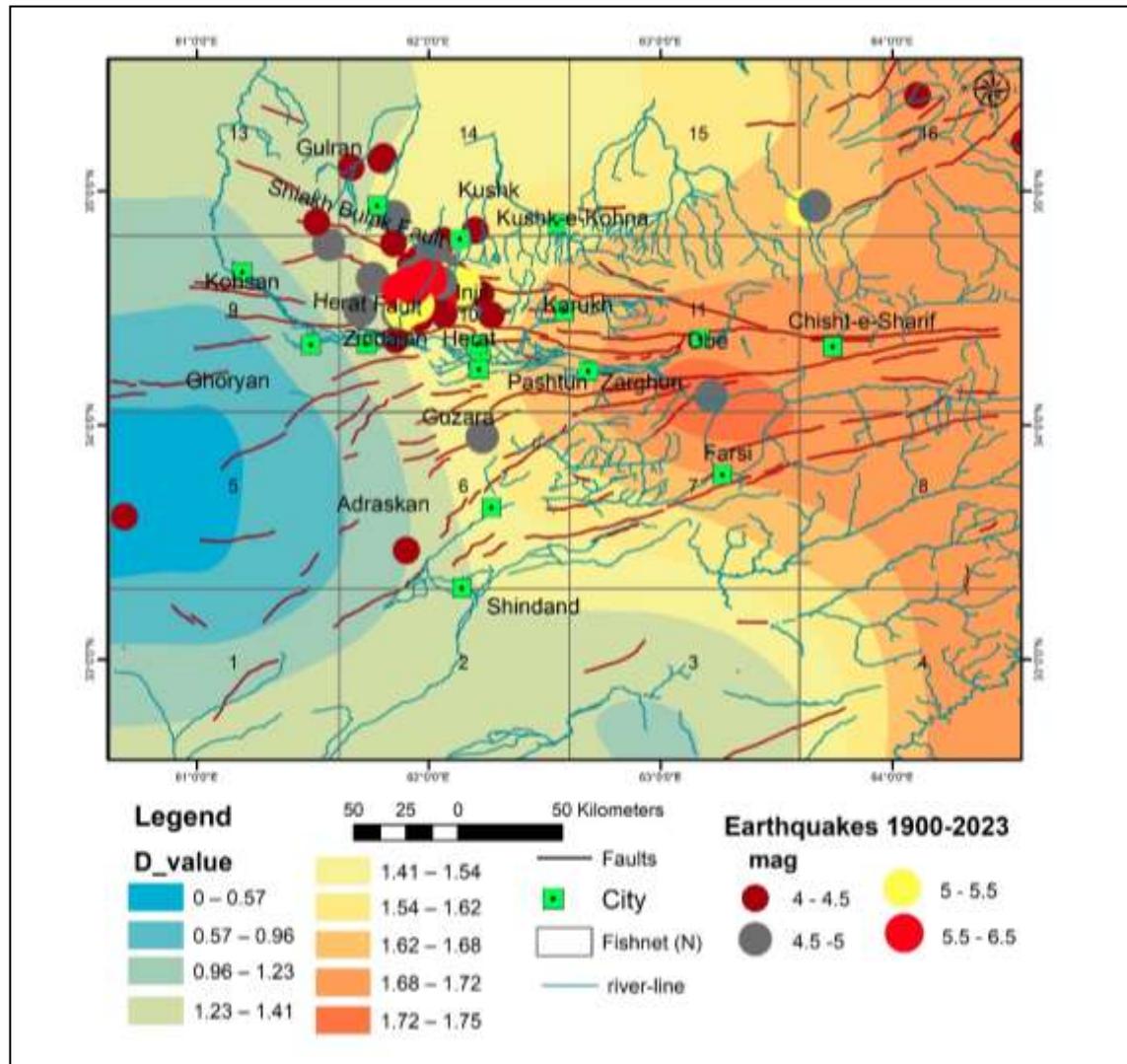


Figure 4: Fault fractal zoning map.

### 5.5 Seismicity Parameter (b-value)

The spatial distribution of b-values shows lower values around the Herat, Siakhobulak, and Qarghanaw faults (<0.7), suggesting higher stress concentration and increased

rupture probability [6,8,10]. Higher values (>1.0) were observed in peripheral areas, reflecting lower stress and fault creep as shown in Figure 5.

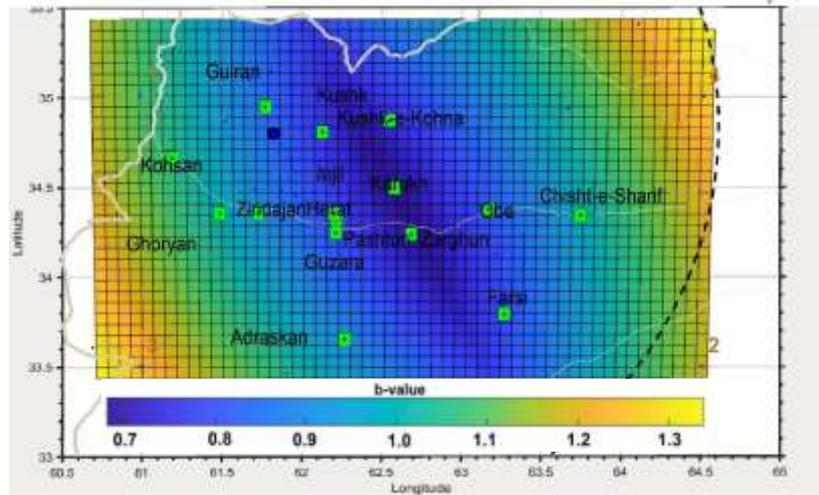


Figure 5: b-value distribution map.

### 5.6 Stress Regime Analysis

Stress inversion analysis of 21 earthquakes ( $m_b \geq 4$ , 1900–2023) indicates a convergent tectonic regime, with a mean Stress Regime Index ( $R'$ ) of  $2.32 \pm 0.33$ . The maximum

horizontal stress orientation is  $Sh_{max} = N167^\circ E \pm 25.1$ , consistent with the regional stress field produced by the collision of the Indian and Eurasian plates [5,16,17] as shown in Figure 6.

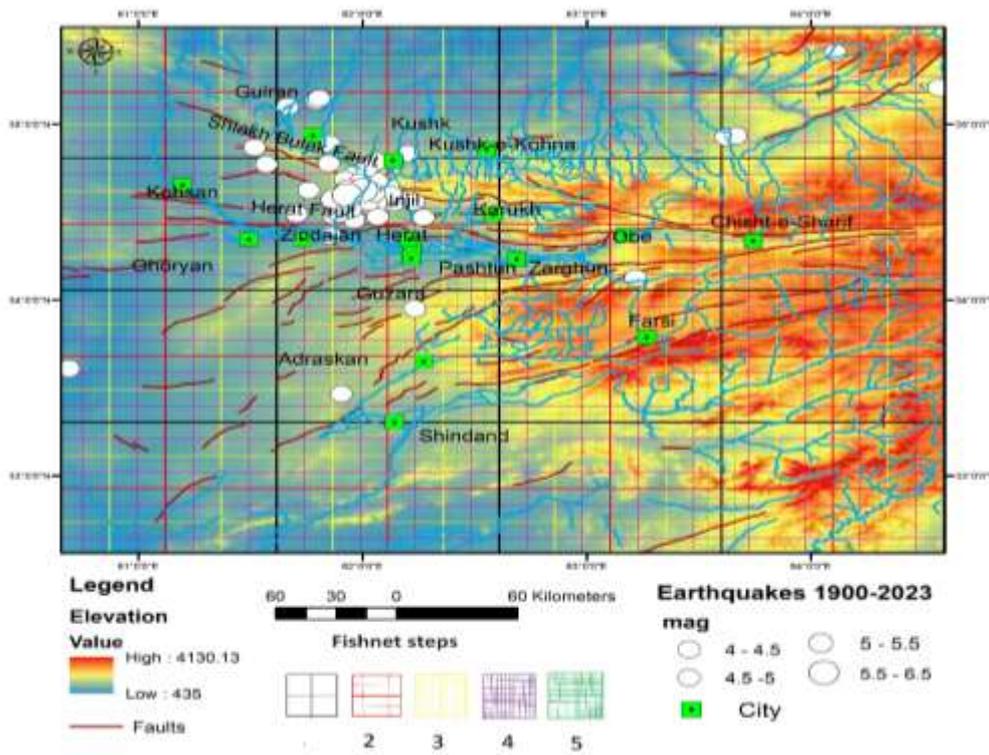


Figure 6: Stress inversion.

### 5.7 Correlation of D-value and b-value

A negative correlation ( $r = -0.78$ ) was found between D-values and b-values. Zones with high D-values and low b-values correspond

to areas of increased stress and potential seismic hazard, particularly along the central Herat fault system as shown in Figure 7 [5,8,22,23].

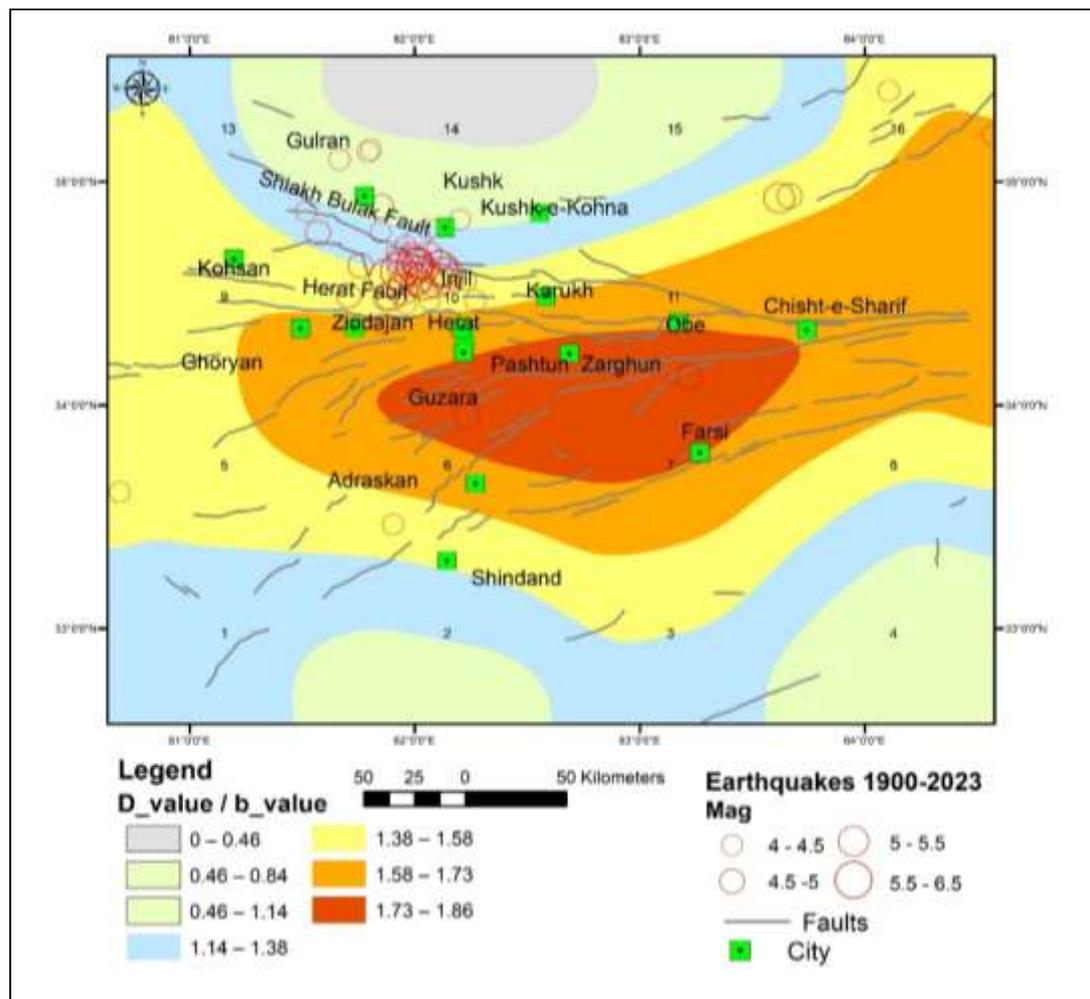


Figure 7: D/b-value ratio zoning map.

### DISCUSSION

The results of this study confirm that the Herat (Harirud) fault system is among the most seismically active regions of Afghanistan. The high fractal dimensions (D-values  $>1.5$ ) in the central parts of the fault zone indicate a dense fault network and high structural complexity. This is consistent with earlier studies that associated higher D-values with increased tectonic activity and fault irregularity [14,22]. In contrast, lower D-values in peripheral zones suggest more mature fault structures with limited surface deformation.

The b-value analysis further supports this interpretation. Values below 0.7 were detected near the Herat, Siakhobulak, and Qarghanaw faults, corresponding to areas of higher shear stress and greater probability of large earthquakes. This agrees with previous findings that low b-values typically mark asperities where rupture is more likely to nucleate [6,8,23]. The negative correlation between D-values and b-values ( $r = -0.78$ ) also reflects global observations in Turkey and Japan, where complex fault networks coincide with higher seismic hazard [5]. Stress inversion analysis revealed a convergent regime, with maximum

horizontal stress oriented N167°E. This orientation aligns with the regional tectonic framework driven by the ongoing collision between the Indian and Eurasian plates [5,16]. Similar stress orientations have been reported in the Hindu Kush–Pamir region, where large intermediate-depth earthquakes frequently occur [2,5].

From a hazard perspective, the Pashtun Zarghoon, Farsi, Zagah, and Obek areas represent the most critical zones, as they coincide with both high D-values and low b-values. These regions should be considered priority areas for seismic risk assessment and earthquake-resistant construction planning.

A limitation of this study is the reliance on historical earthquake records, which may be incomplete, and the use of available instrumental catalogs, which may not capture all smaller events. Future studies should integrate GPS-based strain measurements and high-resolution seismic monitoring to refine stress field models.

Overall, the combination of fractal analysis, b-value mapping, and stress inversion provides a robust framework for assessing seismic hazard in western Afghanistan. These methods highlight the need to update national earthquake hazard maps to incorporate the active role of the Herat fault system.

## CONCLUSION

This study investigated the seismotectonic characteristics of the Herat fault system in western Afghanistan using seismicity parameters, fractal analysis, and stress inversion techniques. The results show that the Herat fault and its subsidiary faults exhibit high fractal dimensions, indicating structural complexity and active deformation. The spatial distribution of b-values further confirms that zones with low values correspond to areas of high stress concentration and greater earthquake potential.

The combined interpretation of D-values, b-values, and stress regime analysis highlights Pashtun Zarghoon, Farsi, Zagah, and Obek

as priority zones for future seismic hazard. These findings underline the importance of updating Afghanistan's seismic hazard maps to incorporate the role of the Herat fault system. Strengthening earthquake-resistant construction practices in these high-risk areas is critical for reducing potential impacts.

While this study provides a robust framework for regional hazard assessment, it also underscores the need for improved seismic monitoring and integration of GPS-based strain data to refine stress models. Future research combining geological, geophysical, and statistical approaches will be essential for a more comprehensive understanding of seismic risk in Afghanistan.

## Declaration by Authors

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**Conflict of Interest:** The authors declare no conflict of interest.

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