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Seismic Hazard Mapping of Southern Kerman Using GIS: Integrating Active Geostructural Features

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***Abstract*:** The study area is located along the Baft–Arzuiyeh–Hajiabad road, approximately 20km east of Hajiabad, covering an area of about 33km × 33km. Structurally, this region lies within two major tectonic zones of Iran: the Sanandaj-Sirjan and the Zagros zones. These zones play a crucial role in shaping the geological and seismic characteristics of the area. Seismic data analysis indicates that earthquakes recorded in the study region have not exceeded a magnitude of mb:5. However, the presence of complex and highly deformed fault systems suggests significant tectonic activity. The faults in this area exhibit a combination of structural features, contributing to their intricate nature and high seismic potential. Using Geographic Information System (GIS) techniques, this study aims to develop a seismic hazard map for the southern Kerman region. By integrating geological, tectonic, and seismic data, the research provides a comprehensive assessment of the area's seismic risk. The findings highlight the importance of continuous monitoring and structural analysis in understanding the region's geodynamic behavior. The results can aid in seismic risk mitigation and urban planning, ensuring better preparedness for potential earthquakes in the region.

Keywords: Seismic hazard mapping, GIS-based analysis, Active geostructures, Seismicity, Southern Kerman.

I. INTRODUCTION

Earthquakes are among the most devastating natural disasters, causing significant loss of life, economic damage, and environmental changes (Liu et al., 2012). The study of seismicity, which involves analyzing the frequency, magnitude, and distribution of earthquakes, is crucial for understanding the risks associated with tectonic activity (Al-Ahmadi et al., 2014). Seismology, the scientific study of earthquakes and seismic waves, plays a vital role in assessing these risks and improving preparedness strategies (Ahmad et al., 2017). Given the unpredictability of earthquakes, it is essential to develop effective methods for monitoring and mapping seismic hazards (Nyimbili et al., 2018). Faults are structural discontinuities in the Earth's crust where significant displacement has occurred due to tectonic forces (Khan, 2020). They are classified into different types based on their movement, including normal faults, reverse faults, and strike-slip faults (Karimzadeh et al., 2014). The activity of faults determines the seismic behavior of a region (Rahman et al., 2015). Active faults, which have shown movement in recent geological history, are particularly important in seismic hazard assessment (Aslam & Naseer, 2020). Understanding fault structures helps seismologists predict the potential for future earthquakes and assess their possible impacts (Wang, 2011). Seismic behavior refers to the way an area responds to tectonic forces and how energy is released during an earthquake (Tavakoli & Ghafory-Ashtiany, 1999). This behavior is influenced by various factors, including the geological composition, fault characteristics, and stress accumulation in the Earth's crust (Nath & Thingbaijam, 2012). Some regions experience frequent, low-magnitude earthquakes, while others may have long periods of seismic inactivity followed by major earthquakes (Verma & Bansal, 2013). Studying these patterns allows researchers to estimate seismic risks and improve building codes and infrastructure resilience (McCalpin, 2009).

Seismic hazard assessment is a fundamental aspect of earthquake research. It involves analyzing past earthquakes, fault activity, and geological conditions to predict future seismic events (Meletti et al., 2008). This assessment is critical for urban planning, engineering, and disaster management (Pei et al., 2022). By identifying high-risk zones, governments and organizations can implement measures to reduce potential damage, such as enforcing stricter construction standards and designing earthquake-resistant structures (Candia et al., 2019). Earthquake monitoring and seismography are essential tools in seismic research (Deif et al., 2011). Seismographs detect and record ground movements caused by seismic waves, providing valuable data for analyzing earthquakes (Rahman et al., 2021). Advances in technology have led to the development of dense seismographic networks that enable real-time monitoring of seismic activity. These networks help scientists track seismic events, study fault behavior, and improve early warning systems (Faure Walker et al., 2021).

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Seismic mapping plays a crucial role in understanding and visualizing earthquake-prone areas (Ansari et al., 2022). By using Geographic Information Systems (GIS), researchers can integrate various datasets, including fault lines, historical earthquake records, and soil characteristics, to create detailed seismic hazard maps (Hamdy et al., 2022). These maps provide essential information for decision-makers, allowing them to implement appropriate land-use planning and disaster mitigation strategies (Sauti et al., 2021). The integration of active geostructural features in seismic mapping enhances the accuracy of hazard assessments (Moustafa et al., 2022). Active geostructures, such as fault zones and tectonic boundaries, significantly influence seismic activity. By incorporating these factors into GIS-based analyses, scientists can develop more precise models that reflect the actual seismic potential of a region (Pancholi et al., 2022). This approach improves risk assessment and helps prioritize areas that require urgent attention (Sauti et al., 2021). The importance of seismic hazard mapping extends beyond scientific research (Ahmad et al., 2017). It directly contributes to public safety and disaster preparedness. Governments, engineers, and urban planners rely on seismic maps to design infrastructure that can withstand earthquakes (Nyimbili et al., 2018). Moreover, these maps help emergency response teams prepare for potential disasters, ensuring efficient evacuation plans and resource allocation in the event of an earthquake (Deif et al., 2011). In regions with high seismic activity, continuous monitoring and updated mapping efforts are necessary (McCalpin, 2009). Seismic hazards are dynamic, and new data must be incorporated to refine risk assessments (Tavakoli and Ghafory-Ashtiany, 1999). Technological advancements, such as remote sensing and artificial intelligence, are further enhancing the accuracy of seismic studies (Faure Walker et al., 2021; Jena et al., 2021). These innovations provide better predictive capabilities, ultimately reducing the impact of earthquakes on human populations (Pourghasemi et al., 2023).

The primary objective of this study is to develop a GIS-based seismic hazard map for the southern Kerman region by integrating active geostructural features, fault distributions, and historical earthquake data. This research aims to assess the seismic risks in the area by analyzing tectonic activity, fault complexity, and past seismic events. By utilizing advanced spatial analysis techniques, this study provides a comprehensive understanding of the region's seismic behavior, which can be used for urban planning, infrastructure development, and disaster risk reduction. Additionally, the research seeks to improve the accuracy of seismic hazard assessments by incorporating high-resolution geological and geophysical data, ensuring better preparedness for potential earthquakes. The necessity of this study arises from the high tectonic activity and complex fault systems present in the southern Kerman region. Although earthquakes in this area have not exceeded mb:5, the presence of active faults with significant deformation indicates a potential risk for future seismic events. Given the region's structural location within the Sanandaj-Sirjan and Zagros tectonic zones, a detailed analysis of seismic hazards is crucial. Understanding seismic patterns will enable authorities to implement effective risk management strategies, enforce earthquake-resistant construction regulations, and enhance early warning systems. The findings of this study will contribute to scientific knowledge on regional seismicity and help protect communities from earthquake-related disasters.

II. Iran Seismic Hazard Mapping

Seismicity refers to the occurrence, frequency, and magnitude of earthquakes in a given region (Sauti et al., 2021). It is a crucial indicator of the Earth's internal dynamics and provides valuable insights into tectonic processes (Candia et al., 2019). Earthquakes occur due to the sudden release of energy accumulated along fault lines, which results from the movement of tectonic plates (Liu et al., 2012). Studying seismicity helps geologists and engineers assess earthquake risks and take necessary precautions to mitigate potential damage (Moustafa et al., 2022). The study of seismicity is vital for disaster preparedness, urban planning, and infrastructure development (Pancholi et al., 2022). Regions with high seismic activity require stricter building codes to ensure structures can withstand earthquakes (Ahmad et al., 2017). Understanding seismicity also contributes to the design of early warning systems (Faure Walker et al., 2021), which can save lives by providing timely alerts before major tremors occur (Jena et al., 2021). Additionally, seismic studies help in identifying and monitoring active faults, which are critical for long-term risk assessments (Tavakoli and Ghafory-Ashtiany, 1999).

Iran is one of the most seismically active countries in the world due to its location at the convergence of the Arabian and Eurasian tectonic plates (Hashemi et al., 2019). The country has experienced numerous devastating earthquakes throughout history (Ghanbarian et al., 2021), with some causing extensive destruction and loss of life (Safari et al., 2010). The high seismicity in Iran is primarily associated with the Zagros Fold-Thrust Belt, the Alborz Mountains, and the eastern tectonic zones (Razaghian et al., 2018). These regions are characterized by intense fault activity, making Iran highly susceptible to future earthquakes. Figure 1 shows the overall seismic hazard zonation map of Iran.

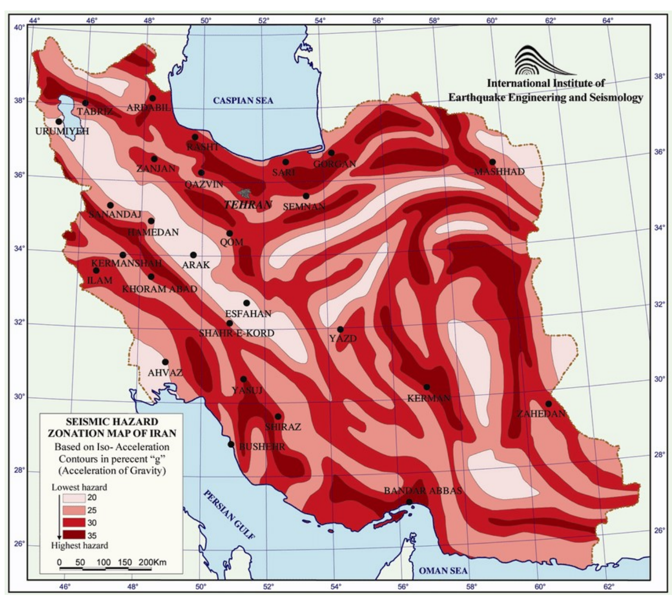

Fig. 1 Seismic hazard zonation map of Iran
(Tavakoli & Ghafory-Ashtiany, 2012)

Iran is home to several major fault systems, including the Main Zagros Reverse Fault, the North Tabriz Fault, and the Alborz Fault System (Amini-Hosseini & Hosseinioon, 2012). These faults accommodate significant tectonic stress and are responsible for many of Iran's earthquakes (Karimzadeh et al., 2015). Active faults in Iran exhibit different movement patterns, including thrust, strike-slip, and oblique-slip mechanisms, which contribute to the country's complex seismic behavior (Karimzadeh et al., 2017). The presence of multiple fault systems highlights the importance of continuous seismic monitoring and hazard assessment (Kamranzad et al., 2020). Seismic hazard mapping is a crucial tool for assessing earthquake risks and identifying vulnerable areas (Moradi et al., 2015). These maps integrate geological, geophysical, and historical seismic data to provide a visual representation of earthquake-prone zones (Amini-Hosseini & Hosseinioon, 2012). By using GIS, researchers can analyze fault distributions, soil conditions, and seismic wave propagation patterns to create accurate hazard models (Kamranzad et al., 2020). Such maps are essential for designing earthquake-resistant infrastructure and guiding land-use planning in high-risk regions (Karimzadeh et al., 2017). GIS-based seismic mapping allows for the integration of multiple datasets, making it a powerful tool for earthquake risk assessment (Tavakoli & Ghafory-Ashtiany, 1999). With GIS, researchers can overlay fault locations, historical earthquake epicenters, population density, and building structures to assess potential damage scenarios (Hamdy et al., 2022). This technology enhances the accuracy of hazard assessments and enables decision-makers to develop effective mitigation strategies (Delavar et al., 2015).

Active tectonics refers to the ongoing movement and deformation of the Earth's crust due to tectonic forces (Walker & Jackson, 2004). It plays a significant role in shaping seismic activity by generating new faults and reactivating existing ones (Tavakoli & Ghafory-Ashtiany, 1999). Iran's complex tectonic setting, marked by continental collision and subduction, leads to frequent and intense earthquakes (Amini-Hosseini & Hosseinioon, 2012). Understanding active tectonic processes helps in predicting future seismic hazards and assessing the long-term evolution of fault systems (Kamranzad et al., 2020). Active tectonics directly influences seismic hazard mapping by determining earthquake recurrence intervals, fault slip rates, and ground deformation patterns (Karimzadeh et al., 2015). Regions with high tectonic activity require detailed seismic hazard maps to identify areas of extreme vulnerability (Amini-Hosseini & Hosseinioon, 2012). In Iran, studies of active tectonics help scientists estimate the probability of large earthquakes in specific fault zones and prioritize regions that need immediate risk mitigation efforts (Mousavi et al., 2013). Iran is divided into several seismotectonic provinces, each with distinct geological and tectonic characteristics that influence earthquake activity (Zafarani & Ghafoori, 2013). Figure 2 illustrates the seismotectonic provinces of Iran. The major seismotectonic provinces include the Zagros Fold-Thrust Belt, Alborz Mountains, Central Iran, Kopeh Dagh, Makran Subduction Zone, and Eastern Iran (Mirzaei et al., 1998). Among these, the Zagros region is the most seismically active due to the ongoing collision between the Arabian and Eurasian plates, generating frequent moderate to strong earthquakes (Nowroozi & Ahmadi, 1986).

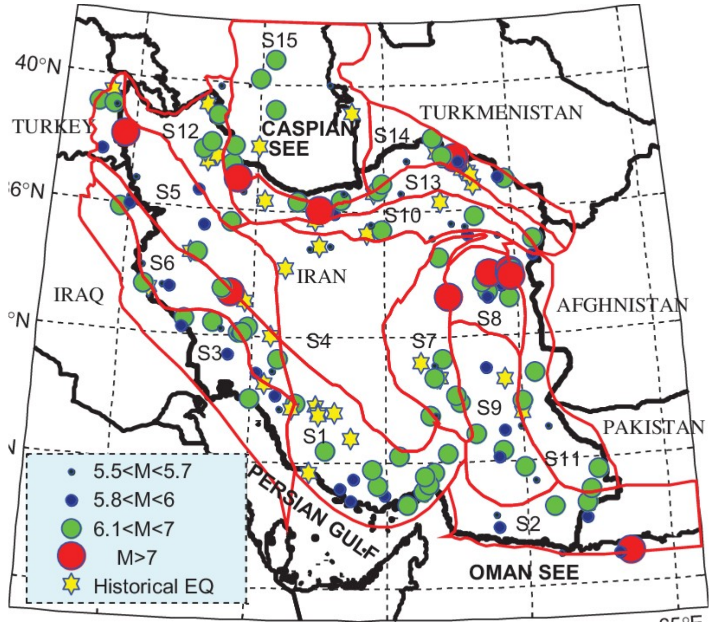

Fig. 2 The 15 seismotectonic provinces of Iran (Zafarani & Ghafoori, 2013)

The Alborz and Kopeh Dagh regions, located in northern Iran, are characterized by active strike-slip and thrust faults, including the North Tehran Fault (Arian, 2015), which poses a significant risk to highly populated areas like Tehran (Nazarinezhad et al., 2024). The Makran Subduction Zone, in southeastern Iran, differs from other regions as it experiences subduction-related megathrust earthquakes, similar to those occurring in tectonic plate boundaries like Japan and Indonesia (Niassarifard et al., 2021). The seismotectonic provinces of Iran play a crucial role in the country's earthquake patterns by controlling fault movements and stress accumulation (Tavakoli & Ghafory-Ashtiany, 1999). The Zagros and Alborz regions generate most of Iran's shallow earthquakes, while deep-focus events are associated with the Makran and Central Iran provinces (Kamranzad et al., 2020; Ghanbarian & Derakhshani, 2022). These provinces define the seismic hazard levels across the country, influencing building regulations, urban planning, and disaster preparedness strategies (Mousavi et al., 2013). Understanding the behavior of these provinces helps seismologists assess earthquake probabilities, identify high-risk areas, and improve early warning systems (Zafarani & Ghafoori, 2013). Given Iran's history of devastating earthquakes, continuous study of its seismotectonic framework is essential for mitigating future seismic disasters and enhancing national resilience (Mirzaei et al., 1998).

Given Iran's high seismic activity, earthquake preparedness is a top priority for government agencies, engineers, and urban planners. Implementing strict building regulations, improving public awareness, and developing efficient disaster response strategies are essential for reducing earthquake impacts. Seismic hazard maps guide authorities in enforcing construction standards that ensure buildings can withstand strong tremors. Although precise earthquake prediction remains challenging, advancements in seismology and geophysical monitoring have improved our understanding of seismic patterns. By analyzing seismic waves, fault movements, and ground deformation, scientists can estimate the likelihood of future earthquakes.

III. Studied Location

The study area is located along the road connecting Baft, Arzuiyeh, and Hajiabad, approximately 20 km east of Hajiabad. The area covers an approximate region of 33 km by 33 km. It spans across two provinces, Kerman and Hormozgan, with specific geographical coordinates: Longitude ranging from 56°00′ to 56°20′ East and Latitude between 28°30′ to 28°12′37″ North. A QuickBird satellite image from Google Earth provides a clear view of the study area's geographical location. In terms of settlements, the northern half of the study area includes several towns and villages, such as Arzuiyeh, Shah Maran, Dasht Var, Vekilabad, Ebrahimabad, Karimabad, Deh Sheikh, Sultanabad, Hosseinabad, Mohammadabad, Mahmoodabad, Abbasabad, Aliabad, and Jannatabad, all of which are part of Kerman province. In contrast, the southern half of the area includes villages like Jayin, Shamileh, Fargan, Rahimabad, Nezamabad, Shahrud, and Fargan, which are located in Hormozgan province.

Geologically, the study area is structurally situated between two major tectonic zones of Iran: the Sanandaj-Sirjan Zone and the Zagros Zone. The mountain range in the central part of the region runs in a northwest-southeast direction, where thrust faults with the same orientation are located. This area marks the tectonic boundary between the Sanandaj-Sirjan sediments and the Zagros outcrops. As a result, the northern part of the region belongs to the Sanandaj-Sirjan Zone, while the southern part lies within the Zagros Tectonic Zone. In the central belt, where these two structural zones converge, there are outcrops of the Mixed Color Formation (CM), which include Lower Cretaceous flysch along with ultramafic rocks and Eocene flysch, all of which are exposed in the area. Generally, the region under study exhibits an imbricated structure, characterized by thrusting with a general convergence direction from the northeast and north towards the southwest and south. It is believed that tectonic events in this area, particularly the north-south thrusting resulting from orogenic movements after the Late Cretaceous, along with the compressional phases during the Tertiary to Pliocene-Quaternary periods, have shaped its current geological structure. Figure 3 provides the geological map of the studied site.

The region's location within the two tectonic zones of Sanandaj-Sirjan and Zagros, as well as the boundary separating them, has led to the formation of a relatively complex geological structure. The tectonic events that have shaped this area are largely controlled by two main phenomena. The first involves tensional phases that resulted in the formation of a rift, associated with the deepening of the Neo-Tethys Sea during the Middle Triassic period. The second phenomenon consists of compressional phases, responsible for the closure of the deep Neo-Tethys Sea and the subsequent subduction of the Central Iran Plateau over the Zagros Belt during the Lower Cretaceous. This compressional activity continued through the Alpine orogeny and into the Post-Pliocene, contributing to the development of imbricated structures in the study area. These tectonic processes have played a crucial role in the region's structural evolution, influencing its seismic activity and overall geological characteristics. Given the complex tectonic setting of the study area, which spans across the Sanandaj-Sirjan and Zagros tectonic zones, the region's structural features are intricately shaped by both tensional and compressional tectonic phases. This geological complexity, characterized by active faulting, thrusting, and significant tectonic deformation, makes the region highly susceptible to seismic activity.

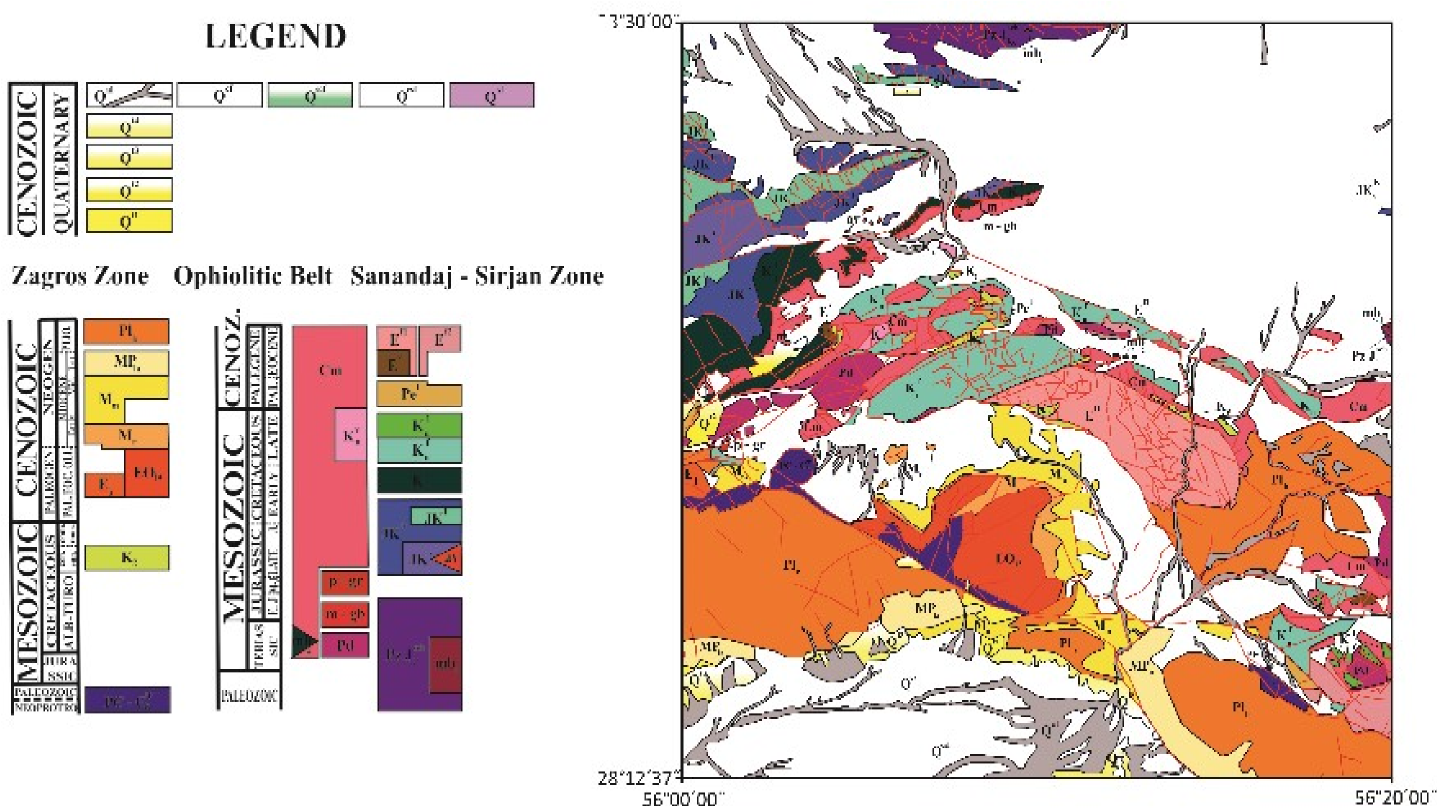

Fig. 3 Geological map for studied region (Geological Survey of Iran 2009)

Due to the ongoing tectonic movements and the presence of several fault systems, the seismic behavior of the area remains a critical concern. Therefore, there is an urgent need for detailed seismic studies to assess the region's earthquake risk, understand the underlying seismic patterns, and develop effective strategies for mitigating potential hazards.

IV. Materials and Methods

In this study, we employed a methodology that integrated GIS, remote sensing data, seismic data, and field-based analysis to investigate the relationship between tectonic systems, seismicity, and the seismotectonic characteristics of the study area (Figure 4). The region spans the tectonic boundaries of the Sanandaj-Sirjan and Zagros zones, which are crucial in understanding the area's seismic behavior. To begin, we collected seismic data from regional seismic stations, covering earthquake occurrences, magnitudes, epicenter locations, and depths. This data helped us map the seismicity of the region and identify patterns in the distribution and frequency of earthquakes. The analysis of these seismic events provided an understanding of how they relate to the active fault zones and tectonic boundaries present in the area.

We further complemented the seismic analysis by using remote sensing data, including satellite imagery from Google Earth and QuickBird satellites, to study the surface geology and fault systems. These images allowed for the identification of key geological features, such as active faults, thrust zones, and folds, which directly influence seismic activity. By integrating these remote sensing images with other datasets, we created a more accurate representation of the region's structural and tectonic dynamics. To spatially analyze the correlation between tectonic features and seismic activity, we used GIS tools. GIS allowed us to generate detailed maps that depicted the distribution of faults, earthquakes, and tectonic zones in the region. By overlaying this data, we were able to identify correlations between seismic events and fault systems, gaining insights into how tectonic movements contribute to the region's seismicity.

In addition to these methods, we conducted field sampling at 30 seismic/tec stations throughout the study area. At each of these stations, we collected data on local seismicity and geological features. Using the data gathered, we created stereonets and rose diagrams to analyze the orientation and distribution of fault systems in the region. The stereonets were particularly useful for visualizing the fault geometries, while the rose diagrams helped us understand the predominant fault orientations and tectonic stress directions. We also performed field-based observations to directly investigate the region's geological structures, fault lines, and active tectonic features. This hands-on analysis allowed for a more precise understanding of how the active fault systems behave and their role in the region's seismic activity. The combination of field data and theoretical modeling enriched our overall understanding of the tectonic and seismic characteristics of the area. Finally, we synthesized the findings from seismic data analysis, remote sensing, GIS modeling, and fieldwork to assess the seismic risk of the region. The results were used to propose earthquake mitigation strategies, hazard mapping, and recommendations for urban planning. This integrated approach enabled us to establish a clear relationship between the region's tectonic systems and seismic behavior, providing valuable insights for future seismic risk management and preparedness.

V. Results and Discussion

Considering the tectonic structures in the region (Figure 5), six seismotectonic zones have been identified, with a rose diagram prepared for each of these zones to represent the primary tectonic structures. This process was consistently repeated across the study area. For each zone, five main stations were selected for detailed analysis, allowing for a comprehensive understanding of the seismic and tectonic characteristics of each area. The rose diagrams for each of the six seismotectonic zones were generated to visually depict the dominant fault orientations and tectonic stress directions. These diagrams played a crucial role in highlighting the tectonic fabric of the region, providing valuable insights into the ongoing tectonic processes. Figure 6 illustrates the rose diagrams for all six zones, demonstrating the spatial distribution and orientation of the fault systems within the study area.

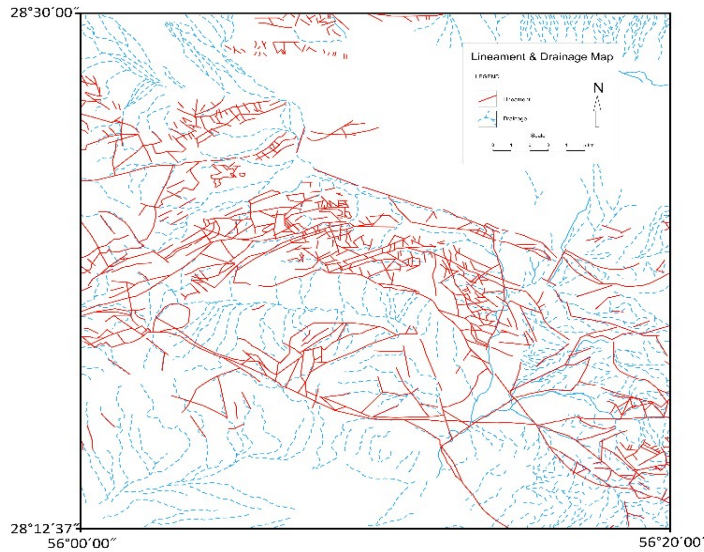

Fig. 4 Tectonic lineaments of the studied region

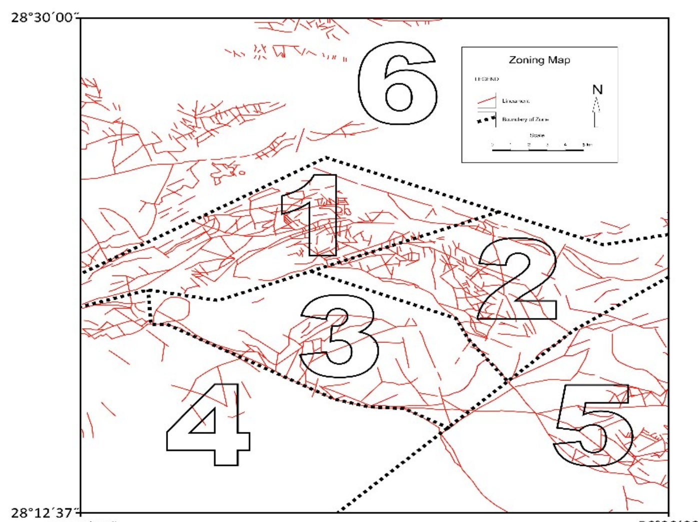

Fig. 5 Tectonic system of the studied region

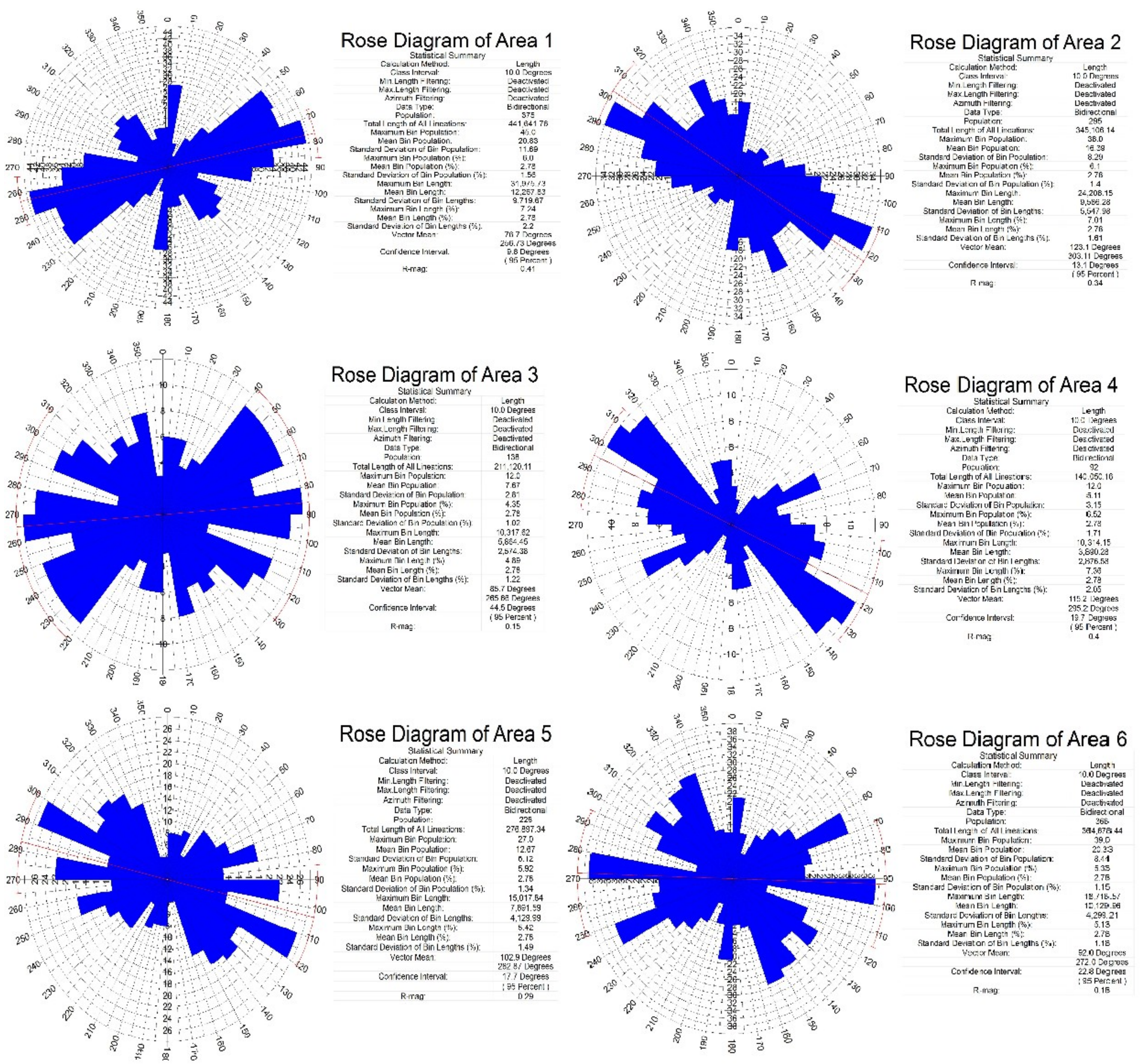

Fig. 6 Rose diagrams for various zones that has been identified in studied region

This approach facilitated a thorough analysis of the region's tectonic behavior and contributed to a better understanding of its seismic activity. The data obtained from the International Institute of Earthquake Engineering and Seismology (IIEES) indicates that the earthquakes that occurred in the study area have not exceeded a magnitude of mb:5. These earthquakes have exhibited varying numbers and distributions over different time periods. The following time intervals highlight these variations:

- Pre-2000 period,
- 2000 to 2006 period,
- 2006 to 2008 period,
- 2008 to 2023 period,

Figure 7 shows the distribution of earthquakes from before 2000 to presents. The overall distribution of earthquakes based on their occurrence time reveals a migration pattern, with earthquakes gradually shifting from the southeast to the southwest of the region over time. This migration could be indicative of changes in the tectonic stress fields or fault dynamics in the study area, suggesting a shift in the active tectonic processes influencing the region's seismic activity. The analysis of these patterns provides valuable insights into the temporal evolution of seismic events and their spatial distribution, contributing to a better understanding of the region's earthquake behavior.

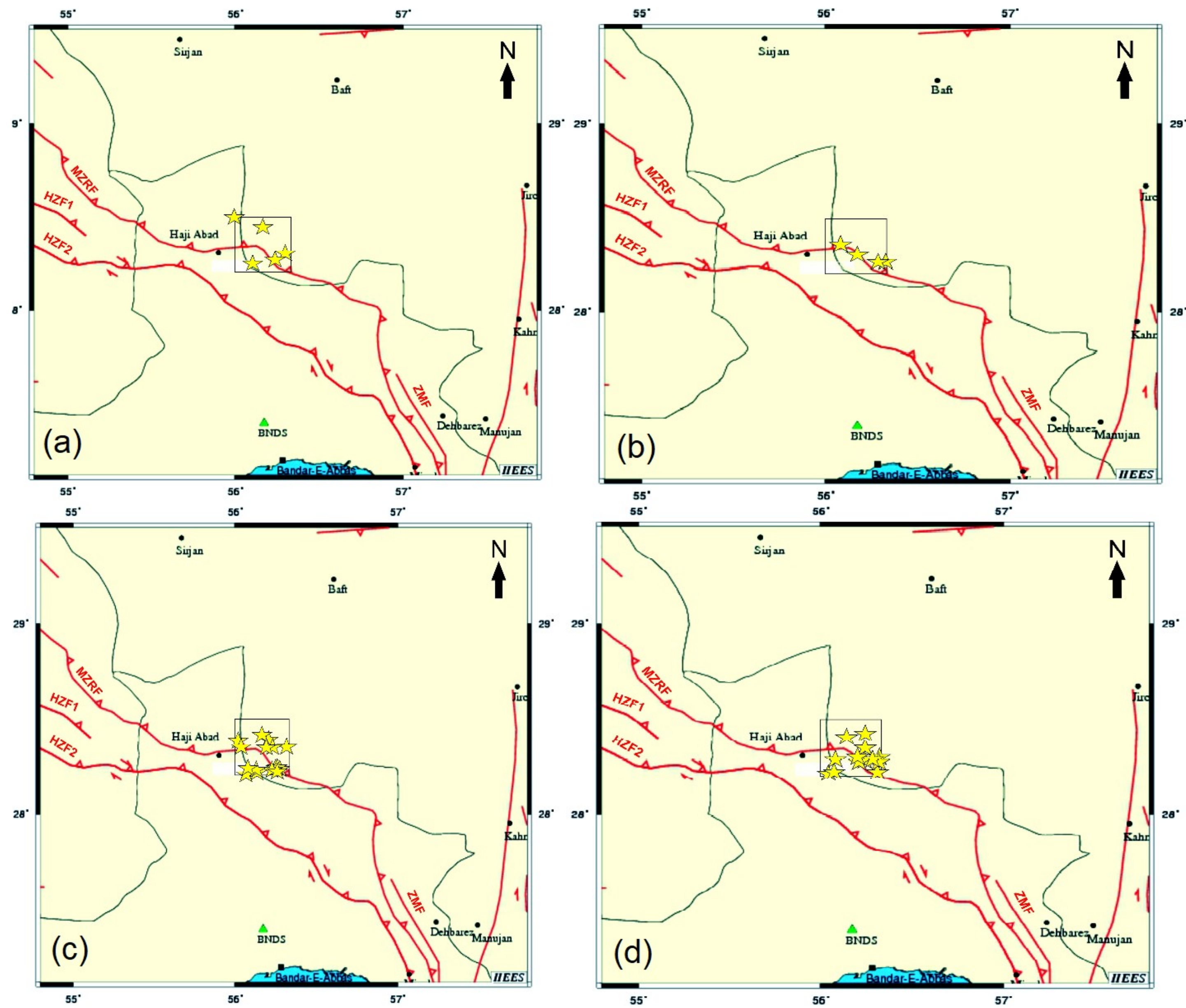

Fig. 7 Distribution of earthquakes in studied region; (a) pre-2000, (b) 2000 to 2006, (c) 2006 to 2008, (d) 2008 to 2023 periods (For the maps used IEES platform)

VI. Conclusion

This study provides a detailed analysis of the seismic and tectonic characteristics of the southern Kerman region, located along the Baft–Arzuiyeh–Hajiabad road. The region lies at the intersection of two significant tectonic zones of Iran, Sanandaj-Sirjan and Zagros, which play a crucial role in shaping both the geological structure and seismic activity. Despite the recorded earthquakes in the area not exceeding a magnitude of mb:5, the presence of complex and highly deformed fault systems indicates significant tectonic activity, contributing to the region's seismic potential. The integration of seismic data, remote sensing, GIS techniques, and field-based analysis allowed for a comprehensive assessment of seismic risks and tectonic behaviors. The study revealed the intricate nature of the fault systems in the region, which are influenced by both compressional and tensional tectonic forces. The GIS-based seismic hazard map developed in this study highlights the critical need for continuous seismic monitoring and analysis of the region's structural and geodynamic behavior. Furthermore, the findings underscore the importance of developing effective earthquake risk mitigation strategies and urban planning to enhance preparedness for future seismic events. Given the complex tectonic interactions in the study area, this research provides valuable insights that can contribute to better seismic risk assessment, potentially reducing the impact of future earthquakes on the local population and infrastructure. The integration of geological, seismic, and tectonic data ensures that the results can inform decision-making processes and guide efforts in managing earthquake hazards in the southern Kerman region.

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AUTHORS' CONTRIBUTIONS

Maryam Dehghananari conducted the main data analysis, contributed to the data collection, preprocessing, interpretation, and was responsible for drafting the initial manuscript. She performed conceptual and critical revision of the manuscript, overall project administration and final approval of the version to be published. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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