The Sarvabad Fault, a new segment along the Main Recent Fault (MRF), Zagros, western Iran

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Article

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Abstract

The Main Recent Fault (MRF) is an active right-lateral strike-slip fault system along the Zagros collision in SW Iran. The geometric and kinematic characteristics of this fault are known along most of its segments. However, a part of this fault exposed between the Morvarid and Marivan segments is ambiguous. This paper introduces the Sarvabad fault segment with a length of about 50 km along the NW parts of the MRF. For this purpose, digital elevation model (DEM), detailed structural field data, and the geological mapping were used. These were complemented by morphometric analyses and the analytical hierarchy process (AHP). The results revealed that the attitude of the Sarvabad Fault is N52°W/80°NE (22°S slip rake angle) in the central and SE parts. In the NW parts of the study area, the strike of this fault changes to N70°W and dips 80°E (25°S slip rake angle). Measuring the morphometric indices and the analysis of their results with the AHP model indicated that the NW parts of the study area have a higher relative tectonic activity than the SE parts. In addition, the parts of the study area along the Sarvabad Fault show a high relative tectonic activity. The most notable reasons for active tectonics along the Sarvabad Fault are V-shaped valleys, fault-line valleys, and asymmetric basins.

1. Introduction

The MRF is a manifestation of the oblique collision between the Central Iran and Arabian plates and closure of the Neo-Tethys Ocean [1–16]. Several previous studies have presented evidence for dextral movements along the MRF using geomorphological and geological markers. Geological evidence and drainage pattern changes indicate about 50 km of offset along the MRF, leading to a dextral slip rate of about 10–17 mm y⁻¹ [14]. The length of pull-apart basins [17] and geomorphological features [9] give a total offset of about 10–15 km and 16 km, respectively. This 16 km offset leads to about 1.6 to 3.2 mm y⁻¹ slip rate. In addition, GPS measurements show different fault slip rate values on the MRF. These slip rate values are about 3 ± 2 mm y⁻¹ [18], 2–4 mm y⁻¹ [19] and 4–6 mm y⁻¹ [20]. Dating cobble samples [11] and a 3D mechanical model using GPS velocities [10] indicate the slip rates of about 3.5–12.5 mm y⁻¹ and 2.3 mm y⁻¹ along the MRF, respectively.

With a general NW-SE trend, the MRF extends as several linear segments from the Turkey-Iran border to the SE [14, 16]. These NW-SE trending fault segments generally follow the Main Zagros Reverse Fault (MZRF) [15]. The MRF consists of several over 100 km-long en echelon segments some of which cut the MZRF. The MRF right-lateral slip also continues toward the NW and joins the North Anatolian Fault (NAF). The Piranshahr Fault (PF) is located at the northwestern end of the MRF and is adjacent to the NAF zone. In the NW part of the MRF (the Piranshahr Fault), the SW-dipping dextral reverse fault initiated due to dextral transpression tectonics and was later overprinted by the normal faulting and transtension tectonics [7]. The Durood fault is one of the seismic faults of Zagros Mountains and it is exposed at the SE parts of the MRF. The MRF continues towards the SE and is terminated at a series of strike-slip faults with a N-NW trend [21]. The MRF trend changes from SE to central and NW segments and the slip along the fault zone leads to normal and reverse components. Geologically, from the SE to the central parts of
the MRF, the different segments of this fault have been named and studied [9, 11, 14–16]. These segments are the Dorud, Nahavand, Garun, Sahneh, and Morvarid Faults, respectively. In addition, the different segments of the NW part of the MRF (such as the Piranshahr, Marivan, and Sardasht Faults) have been named and studied based on geological and morphological evidence [2, 3, 6, 7] (Fig. 1B).

Although the MRF is a very important seismic structure in the Zagros Mountains, a part of it exposed between the Morvarid and Marivan segments has remained hidden from the view of researchers and there is little information about its geological structures. Detailed structural data and morphometric analyses have not been previously presented for this part of the MRF. Therefore, in this study, the Sarvabad fault segment between the Morvarid and Marivan segments is introduced for the first time. Then, the structural and geomorphological features of this fault are presented. We aim to present kinematic and geometric evidence for right-lateral strike-slip movement with a normal component on the Sarvabad Fault. Then, we present detailed evidence for tectonic activity along this fault by classifying the geomorphological indices and using the analytical hierarchy process (AHP).

2. Geological Setting And Rock Units

The Zagros orogeny was formed by the closure of the Neo-Tethys Ocean and the collision between the Arabian and Iranian plates [22–28]. Then, the oceanic crust obducted onto the Arabian Plate during the Late Cretaceous. This was followed by a middle Miocene continent-continent collision [29]. The Zagros orogeny is subdivided into four major zones from the NE to the SW: the UDMA; SSZ; HZB and the SFB [30]. In another division, the Zagros orogeny is subdivided into three main structural zones from the SW to the NE: (1) the inner HZB and the outer SFB; (2) the Zagros Suture Zone (ZSZ) including ophiolite, radiolarite, and Bisotun limestone; (3) the SSZ which contains metamorphic rocks [31]. The SSZ is located at the SW of the UMDA and is composed of metamorphosed Paleozoic to Cretaceous rock units [30]. Geochemical analyses and the radiometric ages of the igneous rocks indicate that Middle to Late Jurassic plutons have intruded into the rock units of the SSZ [32]. The NW-SE trending HZB is the inner part of the Arabian plate margin. The SFB is characterized by the fold structures with blind thrust faults. The SFB and the HZB are separated by the HZF (Fig. 1). The MZRF is the suture line of the Zagros orogeny [6, 15, 23].

Most of the deformation and oblique convergence in the Zagros Mountains occurred during the Cenozoic. Moreover, the strike-slip component of this convergence is accommodated by major strike-slip faults [6]. In general, the Zagros oblique convergence has been partitioned into the MRF (strike-slip displacement) and the major NW-SE trending thrusts (reverse slip displacement) based on earthquake focal mechanisms [14, 15].

The study area is located in the boundary between the SSZ and the suture zone in the collision zone of the Zagros orogeny. Cretaceous flysh with turbidites (Kf), metamorphic rocks with limestone units (KPM), and crystalized limestone and marble rocks (K1) are exposed towards the NE parts of the Sarvabad Fault. Bedded to massive limestone of Bisotun unit (MZI), chemical siliceous sediments and radiolarites (MZIr),
and carbonates and radiolarites (MZr) are exposed towards the SW parts of the study area (Fig. 2). Miocene colored marls, sandstones, and red shales (M), Oligocene-Miocene shallow sediments (OMl), and ophiolite complexes consisting of gabbro to diorite with ultrabasic inclusions (G) are deposited in the suture zone (Fig. 2).

3. Materials And Methods

In this research, we propose kinematic and geometric evidence for a new segment fault with a right-lateral strike-slip movement along the MRF using geological field data and morphometric analyses. Indeed, the NW-SE trending Sarvabad fault segment in the Sarvabad area is introduced for the first time. Investigating the indicators of the fault plane surface in field studies was an important factor in the identification of this fault. Then, Af (asymmetric factor), Sl (stream length-gradient), Bs (basin shape), Vf (the ratio of valley floor width, T (transverse topographic symmetry), and Hi (hypsometric integral) geomorphic indices were developed to identify tectonic activity along the Sarvabad Fault [8, 33, 34]. Afterward, for study of the relative tectonic activity using the AHP, the relative weight of each corresponding index was considered. Finally, to standardize the data, the weighted average of each factor was analyzed.

4. The Structure Of The Sarvabad Fault Zone

The movement of the MRF relative to other structures in the HZB indicates that the deformation changed from reverse to strike-slip in the middle Miocene. The MRF cuts the Miocene and Late Cretaceous thrust sheets along the SE segments as the low-angle radiolarite and ophiolite thrust sheets are cut by movement of this fault [35]. The inception of activity of the MRF (10 – 5 Ma) is due to the slab break-off underneath the Zagros Belt [9]. It may even be related to the late Pliocene [36].

The MRF is a major strike-slip fault zone and its trend is parallel to the MZRF. The MRF follows the ZSZ and accommodates the strike-slip component of oblique convergence between Arabia and Eurasia plates [14–16, 37]. This fault is divided into several segments from 33° to 35°N including the Dorud, Nahavand, Qale-Hatam, Sahneh, and Morvarid (the SE and central fault segments of the MRF) (Fig. 1A). From 35°N, other major fault segments of the MRF continue towards the NW, to join the NAF, and form a right-lateral shear in the border zone between Iran and Turkey. These fault segments from the NW toward the central part of the MRF have been presented by several researchers based on the structural and geomorphological evidence of dextral strike-slip displacement [2, 3, 6, 7]. Indeed, the NW part of the MRF is divided into the Piranshahr, Baneh, Armordeh, Sardasht, Tazhan, and Marivan segments with different lengths (Fig. 1B) [2, 7, 38].

The Sarvabad fault segment (with about 50 km length) is exposed between the Morvarid Fault in the SE and the Marivan and Sardasht Faults in the NW. The mechanism of the Marivan and Sardasht faults (NW parts of the MRF) is a right-lateral strike-slip with an extensional component [14, 38]. The pull-apart
basins near the Sardasht and Piranshahr fault segments, the Marivan-Baneh depression, and the Zaribar Lake have been formed due to the extensional component of the MRF [3, 14, 17].

The NW-SE trending Morvarid Fault (55 km length) is part of the MRF it is exposed in the SE part of the Sarvabad Fault (Fig. 1). The Morvarid Fault is the NE boundary of volcanic rocks in the NE of Kamyaran city [16]. The NW and SE terminations of this fault extend to the Sarvabad and Sahneh fault segments, respectively. Several earthquake epicenters have been found mainly along the NW part of the Morvarid Fault which is the Riedel shear fracture of the MRF that formed during the first stage of deformation [16]. Along the central segments of the MRF (between the Morvarid and Sahneh faults) the right-lateral strike-slip motion on these two segments has formed an extensional area [5]. In the north of Kamyaran city (Fig. 1) and close to Morvarid village, the Morvarid Fault cuts the boundary between the Cretaceous limestone and the Eocene gabbro complex (Fig. 3A). Fault structures and kinematic indicators such as slickenlines have been observed on the Morvarid fault plane (Fig. 3B). The slickenlines and striations indicate a dextral strike-slip movement. The strike and dip of the Morvarid fault plane in this area is N55°W/70°NE (20°S rake angle) (Fig. 3C). The normal component of the strike-slip movement along the Morvarid Fault has caused formation of a depression area on the NE flank of the fault. The SW flank rocks of the fault mainly consist of Eocene gabbro complexes, whereas the NE flank rocks are mainly Cretaceous limestone deposits (Fig. 3A).

A series of fault planes and fault zones have been identified along the Sarvabad Fault which indicate its right-lateral strike-slip motion. Linear valleys have also been developed along the Sarvabad Fault trend. Generally, these valleys indicate geomorphological evidences of strike-slip displacements. In the vicinity of Dagaga village and in the SE of Sarvabad city (Fig. 2), the strike of the Sarvabad Fault (Fig. 4A) is N52°W with 80°NE dip angle (22°S rake angle) is well exposed (Fig. 4B). The fault plane slickenlines and striations indicate a dextral strike-slip movements. In this area, the Sarvabad Fault cuts through slightly metamorphosed Cretaceous shale and limestone and its plane is naturally exposed. Farther NW, we continued field observations along the Sarvabad Fault. Field observations of the Sarvabad fault zone indicate that the recent strike-slip fault zones cut the Cretaceous strata (Fig. 4C). Consisting of several sub-vertical strike-slip faults and with a width of up to 3 m, the Sarvabad fault zone has deformed the Cretaceous strata (Fig. 4D).

Another site was inspected in the NW of Sarvabad city and the SE of Qellace village along the central part of the Sarvabad Fault (Fig. 2). This site selected along the Sarvabad fault segment indicates the extensional component of the dextral movement of the MRF. The fault plane indicates a prominent dextral strike-slip mechanism and the extensional component (Fig. 5A). Moreover, its fault zone has a width of about 20 to 50 cm. The slickenside lineation indicates a dextral strike-slip mechanism. The strike dip of the Sarvabad fault plane in this area is N56°W/75°NE (of 20°S slip rake angle) (Fig. 5B). We continued our field observations along the Sarvabad fault segment to the NW of Qellace village. Near this village, the Miocene colored marl and sandstones are cut by the Sarvabad Fault (Fig. 5C). This area is important because of having linear and narrow valleys along the fault zone. These linear valleys have been developed because the continuous movement of the fault has deformed the rocks, making them
more erosive. These valleys, trending along the fault strike, show the strong geomorphological features of strike-slip fault movements [39].

The Sarvabad fault trace has been observed in the NE of the study area and in several locations. We selected another site along the Sarvabad fault segment to determine the fault mechanism. The Oligo-Miocene limestone in the NW of Qellace village was deformed due to the activity of the fault. Most of the limestone bedding trends on NE and SW flanks of the fault are approximately N60°W to N72°W and have different dip angles. There are two sets of bedding on both sides of the fault. However, one set dips 65°NE (NE flank) and the other set dips 40°SW (SW flank) (Fig. 5D). The attitude of the Sarvabad Fault in this site is N68°W/82°NE and 16°S rake angle (Fig. 5E, F). The last area where the fault outcrop was observed in the field studies was in the east of Dezli village (Fig. 2). In this area the Sarvabad Fault joins to the Marivan and Sardasht faults. The Sarvabad fault zone is exposed as a linear fault valley between the bedded to massive, intensely folded, biogenic limestone in the SW and the Oligo-Miocene limestone in the NE (Fig. 6A). Generally, the kinematics and geometry of the Sarvabad Fault in area (Fig. 6) are similar to those of the other parts of the study area. A well-preserved fault scarp is the evidence of strike-slip movement (Fig. 6B). The escarpment of the Sarvabad segment is formed in Oligo-Miocene limestone. The fault plane indicators (as the slickenlines) show a dextral strike-slip mechanism (Fig. 6C). The strike and dip of the fault is N70°W/80°NE and 25°S rake angle (Fig. 6C). More than this prominent fault scarp, the Sarvabad fault segment in the NW part of the study area crosscuts the shale and marl strata (Fig. 6D). However, due to the ductility of these strata, the fault plane cannot be defined in field observations.

5. The Morphometric Analysis Of The Sarvabad Fault

Geomorphic indices have been developed in many tectonically active regions experiencing rapid tectonic deformation [8, 33, 40, 41]. These indices are used as a quantitative method for differential morphotectonic analyses related to depositional processes and erosion. To investigate the active tectonic associated with the Sarvabad Fault in this study, the ASTER digital elevation model (30-m resolution) have been used to drainage and basins extraction (Fig. 7A). Then, the study area was divided into 17 basins for calculating the morphometric indices, (Fig. 7B). The calculation methods and classification of the indices values are based on the El Hamdouni et al. (2008) [34].

5.1. The stream length gradient index (SI)

The SI index is sensitive to changes in the river channel gradient. Therefore, it is a useful method for understanding the displacements caused by tectonic forces [42]. Low values of SI index in the strike-slip fault valleys may indicate active tectonics as rocks in the valley are crushed because of fault slip and river flows [40]. The numerical value of the SI index depends on the river strength. Also, this index is sensitive to the strength of rocks. Indeed, it is difficult to separate the effects of active tectonics and rock strength in this index. A high value of this index shows areas with a high tectonic activity, whereas a low value of it indicates areas with a low tectonic activity.
The rock strength map of the study area was divided into 5 categories to investigate the role of lithology in the values of the SI index [8]. These categories are very low, low, moderate, high, and very high (Fig. 8A). According to the map of SI map, this index has high values in the N-NW part and along the Sarvabad fault zone. The main streams in these parts of the area pass low to very low resistance rocks. So, the high rate of this index can be attributed to the tectonic forces as well as the activity of the faults (Fig. 8B). The high values of this index are along the Sarvabad fault zone. These high indices are in the Suretu, Rezaw, Hazarkhani, Mirig, Weyse, and Kanidinar basins (Fig. 8B).

5.2. The hypsometric integral index (Hi)

The Hi index shows the distribution of elevation levels in a basin [40]. Low values of this index are possibly related to older landscapes, while its high values are related to recent tectonic activity [34]. The hypsometric curve is obtained from the ratio of the total height of the basin to the entire area of the region. By calculating the hypsometric integral in the basins, the shape of the hypsometric curve can be described.

Hypsometric values are divided into three classes of tectonic activity including 1, 2, and 3 according to the degree of concavity and convexity. Hence, convex hypsometric curves with Hi values of more than 0.5 are classified as Class 1 (high activity), convex-concave hypsometric curves with Hi values of between 0.4 and 0.5 are considered as Class 2 (medium activity), and concave hypsometric curves with Hi values of less than 0.4 are classified as Class 3 (low activity) [34]. In the study area, the calculated value of this index is more than 0.5 (Class 1) (Fig. 9A). The plotted curves of the Hi index also confirm the activity of the basins (Fig. 9B). Generally, the Suretu, Rezaw, Hazarkhani, Mirig, Weyse, and Kanidinar basins along the Sarvabad fault show Class 1 Hi index (Fig. 9A).

5.3. The drainage basin asymmetry index (Af)

The tectonic activity of the region can affect the geometric shape of the basins. The Af index is used to detect tectonic tilting in drainage basins and works best in basins with a uniform lithology. The values of Af index were calculated for 17 basins and divided into three classes of high (Class 1), moderate (Class 2), and low (Class 3) [34]. The results of the Af index show that the Hezarkhani, Mirig, Kordare, and Hewraman basins which are located in the northern and central parts of the study area have been more tilted (Fig. 10A).

5.4. The basin shape index (Bs)

The basin shape index (Bs) enables us to distinguish basins with a significant elongation from those whose shape is close to a circle [43]. High values of the Bs index are associated with higher relative tectonic activity and generally with elongated basins. Low values of this index generally indicate low tectonic activity as well as circular-shaped basins. Except for the Negel, Aryan, and Besaran basins in the SE of the study area, all of the basins show classes 2 and 3. This is the case for the Hezarkhani and Rezaw basins along the SRF (Fig. 10B).

5.5. The ratio of valley floor width to valley height (Vf)
The erosion of river valleys and the morphology of valleys in the vertical section are useful tools for interpreting the tectonic activity. So, the Vf index is obtained by calculating the ratio of the width of the valley floor to its average height. It is one of the most sensitive indices to tectonic uplift. This index is relatively high for wide valleys and low for young V-shaped valleys. The values of the Vf index are divided into three classes: Class 1 (high tectonic activity), Class 2 (moderate tectonic activity), and Class 3 (low tectonic activity) [34]. The values of Vf index are relatively high for most basins of the study area and most of the basins except the eastern basins show relatively high tectonic activity. According to the Vf map as shown in Fig. 11A, the SRF has increased the values of this index because all the basins along this fault (Suretu, Rezaw, Hazarkhani, Weyse, and Kanidinar basins) belong to Class 1 (Fig. 11A).

5.6. The transverse topographic symmetry index (T)

The T index is used to evaluate tilting caused by tectonic activity. Calculation of tilting in tectonic active areas indicates the changes in uplift rate. This index varies from 0 (minimum tilting) to 1 (maximum tilting). In this study, the T values were obtained by drawing the parallel lines and calculating the mean values in each basin [8]. The T-index values were relatively high in most of the study area except the Kordare and Hewraman basins. Generally, the high values of this index were obtained along the SRF and the NE and SW parts of the study area (Fig. 11B).

6. The Analytical Hierarchy Process

The AHP is a popular method for calculating the weighting factors with a preference matrix. In this method, all calculated factors are compared with each other and with the help of reproducible preference factors [44]. The AHP values vary between 1 and 9 according to the importance of the factors and are describe the comparisons (preference/dominance) [45]. Indeed, the elements of each level are compared in pairs at a higher level than their respective elements. Then, the criteria weights are calculated based on the set goal. Afterward, by combining the relative weights, the final weight of each option (called the absolute weight) is determined. Depending on the importance of each criterion, numerical values are assigned to each criterion and the most important criteria are identified.

Many studies have been conducted to evaluate the relative tectonic activity in different regions by using morphometric indices [46, 47] or a combination of several geomorphic indices [8, 33, 34, 48]. The preference values of the morphotectonic indices can be different from the classification of the Index of Relative Active Tectonics (Iat) [34]. The AHP method is one of the most effective techniques for analyzing the relative active tectonics [8, 33]. In this study, based on this method, the tectonic activity and the needed weighting factors around the study area were calculated with the help of a preference matrix and the geomorphic indices of active tectonics (Af, Sl, Vf, T and Hi indices). In this study, the AHP plug-in in ArcGIS 10.5 software was used to calculate the final weight of each index. Thus, the main indices have high weights, whereas the indices controlled by factors such as topography and lithology have low weights [33]. Because of differences among the basins of the study area regarding lithology, topography, and tectonics, the results of some indices were not satisfactory. This may reduce the accuracy of the final results. So, for the classification of the indices, they were placed in a matrix according to their importance.
and rank (Fig. 12). The SI index has the highest weight in the matrix because it has a high potential in assessment of relative tectonic activity [8, 33, 40, 49]. In evaluating the Vf index, lithology, basin size, and flow intensity should be considered. Hence, this index is of less importance [34, 50]. In areas with relatively uniform lithology, the Af index is useful, where climate and lithology diversity do not have a large effect on asymmetry [40]. So, The Af index is more suitable for areas undergoing tilting if the basin is parallel to the tilting axis. So, this index is less valued in the matrix.

Saaty (1990) introduced a coefficient called the consistency rate (CR) which shows the consistency of the comparisons [44]. The obtained CR coefficient should be less than 0.1, otherwise, the matrix should be modified and revised. In this study, the value of the CR coefficient obtained is 0.04, which is acceptable and indicates the high accuracy of the matrix and calculations. In this study, after weighting the morphometric indices (Fig. 12), the weight map of each of these indices was drawn separately and shown in Fig. 13.

One of the new methods for evaluating the active tectonics of a region is the simple additive weighting (SAW) method which is based on the weighting of geometric indices [33]. The SAW method uses weighted linear combination and scoring in calculations. In fact, this method is based on the weighted average. Therefore, in active tectonics, an evaluation score for each index is calculated by multiplying the raster layer by its weight. This is directly assigned by the decision maker. In this study, to assess the active tectonics along the Sarvabad fault zone, all indices were multiplied by their weights according to the following equation implemented in ArcGIS 10.5 software:

\[
A = ((S\times0.4203) + (V\times0.2595) + (H\times0.1498) + (B\times0.0879) + (A\times0.0501) + (T\times0.0323))
\]

Based on the output of the SAW method in the study area, the tectonic activity of the basins ranges from 0.7 to 1.6 which is divided into four classes of low, moderate high and very high relative tectonic activity (Fig. 14).

According to the obtained results, 55.3% (1165.33 km\(^2\)), 7.15% (150.82 km\(^2\)), 29.25% (615.57 km\(^2\)), and 8.3% (175.04 km\(^2\)) of the area have a very high, high, moderate, and low relative tectonic activity, respectively. As can be seen in the final relative tectonic activity map, the NW parts of the region have a higher relative tectonic activity than the SE parts. In addition, in the central parts of the region and along the Sarvabad fault zone, a band with a high relative tectonic activity is observed which is probably related to the activity of this fault. Parts of the study area that show a very high relative tectonic activity mainly host the activity of the main faults. Showing a high relative tectonic activity, the Suretu, Rezaw, Hazarkhani, Weyse, and Kanidinar basins are located along the Sarvabad Fault. The Mirig, Kordare, and Pirkhezran basins show a very high relative tectonic activity caused by the outcrops and activities of faults with an almost N-S and NW-SE trend. Moreover, about 37.55% of the total study area (specifically the Negel, Danikesh, Avihang, Besaran, and Aryan basins in the SW and the Hewraman and Hajij basins in the west of the study area) are classified in the moderate and low relative tectonic activity classes. The faults have a low density in most of these basins. However, in the Aryan and Hajij basins, despite the fault outcrops with a NW-SE trend, the relative tectonic activity is classified in the moderate class.
Therefore, in addition to faults as the main factor, other factors may play a role in the tectonic activity of the region.

Generally, the active tectonics of the study area in the NW of the Zagros Belt correspond to the activity of the Sarvabad Fault which is a segment along the MRF. The present-day kinematics of this belt are characterized by 3–6 mm y$^{-1}$ of shortening and 4–6 mm y$^{-1}$ of right-lateral strike-slip motion (1.6 to 3.2 mm y$^{-1}$ on the MRF) [9, 19, 20]. Thus, this shortening and right-lateral strike-slip movement show evidence of active tectonics in field studies. Field observations indicate that many valleys in the study area have become V-shaped especially when the lithology consists of competent layers. In the Rezaw basin, these V-shaped valleys have been formed in the sequence of thick limestone layers and are perpendicular to the Sarvabad fault trend (Fig. 15A). These V-shaped valleys are almost symmetrical and have formed prominent scarps (Fig. 15B). Fault-line valleys are another evidence of active tectonics in the study area as these valleys are usually straight for long distances. In the Suretu basin, in the south of the study area, a linear fault valley along with a parallel drainage pattern follows the Sarvabad fault trace (Fig. 15C). Field studies also show evidence of the asymmetry of basins and sub-basins in the study area. Examples of this asymmetry can be seen in the Hazarkhani basin (Fig. 15D).

In addition to field evidence, the seismicity of the region also indicates the tectonic activity of the study area. The seismicity of the study area is mostly related to the MRF. The MRF is an active fault and a number of destructive earthquakes occurred near or on this fault [14, 16]. The Silakhor earthquake of 1909 ($M_S=7.4$), the Firuzabad earthquake of 1958 ($M_S=6.6$), and the Silakhor earthquake of 2006 ($M_w=6.1$) (along the SE segments of the MRF), the earthquake event of 1957 ($M_S=6.7$) (along the central segments of the MRF), the earthquake events ($M_w=4.4$ to $5.6$) along the NW segment of the MRF, and the Sarvabad earthquake event of 2019 ($M_w=4.6$) (Sarvabad segment) are the most important events along the MRF [7, 14, 16, 51–53]. The earthquake focal mechanisms along the MRF mostly indicate a right-lateral strike-slip displacement.

7. Conclusion

With a length of about 50 km, the Sarvabad Fault is a new segment along the MRF. This fault is exposed between the Marivan and Sardasht Faults in the NW and the Morvarid Fault in the SE. With a length of about 55 km, the NW-SE trending Morvarid Fault is a segment of the MRF. The attitude of the Morvarid Fault plane is N55°W/70°NE with a slip rake angle of 20°S and a right-lateral strike-slip mechanism. In the central part of the study area and in the SE of Sarvabad city, the attitude of the Sarvabad Fault is N52°W/80°NE with a slip rake angle of 22°S. In the NW part of the study area, the Sarvabad fault zone is exposed as a linear fault valley between the bedded to massive limestone in the SW and the Oligo-Miocene limestone in the NE. The attitude of the Sarvabad Fault in this part of the study area is N70°W/80°NE with a slip rake angle of 25°S. The striations and nearly horizontal slickenlines on the Sarvabad fault plane indicate a right-lateral strike-slip mechanism. The study of morphometric indices and the use of the AHP and the SAW model in the assessment of active tectonics showed the tectonic
activity of the study area. Generally, the NW parts of the region show a higher relative tectonic activity than the SE parts. There is a high tectonic activity at the center of the study area and along the Sarvabad Fault. This is probably due to the activity of this fault. Showing a very high relative tectonic activity, the Weyse, Hazarkhani, Suretu, Rezaw, and Kanidinar basins are located along the Sarvabad fault zone. The outcrops and activities of the faults with an almost N-S and NW-SE trend may have caused the high tectonic activity in the Mirig, Kordare, and Pirkhezran basins. V-shaped valleys, fault-line valleys with parallel drainage patterns, and asymmetric basins are the most prominent evidence of tectonic activity along the Sarvabad fault zone.

Declarations

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Availability of data and materials

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Competing interests

Salah Eshterabeh and Reza Alipoor declare that they have no conflicts of interest relevant to the content of this review.

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**Figures**

**Figure 1**

A: The tectonic map of NW Iran indicating the MRF segments [7, 16]. The faults are abbreviated as follows: Dorud: (DF); Qale-Hatam: (QF); Nahavand: (NF); Garoon: (GF); Sahneh: (SF); Morvarid: (MOF); Sarvabad: (SRF); Marivan: (MF); Sardasht: (SDF); Piranshahr: (PF); Tabriz: (TF); High Zagros: (HZF); Mountain Front: (MFF); Main Zagros Reverse: (MZRF); Zagros Foredeep:(ZFF). The following are the other abbreviations: Urumieh-Dokhtar Magmatic Arc:(UDMA); Sanandaj-Sirjan Zone: (SSZ); High Zagros Belt:(HZB); Simply Folded Belt: (SFB). The black rectangle shows Figure B. B: The satellite image of the NW part of the MRF. The rectangle shows the Sarvabad fault segment and the location of Figure B.
Figure 2

The geological map of the study area and the locations of the subsequent figures.
Figure 3

A: The Morvarid fault segment near Morvarid village cuts the boundary between the Cretaceous limestone and the Eocene gabbro complex. The black rectangle shows the location of Figure B. B: The close-up view of the Morvarid fault surface in Cretaceous limestone. The white rectangle shows the location of Figure C. C: The slickenlines with 20°S rake angle on the Morvarid fault plane show dextral strike-slip movements.
Figure 4

A: The Sarvabad fault zone cuts the Cretaceous shale and limestone. B: The rake angle on fault plane (22°S) indicate dextral strike-slip movements. C and D: The close-up view of the Sarvabad segment with a fault zone of up to 3 m in width.
Figure 5

A and B: With a fault zone of about 20-50 cm width, the Sarvabad fault surface indicates a right-lateral strike-slip movement. C: The linear valley of the Sarvabad Fault. D-F: The Sarvabad fault segment cuts the Oligo-Miocene limestone and its slip rake angle (16°S) shows a dextral strike-slip movement.
Figure 6

A: The linear fault valley of the Sarvabad fault segment in the NW part of the study area. B and C: The plane of the Sarvabad fault segment indicating a dextral strike-slip movement. D: The Sarvabad Fault crosscuts the shale and marl strata.
Figure 7

A: The faults and drainage systems of the study area on the shaded digital elevation model. B: The distribution of the basins over the study area.

Figure 8

A: The lithological strength level. B: The final SI map of the study area.
Figure 9

A: The final Hi index map of the study area. B: The hypsometric curves of the basins around the study area.

Figure 10

A: The final Af index map of the study area. B: The final Bs index map of the study area.
Figure 11

A: The final Vf index map of the study area. B: The final T index map of the study area.

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Figure 12

The matrix weighting the morphometric indices.
Figure 13

A: The weighting map of the morphometric indices. A: (Af index); B: (Hi index); C: (Sl index); D: (Bs index); E: (T index); F: (Vf index).
Figure 14

The final relative tectonic activity of the study area based on the simple additive weighting model.
Figure 15