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Variation of seismicity parameters and its link to tectonic features of the central portion of the Zagros Fold-Thrust Belt, Iran

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Abstract: The Zagros Fold-Thrust Belt is one of the most tectonically active regions in the world. The seismicity of this belt is affected by various factors and has certain complexities. This paper provides the results of assessment of temporal and spatial seismicity variations of the central portion of the belt in Fars and Bushehr provinces and their link to regional tectonic properties. Relatively, everywhere in the belt, the geometry of the folds has been mainly affected by thrusts and basement faults. There is a meaningful link between seismic activity and folding in the belt. The most abundant types of folds are detachment folds, fault bend and fault propagation folds. They play an important role in the spatial seismicity of the area. The maximum number of seismic events have medium magnitude which ranges between 2.5 and 3. There is a decreasing trend of a and b parameters from south-west to north and north-east where the occurrence of higher magnitude earthquakes is expected. Temporal analysis of seismicity shows that earthquakes with magnitude ≥6.5 have a ten-year return period in the region. The occurrence of several earthquake groups in the belt was in the form of swarms showing point or linear spatial distribution. Some of these possible swarms are around transverse faults, salt domes and some are related to blind faults, which indicate the complexity of the seismicity in this belt. Spatial distribution of low magnitude seismic clusters is also influenced by two other factors (1) existence of frequent salt domes many of which might be active and their spatial links to major faults and (2) human-related activities, especially hydrocarbon extraction.

Keywords: Zagros Fold-Thrust Belt, Gutenberg-Richter, seismicity, earthquake swarms, active tectonics, seismotectonics, basement fault

Introduction

The Zagros Fold-Thrust Belt is one of the most tectonically active regions in the world, and is located in the middle of the Alpine–Himalayan belt (Fig 1). This belt has an average convergence of more than 20 mm per year and consumes the deformation due to the northward movement of the Arabian plate in the form of folding, faulting and seismic activity (Tatar et al. 2002; Vernant et al. 2004). Deformation in the Zagros occurs in basement and sedimentary rocks and this phenomenon has also been observed in the seismicity of the region (Hatzfeld & Molnar 2010). Many studies have been done on the tectonics of the Zagros Fold-Thrust Belt considering various aspects such as crustal deformation and thickening, the role of transverse faults in the regional deformation pattern, rotation of the axis of the folds, the effect of competent layers in folding style, and so on (e.g., Hessami 2002; Sepehr & Cosgrove 2004; Malekzade et al. 2007; Hatzfeld & Molnar 2010; Paul et al. 2010; Barnhart et al. 2018; Edey et al. 2020).

The Zagros Fold-Thrust Belt has a north-west–south-east trend and the pattern of the folds changes from the south-west of this zone to its north-east (e.g., Alavi 2004; Vergés et al. 2011; Alipoor et al. 2019). This change is characterized by a decrease in the amplitude of the folds and an increase in their height and the formation of inverted faults in the south-west (Berberian 1995; Alavi 2004; Molinaro et al. 2005; Carruba et al. 2006; Sherkati et al. 2006; Ghanadian et al. 2017).

In the belt, the Precambrian metamorphic basement is covered by 8 to 14 km of sedimentary layers that are folded during Late Cretaceous and Paleogene to Neogene orogenic movements (e.g., Alavi 2004, 2007). In the South-eastern Zagros, in the lowest part of these sediment layers, there is the Hormoz salt layer with a thickness of 1 to 2 km of high plasticity that acts as a decollement layer (e.g., Bahroudi & Talbot 2003). These salt deposits are not the only source, but the major source of Zagros salt domes (Bahroudi & Talbot 2003; Hassanpour et al. 2021). Deformation style and type of folds are different across the belt due to high plasticity of salt deposits that acting and basal and middle detachments and association of folds with often hidden faults in the Zagros Fold-Thrust Belt (e.g., Molinaro et al. 2005; Carruba et al. 2006; Sepehr et al. 2006; Sherkati et al. 2006; Jahani et al. 2009). This can cause seismicity variations in terms of distribution, magnitude, focal depth and mechanism of earthquakes (Talebian & Jackson 2004; Nissen et al. 2007, 2011, 2014; Roustaei et al. 2010; Casini et al. 2011; Barnhart et al. 2018).

The study area is located in south-western Iran in the Zagros Fold-Thrust Belt and in a geographical position of 51 to 54 degrees east longitude and 27 to 30 degrees north latitude and

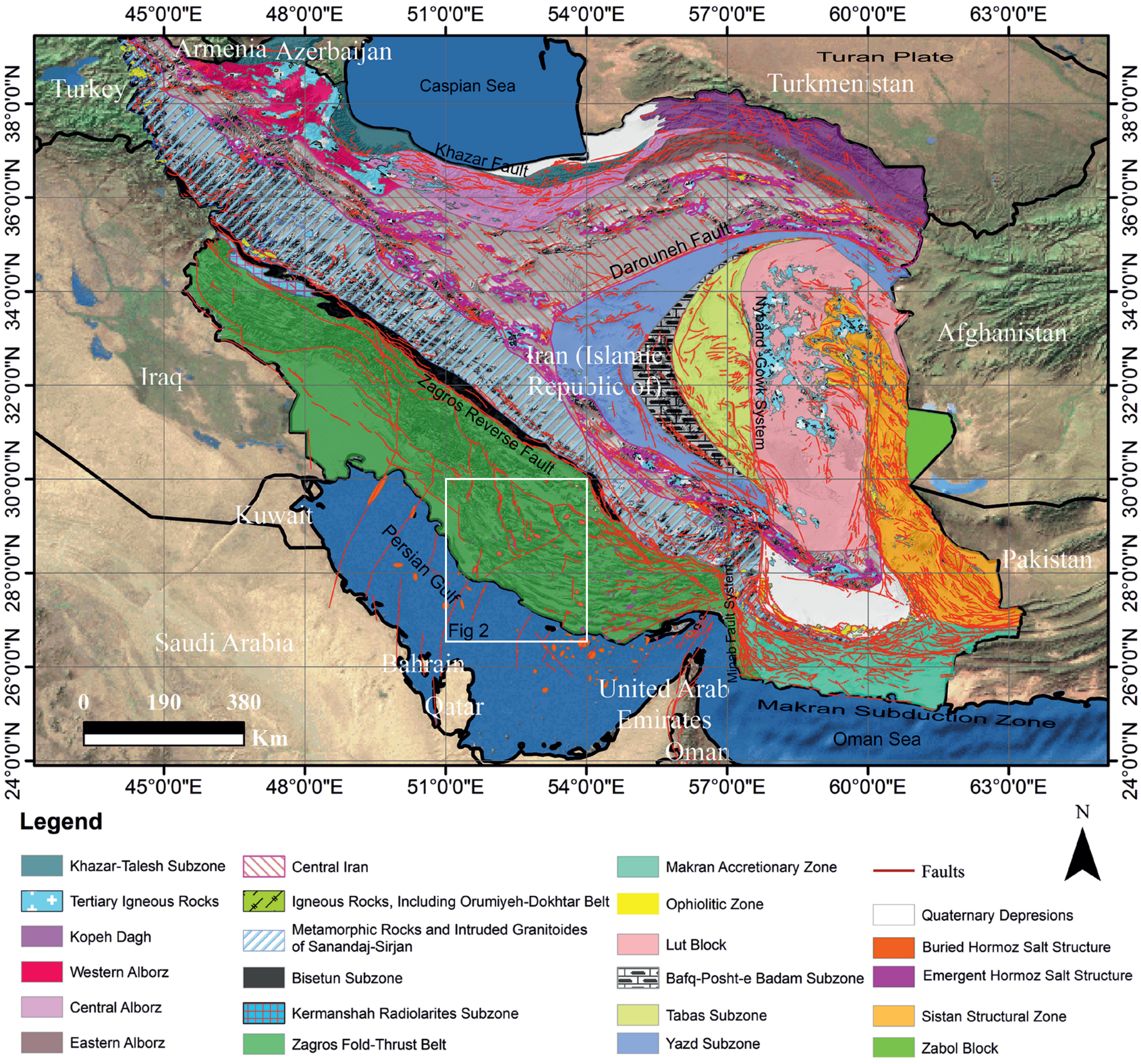


Fig. 1. The map shows structural zonation of Iran and distribution of tectonic zones and subzones across the region. The location of study area in the Zagros Fold-Thrust Belt is shown with a white rectangle on the map.

in Bushehr and Fars provinces (Figs. 1 & 2). Figure 2 shows the location of the study area with main faults and earthquakes. The purpose of this research is to investigate the characteristics of seismicity and its spatial changes in the Zagros Thrust Belt. For this purpose, the seismicity parameters have been determined using the seismic catalogue of the region and spatial changes of these parameters has been mapped. Earthquake swarms and their location have also been investigated. The source of the seismic catalogue is described in section method.

Seismotectonics and seismicity of the Zagros Fold-Thrust Belt

The study of seismicity of the Zagros Fold-Thrust Belt was considered in little documentation before 1970 but grew in number and quality of works afterward. Tchalenko & Braud (1974) study the structure and seismicity of the Main Recent Fault. This important fault was later investigated by Talebian & Jackson (2002). Berberian & Tchalenko (1976) made an assessment on the seismicity of the Bushehr region. The first seismic hazard study in Iran was conducted by Berberian and Mohajer-Ashjai (1977), who mapped the Intensity of earthquakes in Iran. Berberian & Papastamatiou (1978) prepared a field report and seismotectonic discussion on the Khurgu (1978) earthquake in the Bandar Abbas area. Niazi et al. (1978) investigated the variation of earthquake focal depth in the Kermanshah region. Jackson (1980) evaluated the errors of focal depth in Iran and Turkey. Active tectonics and seismicity of the Zagros Fold-Thrust Belt was examined by Jackson & Fitch (1981). Newer works on the Zagros Fold-Thrust Belt are widespread, for example; Nowroozi & Ahmadi (1986) estimated the seismic risk using seismic hazard analysis for different regions of Iran. Berberian (1995) considers the Zagros to be composed of several morphotectonic units that

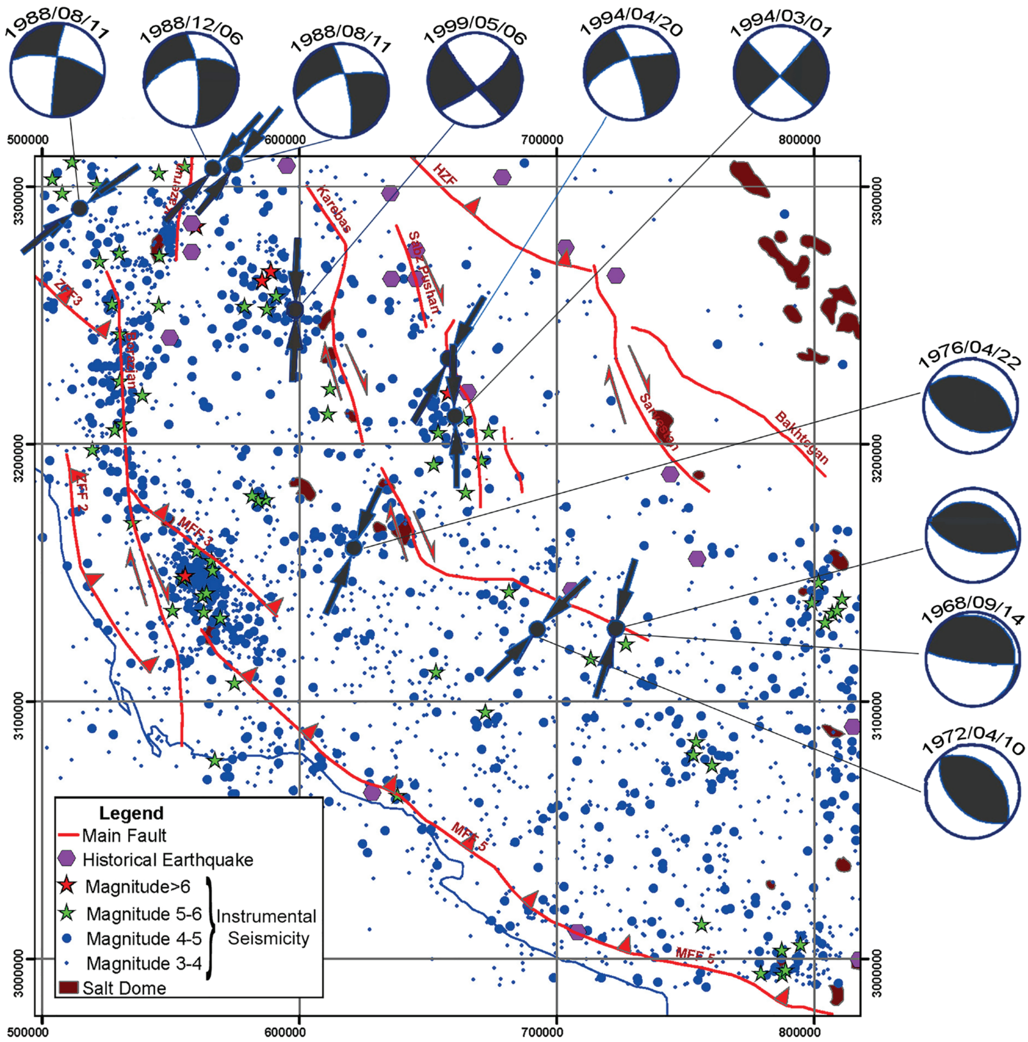


Fig. 2. Location map of the study area that shows distribution of historical earthquakes and instrumental seismicity (magnitude greater than 3). Major faults in the study area (MFF: Mountain Front Fault, ZFF: Zagros Foredeep Fault, HZF: High Zagros Fault); centroid moment tensor solutions are from Hessami et al. (2003). Faults are compiled from 1:250,000 geological maps prepared by Geological Survey of Iran and National Iranian Oil Company including Perry et al. (1965), NIOC (1974), Evers (1977), Fakhari (1994a, b), Houshmandzadeh et al. (1990), Nogol-Sadat & Almasian (1993), Hassanpour et al. (2021), Mohammadrezaei et al. (2020). Coordinate system of map is UTM, Zone 39N and grid numbers are in metres. Location of the map is shown on Fig. 1 by a white rectangle.

have been separated by the development of deep reverse faults. These faults consist of the Main Recent Zagros Fault, High Zagros Fault, Mountain Front Fault, Dezful Embayment Fault and Zagros Foredeep Fault. He mentioned that Zagros Fold-Thrust Belt is an actively deforming belt with longitudinal buried thrusts and transverse strike-slip fault, asymmetric folding, uplift and seismic activity in the sedimentary cover in which there are at least two levels of upper (Gachsaran) and lower (Hormoz) regional detachment (Berberian 1995; Hassanpour et al. 2021). Zamani & Agh-Atabai (2011) did a multifractal analysis of the spatial distribution of earthquake epicenters in the Zagros and other regions of Iran. Nissen et al. (2011) provided information and new interpration of basement faultig based on local network data that demonstrated microseismicity occurs within the Zagros basement (depths of ~20 km and locally ~30 km). Ghassemi (2014) investigated about earthquake swarms in Iran. He examined 24 events of earthquake swarms that have occurred during the historical and instrumental periods of seismic activity in Iran, and concluded that Iran earthquakes occur mostly in the Zagros and then in the south of Central Alborz and Azerbaijan.

The trend of folds in the Zagros Fold-Thrust Belt is north-west–south-east. The anticlines of this region are mostly asymmetric, inverted, inclined to the south-west, parallel layers that are often formed by bending-sliding mechanism (Coleman-Sadd 1978; Alavi 1994). These folds are often in the form of detachment folding (e.g., Sherkati et al. 2006), fault propagation folds or fault bend folds, so that the low amplitude of a fold can indicate the thrust fault below it (Alavi 2007). In the north-east of this belt, the anticlines are usually older and closed or narrow with an angle between the edges between zero and about 70 degrees. To the south-west, the anticlines begin to look younger, and the folds are more open with an interlimb angle between 110 and 140 degrees (Zand-Salimi 2008).

The study of folding style in the Zagros Fold-Thrust Belt has been studied by many researchers, including McQuarrie (2004), Molinaro et al. (2005), Sherkati et al. (2006), Motamedi (2008), Ramsey et al. (2008), and so on. In most of these studies, the geometry and kinematics of folding have been studied using regional structural sections, seismic data and modelling. Mechanisms proposed for the folding style of sedimentary cover in the Zagros Fold-Thrust region include detachment folding (McQuarrie 2004; Sherkati et al. 2006), fault-propagation folding and fault-bend folding (Alavi 2007).

The Zagros is an active tectonic belt in which more than half of Iran's earthquakes occur (Mirzaei et al. 1998). The magnitude of earthquakes in the Zagros is low to medium and shallow in depth. Figure 2 shows the position of earthquakes with magnitudes greater than 3 in the range. Hashemi (2009) studied the spatial variations of seismicity parameter in Iran and concluded that the highest value of b-value is 1.28 in the Zagros and the lowest is 0.84 belongs to the east-centre of Iran. Hashemi (2010) investigated the relative rates of active deformations in the eastern Zagros (Lar and Hermoud anticlines). He calculated the shortening rate in the Lar anticline is 2±1 mm/yr and also concluded that the deformation in the Zagros is progressed by seismic activity. Ghods et al. (2012) investigated the earthquake sequence of the 2006 Silakhour earthquake and implied it for segmentation of the Main Recent Fault. Elliott et al. (2015) characterized the 2013 Khaki Earthquake with seismicity and InSAR studies. They found that there is significant shortening occurring only in the sedimentary cover of the Zagros and both coseismic and aseismic slips are controlled in depth extent by lithology. Khodaverdian et al. (2016) estimated seismic parameters and a spatial seismicity model for Iran and for this purpose, seismic parameters were calculated for networks with distances of one degree longitude and latitude, and a map of spatial changes was prepared. Mousavi (2017) has studied the b-value changes in Iran using the Gutenberg-Richter method, the value of which has been in the range between 0.8 and 1.5. The maximum value of this parameter was in central and eastern Iran, and the lowest was in north-western Iran. Karasözen et al. (2019) presented a relocated catalogue of ~2500 instrumental earthquakes in the Zagros Fold-and-Thrust Belt that highlighting the existence of numerous unmapped faults. They added that focal depth distribution (4–25 km) throughout the Zagros implies earthquakes nucleate both in the sedimentary cover and basement. Khalili & Dilek (2021) studied the April 9 2013 earthquake in Kaki area of Bushehr province and introduced a new blind fault that caused the earthquake with no surface rupture. The 2017 Sarpol-Zahab earthquake (M_w 7.3) is an interesting, important and damaging earthquake that was studied by various authors. Almost all authors emphasized that this earthquake occurred due to shallow dipping thrust fault in the middle depth basement of Zagros Fold-Thrust Belt (Barnhart et al. 2018; Chen et al. 2018; Yang et al. 2018). Jamalreyhani et al. (2021) investigated the origin of a long-lived earthquake cluster in the Fars arc of the Zagros Fold-Thrust Belt that was collocated with the major Shanul natural gas field. They concluded that the 2019–2020 Khalili earthquake sequence might be an example of induced seismicity linked to gas extraction in the Zagros. They stressed that discrimination between anthropogenic and natural seismicity is an important and challenging work in the Zagros.

Method

For this study, at first a basic map was prepared using regional geological maps (scales of 1.250,000 and 1.100,000) and the tectonic map of Iran (Nogol-Sadat & Almasian 1993) prepared by the Geological Survey of Iran. Necessary information such as faults and axial trace of folds were digitized from the paper-based maps after georeferencing the maps in GIS. Further information on folds in the Zagros Range was extracted from previous studies to prepare required map of folds (Fig. 3).

Preparing a complete and accurate catalogue of earthquakes is one of the most important steps in seismicity studies and seismic risk assessment. The first seismic catalogues and also the two most important sources for historical earthquakes in Iran were prepared by Ambraseys & Melville (1982) and Berberian (1994). Mirzaei et al. (1998) also prepared historical and instrumental earthquake data sets. In order to prepare a complete seismic catalogue, the data of the International Institute of Seismology and Earthquake Engineering, the Institute of Geophysics of the University of Tehran and the USGS site were used. The data of Geophysical Institute has been much more complete from 2006 onwards, while in the years between 1900 and 1963, the data presented in the site of the International Institute of Seismology and Earthquake Engineering were more complete. A complete catalogue has been prepared by combining the above data, which includes 6931 earthquakes. The collected seismic data can be divided into three groups or periods. The first set is historical seismicity (pre-1900 AD), the second group includes data of instrumental seismicity from the 1900 to 1963 AD and the third set is from 1964 to 2021 that is, in fact, the complete and modern instrumental data. A total of 39 historic earthquakes have been recorded in the region, of which only 21 have magnitude information. The maximum magnitude belongs to the earthquake with a magnitude of 7.1 in 1440 AD (Ambraseys & Melville 1982).

Two other large historical earthquakes were recorded in 1853 and 1863 AD. The earthquakes of May 7, 1999 in Karebas, November 26, 2010 in Jam, February 5, 2012 in Khormuj, April 9, 2013 in Kaki Bushehr and January 27, 2020 in Khanzenian are among the most important instrumental earthquakes in the region.

To perform seismic analysis, we used Zmap software to determine seismic data series and threshold magnitude.

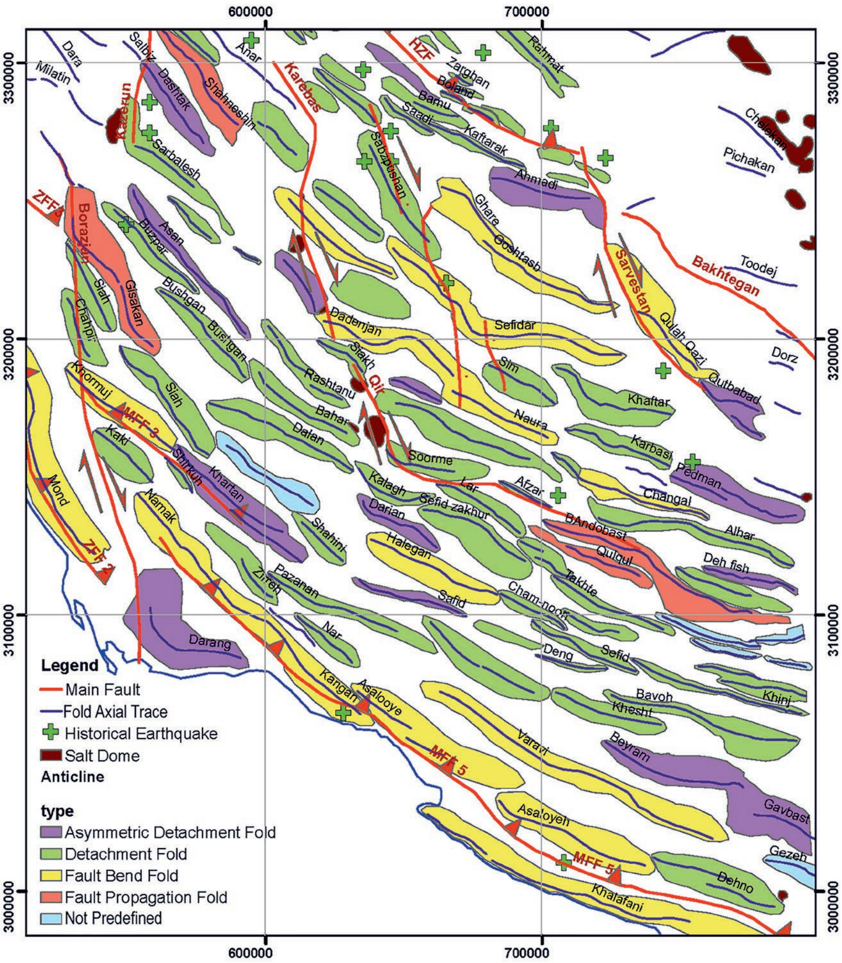


Fig. 3. Compiled map of major structures and fold axial traces showing their type based on published literature. Fold axial traces are compiled from 1:250,000 geological maps prepared by Geological Survey of Iran and National Iranian Oil Company including Perry et al. (1965), NIOC (1974), Evers (1977), Fakhari (1994a, b), Houshmandzadeh et al. (1990). Fold types are based on Mahmoudi-Sivand (1997), Pooraskar (2004), Arian & Hajian (2006), Motamedi & Pourkermani (2006), Yassaghi & Bagheri (2007), Burberry et al. (2008), Jahani et al. (2009), Tavakolian (2009), Zarei (2010), Nowrouzi et al. (2011), Shams (2013), Taghikhani (2013), Maleki et al. (2014a, b), Hamidian Shirazi et al. (2016) and Taghavi et al. (2018).

The result of this analysis is presented in Figs. 4 and 5. The number of seismic data has increased significantly since 2006 due to the increase in national seismography stations and also recording data. The maximum curvature method was used to determine magnitude of completeness (Mc: 2.9) which is a widely used technique (e.g., Wiemer & McNutt 1997; Wiemer & Katsumata 1999; Wiemer 2001). In addition, changes of Mc during the statistical period are also calculated, and the results are presented in Fig. 6. As can be seen, the changes in Mc are not uniform over time due to the gradual completion of recorded data. The value of Mc is statistically higher in the early years due to the failure to record seismic data of small magnitude. Since about 2009, the rate of change has become almost more uniform, that is due to recording of more seismic data with a smaller magnitude through which the value of Mc has also decreased. Therefore, to check the completeness of the data, the time series of the data is divided into three periods and for each period the value of Mc is calculated separately. These periods include the beginning of the statistical period until the beginning of 2005, from 2006 to 2009, and the third period from 2010 onwards. The results of the calculations for each of these periods are presented in Table 1. In Table 1, the first row shows the calculated Mc for the total period; but as mentioned above we used three Mc values for three statistical periods (Table 1; row 2 to 4) for seismicity analysis in the study area. In the period from 2005 to 2009, a decrease in the recorded events and the value of Mc is observed compared to the period from 2009 onwards. The reason for this difference is that in this period of 2005–2009, in addition to being shorter, the average magnitude of earthquakes is lower compared to other periods, although there is no relative decrease in the number of seismic data.

The use of Gutenberg-Richter model in the list of earthquakes in calculating seismic parameters is to be able to model their event statistically with the Poisson distribution function. Poisson's distribution is based on two main assumptions, namely that (1) each event can occur randomly at any time and place, and (2) the occurrence of each event at a specific time and place is statistically independent of other events. Therefore, before using earthquake magnitude data in seismic calculations, they must be analysed based on the Poisson function. In the list of earthquakes these are two types of distributions. One of them is related to aftershocks and foreshocks, which are interdependent in time and space and therefore they are non-Poissonic and the other is related to the distribution of major earthquakes for which Poisson's distribution must be checked. At this step, therefore, firstly the aftershocks and foreshocks are eliminated from the catalogue. One of the best methods for this procedure is the application of combined variable windows in the field of time and place with the

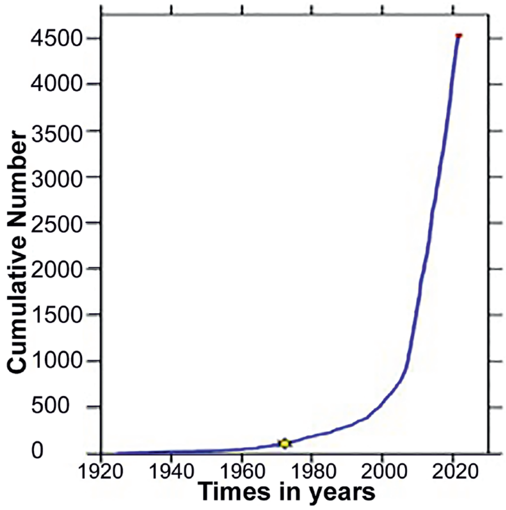


Fig. 4. Cumulative time series diagram of seismic data; yellow star is the largest earthquake in the area.

application of expert judgement to manually remove or add specific earthquakes (Gardner & Knopoff 1974). Table 2 shows the time intervals for the occurrence of aftershocks and foreshocks based on the views of Gardner & Knopoff (1974). In this study, based on the table below and comparing the focal position of earthquakes with respect to the faults causing the main earthquake, aftershocks and foreshocks deleted from the catalogue.

The most common method used to measure the seismicity of an area is the Gutenberg-Richter method. Using this method, the magnitude-frequency relation of the earthquake events is determined, the constant coefficients of which indicate the seismicity of the area. The Gutenberg-Richter relation is as follows:

$$\text{Log } N_c = a - bM$$

In this equation, M is the magnitude of the earthquake and Nc is the cumulative frequency of earthquakes with a magnitude greater than M. a and b are constant coefficients of this equation, which indicate the seismicity of the region. If annual frequency is used, the above equation is as follows:

$$\text{Log } N = a - bM$$

Figure 7 shows the results of this method and the Gutenberg-Richter relation is as follows:

$$\text{Log} N_c = 0.9202M + 6.5041$$

Results and discussion

Spatial variation of seismicity and tectonic features

The Zagros Fold-Thrust Belt is characterized by rapid uplift, high seismicity, and earthquakes of medium to large magnitude in reverse and strike-slip faults. The deformation style in many parts of the Zagros is characterized by asymmetrical

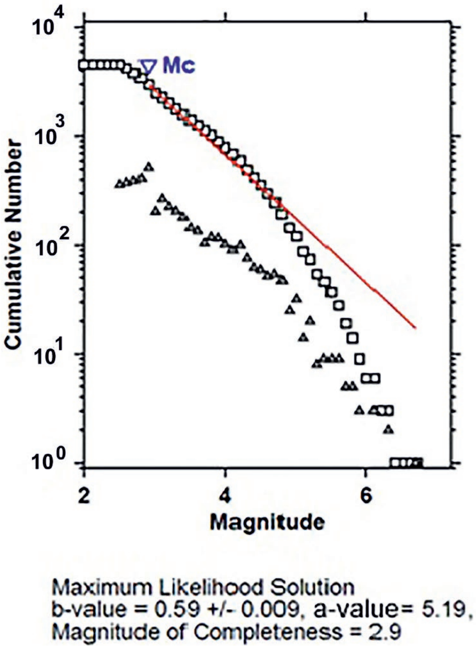


Fig. 5. Mc value in the whole statistical period.

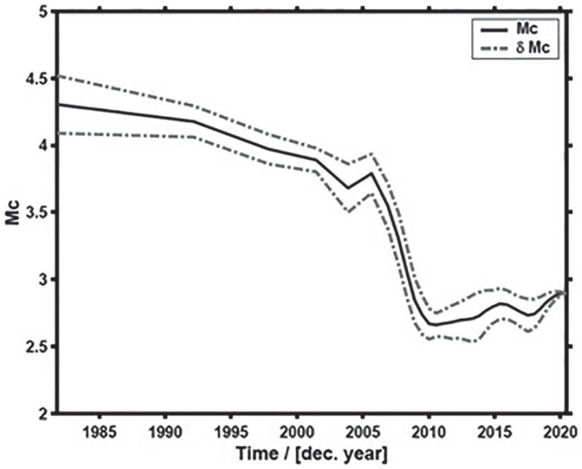


Fig. 6. Changes in Mc value over the statistical period.

Table 1: Mc, a-value and b-value values in different time periods.

Parameter	Mc	a-value	b-value	a (Annual)
Total period	2.9	5.32	0.58±0.008	3.33
1900–2005	4	5.88	0.739±0.02	3.98
2006–2009	2.6	4.77	0.717±0.02	4.05
2009–2021	2.9	5.96	0.872±0.02	4.87

Table 2: Limit values for Di and Ti to identify aftershocks and foreshocks in the spatial and temporal window method.

Magnitude	4	4.5	5	5.5	6	6.5	7	7.5	8
Distance (km)	30	35	40	47	54	61	70	81	94
Time (day)	42	83	155	290	510	790	915	960	985

folds and the lack of significant evidence of obvious reverse faults on the surface, with the exception of known basement faults (Berberian 1995). Most of the folds in the study area are introduced as detachment folds. The folds adjacent to the Mountain Front and Zagros Foredeep faults are mainly fault bend folds, such as the Mand, Assaluyeh, Dehnu, Tabnak, Kangan, and Khormoj anticlines (Fig. 3). There are large asymmetric detachment folds including Darang, Khartang, Ahmadi, Ahram, Asan, Sefid, Qutbabad, Darian, Deh Fish, and Dashtak anticlines (Fig. 3). Burberry et al. (2008) state that asymmetric detachment folds can be formed because of additional shortening which is associated with the development of thrust in the detachment core. As can be seen in Fig. 3, the Darang anticline adjacent to the Borazjan fault, the Khartang anticline adjacent to the Mountain Frontal fault, the Dashtak anticline adjacent to the Kazerun fault, the Qutbabad and Ahmadi anticlines adjacent to the Sarvestan fault are asymmetric detachment fold and the other asymmetric detachment folds mentioned are in the range between the main faults and indicate blind thrusts. The Giskan, Gholghol, and Shahneshin anticlines are fault propagation folds (Fig. 3).

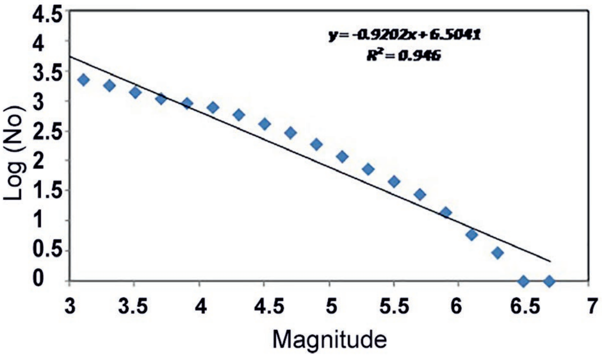
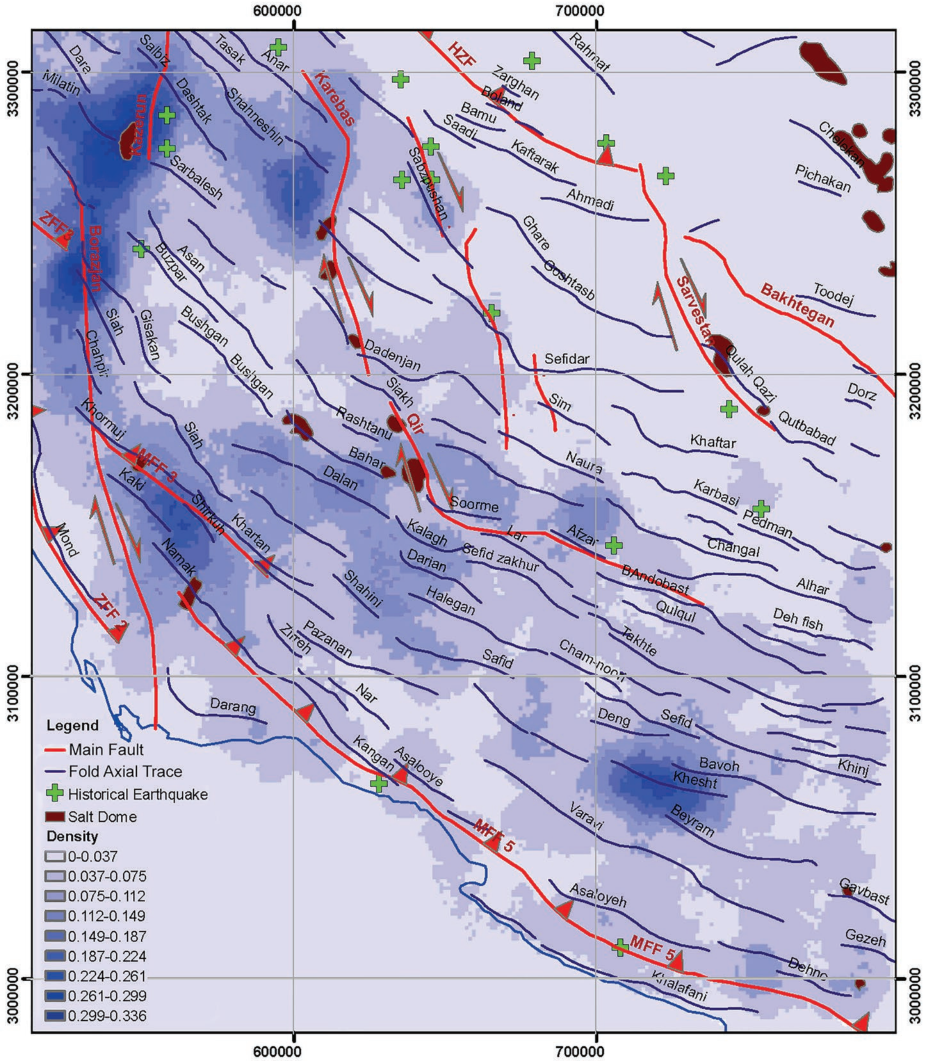


Fig. 7. The Gutenberg-Richter equation over the whole studied area

The Giskan anticline is adjacent to the Borazjan fault that displaced the axis of this anticline (Fig. 3). The Gholghol anticline is adjacent to the Qir fault and the Shahneshin anticline is adjacent to the Kazerun fault.

In the study of seismicity and analysis of seismic data, changes in the density of earthquakes are drawn, and shown in Fig. 8. The density of earthquakes decreases from the

Fig. 8. Spatial variations in the density of earthquakes showing the decrease of seismicity from SW to NE.



south-west to the north-east. As can be seen, the density of earthquakes is near the Kazerun-Borazjan and Mountain Front faults. The density of earthquakes also increases in the area between the Gir and Mountain Frontal faults and around of Khesht, Bavoosh, and Bayram anticlines. Figure 9 also shows the location of earthquakes with magnitudes greater than 5 and historical earthquakes. The occurrence of earthquakes with a magnitude greater than 5 also decreases from the south-west to the north-east.

One of the causes of seismicity in the region is the presence of thrusts faults in the region, which mainly appeared as fault-related folds and they are the source of earthquakes with a magnitude of up to 6.3. As can be seen in Fig. 9, historical earthquakes have occurred mainly in the vicinity of the main faults and more around the Sabzpushan and High Zagros faults. Earthquakes with a magnitude between 5 and 6 have occurred mostly around the Borazjan and Sabzpushan faults, but they are also scattered in other areas of the region, and this also confirms the existence of subsurface faults.

In the studies conducted by Khalili & Dilek (2021) on the earthquake of April 9, 2013 with a magnitude of 6.3 in the Kaki region of Bushehr province, a hidden thrust fault was identified as the cause of the earthquake. It has no surface rupture whereas in previous studies conducted by Yaminifard & Tatar (2013), the southern part of the Borazjan fault was introduced as the cause of the above earthquake. Figure 10 shows the changes in b-value over time. Changes in the b-value range approximately between 0.8 and 1.1 and show an increasing trend between 2015 and 2020.

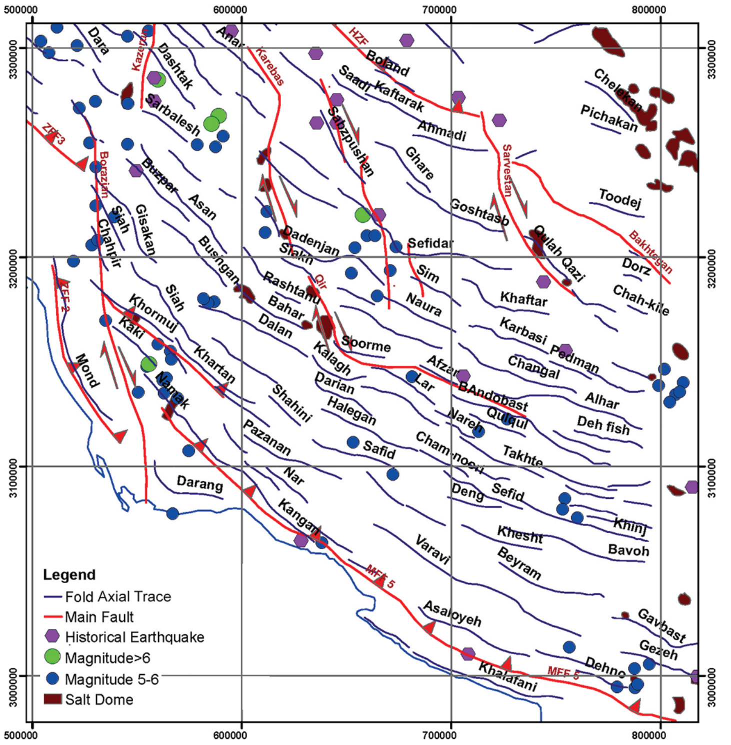


Fig. 9. Spatial variations of earthquakes with magnitudes greater than 5. In the north-east there is no event with this magnitude. Such earthquakes are concentrated around the Kazerun, Borazjan, Qir and MFF faults. There are two historical events and one instrumental event with M>5.0 around the Sarvestan fault.

In determining the spatial variations of a-value and b-value using the Gutenberg-Richter model, the study area was divided into 9 zones, which are one degree of longitude and latitude in size, and for each zone the values of a-value and b-value are calculated. These values are presented in the following Tables 3 and 4.

Changes in seismic parameters a and b also decrease from west to east and from south-west to north-east which indicates the occurrence of more earthquakes in the south-west and west of the study area. On the other hand, the decrease in b-value in the north-east indicates the occurrence of larger earthquakes in these areas.

Earthquake swarms in the area

In several definitions of "Earthquake swarms", this typically refers to a cluster of small to moderate earthquakes that occur over a short period (hours to days or weeks) without a distinct or discernible main-shock (Hill 1977; Miller 2013; Tanner et al. 2020). Swarms are observed in volcanic environments, hydrothermal systems, and other active geothermal areas (Hill 1977; Miller 2013). It should be noted that most case studies on earthquake swarms were done in volcanic regions and areas with temporary or permanent dense seismographic networks that record data very completely (e.g., Klein et al. 1977; Assumpção 1981; Hiemer et al. 2012; Ruhl et al. 2016), but again these studies are based on temporary seismographic stations. All swarm occurrences are not directly associated with movement of fluids and magma in volcanic zones, but tectonic forces can also trigger swarms. Globally, case studies and available information on the earthquake swarms associated with salt tectonics and collapse of salt caverns are much fewer than those done in volcanic zones (e.g., Nayak & Dreger 2018). One of the characteristics of earthquakes in the Zagros is the occurrence of swarms that due to the characteristics of the earth's crust and the presence of unstable layers and gradual release of energy during earthquakes, that characterized the occurrence of multiple and successive earthquakes of medium magnitude in this area. Earthquakes with such magnitudes are usually not destructive and only limited damage can be observed in rural areas. In addition, the occurrence of such earthquakes may continue for several days. Considering that earthquake swarms usually have small magnitude, there is no surface rupture with them, but there are some exceptions for this property (Ghassemi 2014).

The earliest accounts of a historical earthquake swarm in Iran probably date back to 1482 A.D., when a sequence of foreshocks jolted the western Makran region in south-eastern Iran for about 3 months (Ghassemi 2014). Berberian (1976) and then Berberian & Navai (1977) introduced groups of earthquakes in the Zagros that had the character of earthquake swarms. As mentioned before most case studies on the earthquake swarms come from volcanic regions and areas with temporary or permanent dense seismographic networks Unfortunately, no such permanent dense network exists in Iran and no detailed study on earthquake clusters was done using temporary installation of dense seismographs, due to the unfamiliarity of the problem and the budget. So far, no comprehensive studies have been conducted on the occurrence of earthquakes in the folded fault Zagros. In this research, the first spatial and temporal study of the occurrence of earthquakes in this area of Zagros is presented. Drawing the time series of the number of earthquakes that occurred on the days of the year in the study area shows that the number of earthquakes that occur in the year is high and the number of earthquakes that occur in one day is high and varies between 0 and 10 on average.

Due to the fact that earthquake information has been more complete since 2006, a period of time from 2006 onwards has been considered for the daily investigation of earthquakes. The average number of days without earthquakes in the study area was 148 days and 108 days with one earthquake, 55 days with two earthquakes per day and 24 days per year with 3 earthquakes per day were recorded. They also had an average of 7 to 10 earthquakes per day (Table 5). The possible swarms separated from the earthquakes that occurred in the range are presented in Figs. 11 and 12.

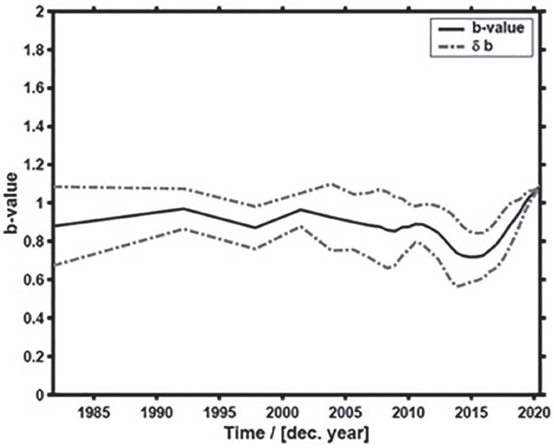


Fig. 10. Changes in b-value values over the statistical period.

Table 3: Changes in the value of a-value in between latitudes (rows) and longitudes (columns).

	51–52	52–53	53–54
29–30	4.886	4.647	3.601
28–29	5.571	5.1086	4.647
27–28	5.0485	5.239	4.886

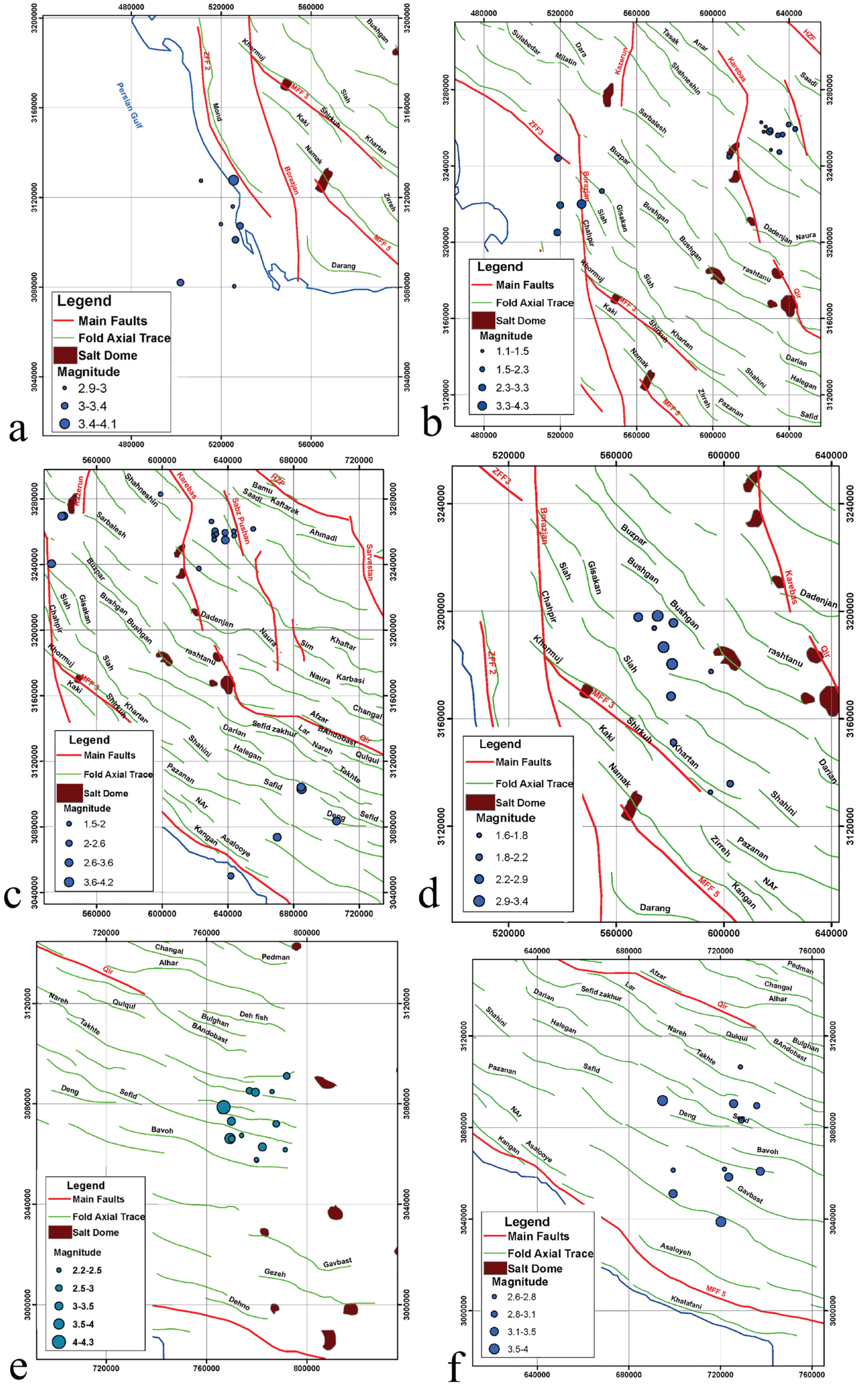
Table 4: Changes in the value of b-value in between latitudes (rows) and longitudes (columns).

	51–52	52–53	53–54
29–30	0.712	0.748	0.659
28–29	0.9032	0.8043	0.748
27–28	0.9877	0.8853	0.712

Table 5: Number of days with earthquakes.

No. of earthquakes per day	0	1	2	3	4	5	6	7	8	9	10
2006	228	96	21	9	6	4	0	1	0	0	0
2007	157	107	58	19	11	3	4	3	0	1	1
2008	154	96	56	28	13	7	3	4	0	2	2
2009	162	111	49	20	12	5	5	1	0	0	0
2010	95	107	75	26	16	14	9	7	4	4	2
2011	153	111	54	20	7	4	2	1	2	5	0
2012	134	109	49	30	13	10	7	5	1	1	1
2013	82	103	64	42	28	11	10	7	3	1	2
2014	166	112	53	15	11	5	1	1	1	0	0
2015	152	121	58	20	4	6	3	0	0	0	1
2016	146	101	67	34	13	2	2	0	0	0	0
2017	151	123	61	21	7	0	0	0	0	0	0
Mean	148	108	55	24	12	6	4	3	1	1	1

Fig. 11. Identified earthquake swarm (possible) periods in the study area: **a** — On 2006/11/3–5, 8 earthquakes with magnitudes between 2 and 4.1 and depth of 9 to 34 km were recorded to the south of the Zagros Foredeep Fault and east of the Borazjan transverse fault. **b** — On 2007/5/3–6/2, occurrence of 17 earthquakes with magnitudes between 1.1 and 4.3 and depths of 5 to 35 km were recorded; 11 events were located as a cluster to the east of the Karebas transverse fault. **c** — On 2007/6/24–27, 21 earthquakes were recorded with magnitudes between 1.5 and 4.2 and depth of 5 to 34 km; this map shows again major clustered earthquakes between Karebas and Sabz-Pushan faults with similar location and just one month after the previous cluster of figure b. **d** — On 2008/1/25–26, 12 earthquakes with magnitudes between 1.6 and 3.4 and depths of 1 to 18 km were mapped in the Bushgan and Siah anticlines. **e** — On 2008/2/7–8, 13 earthquakes with magnitudes between 2.2 and 4.3 and depths of 1 to 33 km were recorded in the densely folded zone. **f** — On 2008/8/8–10, 11 earthquakes with magnitudes between 2.6 and 4 and depths of 7 to 29 km in a folded zone; the location of these event is just several kilometres to the west of recorded earthquakes in figure e.


a
Persian Gulf
ZFF 2
Khormuj
Mond
MFF 3
Shirkuh
Kaki
Namak
Borazjan
Siah
Khartan
Bushgan
Zirreh
MFF 5
Darang
Legend
Main Faults
Fold Axial Trace
Salt Dome
Magnitude
2.9-3
3-3.4
3.4-4.1
b
Sulabedar
Miliatin
Dara
Kazerun
Tasak
Anar
Shahneshin
Karebas
HZF
Saadi
ZFF3
Sarbalesh
Buzpar
Borazjan
Gisakan
Siah
Chahpir
Bushgan
Dadenjan
Naura
rashtanu
Qir
Darian
Halegan
Shahini
Pazanan
Safid
Legend
Main Faults
Fold Axial Trace
Salt Dome
Magnitude
1.1-1.5
1.5-2.3
2.3-3.3
3.3-4.3
c
Kazerun
Shahneshin
Karebas
HZF
Bamu
Saadi
Sabz Pushan
Kaftarak
Ahmadi
Sarvestan
Sim
Khaftar
Karbasi
Changal
Afzar
Sefid zakhur
Lar
BAndobast
Nareh
Qulqul
Takhte
Sefid
Deng
NAr
Kangan
Asalooye
Legend
Main Faults
Fold Axial Trace
Salt Dome
Magnitude
1.5-2
2-2.6
2.6-3.6
3.6-4.2
d
ZFF3
ZFF 2
Borazjan
Buzpar
Bushgan
Karebas
Dadenjan
rashtanu
Qir
Darian
Shahini
Pazanan
Zirreh
NAr
Kangan
MFF 5
Darang
Legend
Main Faults
Fold Axial Trace
Salt Dome
Magnitude
1.6-1.8
1.8-2.2
2.2-2.9
2.9-3.4
e
Changal
Alhar
Pedman
Qir
Nareh
Qulqul
Takhte
Bulghan
BAndobast
Deh fish
Deng
Sefid
Bavoh
Gavbast
Gezeh
Dehno
Legend
Main Faults
Fold Axial Trace
Salt Dome
Magnitude
2.2-2.5
2.5-3
3-3.5
3.5-4
4-4.3
f
Afzar
Pedman
Changal
Alhar
Darian
Sefid zakhur
Lar
Qir
Shahini
Halegan
Nareh
Qulqul
Bulghan
BAndobast
Takhte
Pazanan
Safid
NAr
Deng
Sefid
Kangan
Asalooye
Bavoh
Gavbast
Asaloyeh
MFF 5
Khalafani
Legend
Main Faults
Fold Axial Trace
Salt Dome
Magnitude
2.6-2.8
2.8-3.1
3.1-3.5
3.5-4

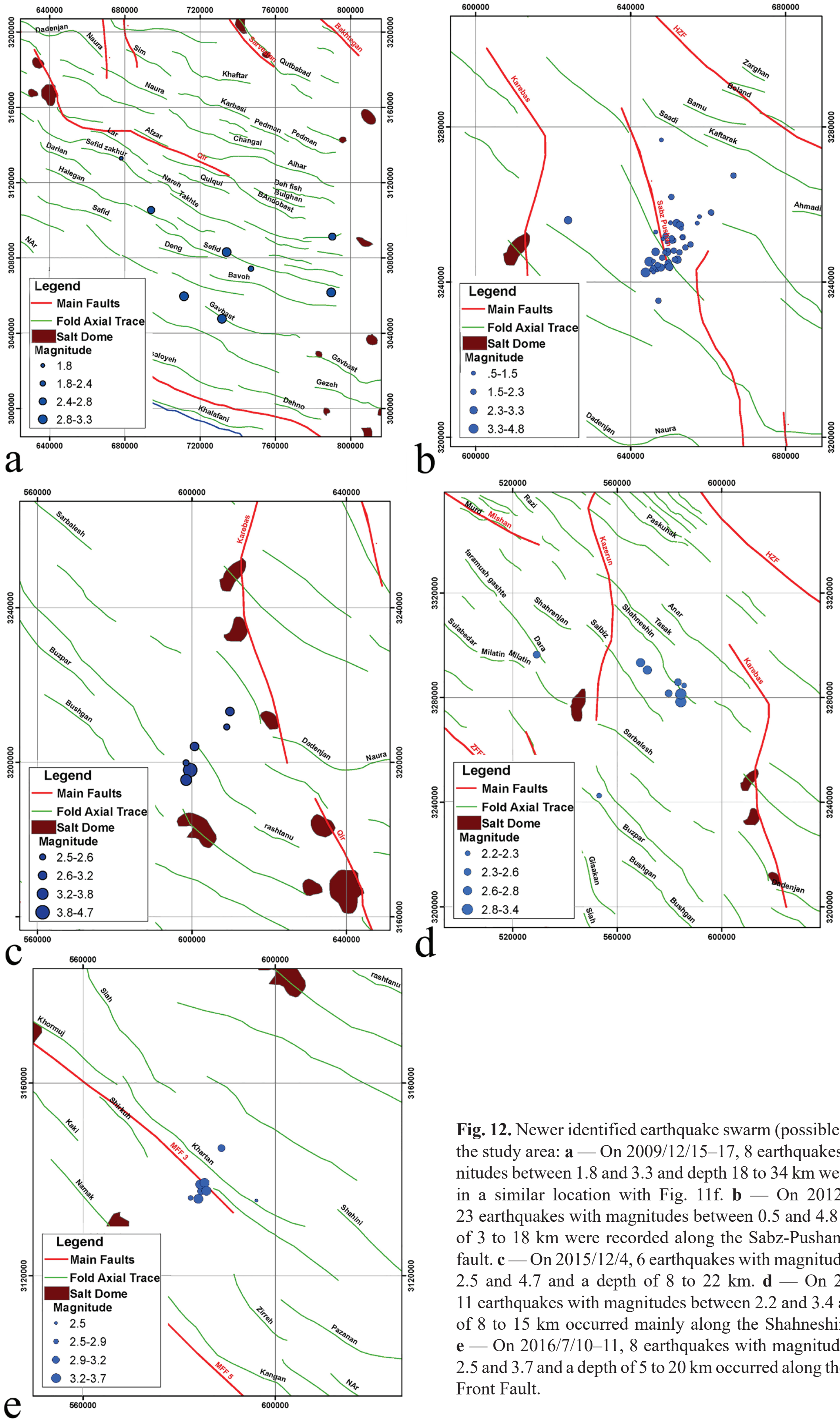


Fig. 12. Newer identified earthquake swarm (possible) periods in the study area: **a** — On 2009/12/15–17, 8 earthquakes with magnitudes between 1.8 and 3.3 and depth 18 to 34 km were recorded in a similar location with Fig. 11f. **b** — On 2012/10/10–12, 23 earthquakes with magnitudes between 0.5 and 4.8 and depths of 3 to 18 km were recorded along the Sabz-Pushan transverse fault. **c** — On 2015/12/4, 6 earthquakes with magnitudes between 2.5 and 4.7 and a depth of 8 to 22 km. **d** — On 2016/5/1–3, 11 earthquakes with magnitudes between 2.2 and 3.4 and a depth of 8 to 15 km occurred mainly along the Shahneshin anticline. **e** — On 2016/7/10–11, 8 earthquakes with magnitudes between 2.5 and 3.7 and a depth of 5 to 20 km occurred along the Mountain Front Fault.

In the study of swarms in this study, it was found that the dispersion of these seismic groups occurred in almost all parts of the range and their distribution was mainly point and in some cases linear. The occurrence of these earthquakes ranged from 6 earthquakes in one day to 23 earthquakes in 3 days. The magnitude of these earthquakes was between 3 and 4 on average and occurred at different depths. Some of these earthquakes show a north-south trend. Figures 11d and 12c, which can be related to transverse faults and their location is adjacent to Borazjan and Kare-Bas faults, follow this trend. Some of these swarms that have a point scattering accumulate around the Sabzpushan fault (Figs. 11c and 12b) can be considered related to this fault. Some of these swarms were not adjacent to the main faults and occurred in the south-eastern part of the range. These swarms can be related to active folds in the region. It should be noted that full consideration of these clusters as swarms require much more data; but this interpretation is a first attempt to propose the importance of this phenomena in the Zagros Range.

Conclusion

Seismicity in the Zagros Fold-Thrust Belt does not have the same pattern in terms of time and space. Spatial and temporal seismic variations of the Central Zagros Fold-Thrust Belt are affected by phenomena such as the active transverse basement faults, major thrust faults including blind thrusts and their intersection with transverse trends, folding style (namely detachment, fault bend and fault propagation), occurrence of swarms due to active salt tectonics or induced seismicity due to hydrocarbon extraction. The main faults of the range have an important role in historical and large magnitude seismicity, especially where they connect with transverse faults. A large number of earthquakes with a magnitude of more than 5 have been recorded in the areas between faults and in the vicinity of the axial trace of the folds, which shows the effect of active folding and blind thrusts on the seismicity of the region. Recorded systemic earthquakes, including the November 26th, 2010 earthquake in Jam with a magnitude of 5.8 and the April 9th, 2013 Kaki Bushehr with a magnitude of 6.2 confirm the effect of hidden faults in the seismicity of the region. In the Zagros Fold-Thrust Belt, a large number of earthquakes occur that show signs of swarms, having a moderate magnitude and without foreshock and aftershock. Full consideration of these clusters as swarms requires temporary stations and more data; but this interpretation is a first attempt to propose the importance of salt caverns collapse, salt-dome activities and salt-tectonics in earthquake swarms in the Zagros Range. They are distributed around the major faults and some around active folds, especially where salt domes exist. Induced seismicity due to hydrocarbon extraction should be considered more important in future research. The frequency of earthquakes in the study area is relatively high in the case which, on average, the number of days of the year in which at least one earthquake occurs is 215 days. Also, on average, the number of days in a year in which at least two earthquakes occur is 107 days. There is a decreasing trend of a and b parameters from south-west to north and north-east where the occurrence of higher magnitude earthquakes is expected. Temporal analysis of seismicity shows that earthquakes with magnitude ≥6.5 have a ten-year return period in the region.

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