Geomorphologic and structural assessment of active tectonics in NE Shiraz (Fars, SW Iran)

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Abstract

The study area is the Rahmat Anticline. This is located in Fars Province (SW Fold Simple Zagros Belt). The aims of this study are morphotectonic studies and structural analysis in several parts of area. For this purpose: 1) morphotectonic indices, drainage basin shape index (Bs), Mountain front Sinuosity Index (Smf) and valley floor width – height ratio (*Vf*) were measured by digital elevation model (DEM) and stream order method; 2) the pattern of stress was determined by inversion method. The results obtained from morphotectonics indices indicate that the study area has a higher level of active tectonics in the north part of the anticline. Based on the results derived from the diagrams, it is suggested that there are three stress directions NE-SW, N-S and NW-SE compressional stress directions in the north anticline, which is obvious in the study area. Fault slip analysis reveals two successive late Cenozoic regional compressional trends, NE-SW and N-S. The latter is in good agreement with the present-day stress. The significance of the NE-SW compression is discussed alternatively in terms of stress deviations or block rotations in relation to the strike-slip fault system. As a result, the study area was divided into two classes of relative tectonic activities. Class 1 is indicative of the most active tectonics, occuring mainly in the north part of the anticline. Class 2, corresponding to lowly active tectonics, occurred mainly along south part of the anticline.

Keywords: Morphotectonic Indices; Inversion Method; Rahmat Anticline; Fars Province; Zagros; Iran.

1- Introduction

The Zagros belt extends about 1500 km from Turkey, through southwestern Iran, stretching as far as the strait of Harmoz (Baker *et al*., 1993). The belt morphogenesis is the morphotectonic expression collision of the Arabian and Iranian plates (Motiei, 1992). The landscapes in these areas result from the complex combination of the effects of active tectonics like faulting and erosional as well as depositional processes. The main structural architecture of the Zagros is defined by the so called Zagros fold belt, which attains an average elevation of over 3000 m a.s.l. (Dehbozorgi *et al*., 2010; Ruszkiczay *et al*., 2009; Zakerinejad *et al*., 2016).

The Zagros Mountain is subdivided into 1- the Zagros Fold and Thrust Belt, which is divided into the outer Zagros Simply Folded Belt and the inner High Zagros Belt. 2- The Zagros Suture Zone, which zone includes the Main Zagros Thrust, and 3- The Sanandaj–Sirjan Zone (Maleki *et al*., 2015, Fig. 1a).

The Zagros Simply Folded Belt is segmented into several zones that differ according to their structural and depositional history (Berberian and King 1981; Jackson and Mckenzi, 1984). The zones are, from east to west, the Fars salient the Dezful recess and Lorestan salient (Regard *et al*., 2004).

Fars Province (In the central parts of the Zagros) is limited to the west from the Kazerun–Boradjan Fault (KBF), a seismically active major right lateral strike-slip fault (Baker *et al* 1993, Sherkati *et al* 2006; Bachmanov *et al* 2004.) and the Minab–Zendan fault system is limited to the East (Stocklin, 1968; Fig. 1b).

The study area is the Rahmat Anticline (East longitude 52 ^{o} 50' to 53 ^{o} 10' and North latitude 29 ^{o} 40’ to 29^{o} 55'), situated in 70 Km Northeast of Shiraz (Zagros Simply Folded Belt of Iran and NE Fars province). The Rahmat Anticline includes faults with combined normal, reverse (Rahmat Fault Zone in the south of anticline) and strike–slip movements. Takht-e- Jamshid (Perspolis) is located in the north anticline (Fig. 1c).

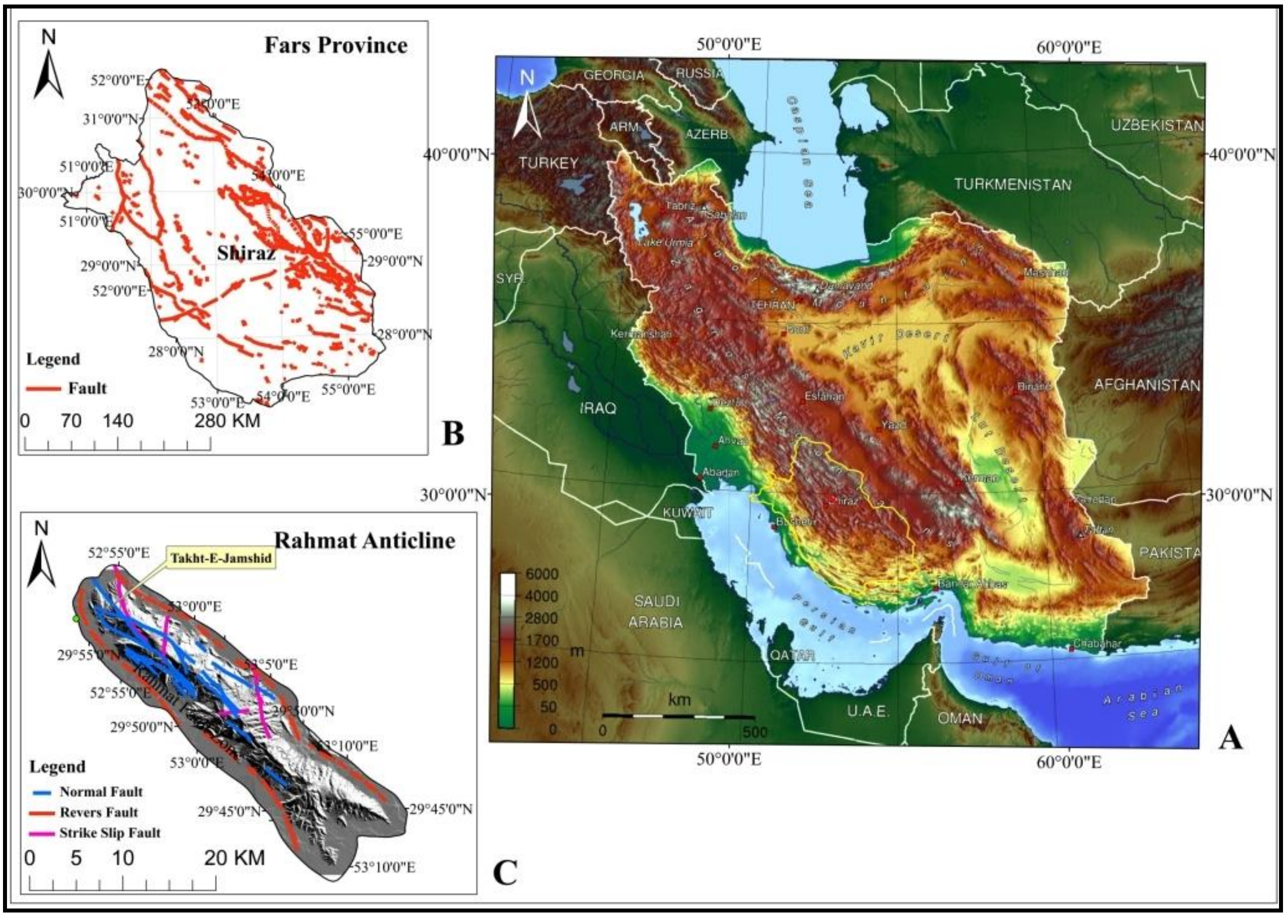


Figure 1A) The structural map of Iran (modified from Maleki et al., 2015) and location of study area. B) Tectonic map and location of fault zones in Fars Province. C) Digital Elevation Model (DEM) of the Rahmat Anticline.

The quantitative expression of the geometric effect of the earth relief in the Zagros belt will allow the identification of zones with common geomorphometry in the Alpine-Himalayan belt and will provide an understanding between the correlation of the regional tectonic processes and geomorphometry. The reconstruction of the past kinematics and tectonic history and geomorphic investigation in Zagros fold–thrust belt explains the history of the successive local/regional directions of stress and shortening and active tectonics through time (Lacombe, et al 2011).

The aims of this study are geomorphologic and structural analysis in several parts of the area Therefore, considering the diversity of the morphotectonic features, geomorphometry method was applied to evaluate relative rates of active tectonics (Burbank and Anderson, 2000; Keller, 1986). The three geomorphic indices were analyzed: Drainage basin shape index (Bs), Mountain front Sinuosity Index (Smf) and valley floor width – height ratio Index (*Vf*). Digital Elevation Models (DEMs) are especially useful to analyze active regional tectonics from topography. Drainage basin was given to each stream by following Strahler (Strahler, 1952) stream ordering technique. Then, Stress pattern was of study region in a combination of determined by inversion method. Hence, we carried out a structural analysis of the tectonic features fieldwork, tectonic analyses based on inversion of fault slip.

2- Geological Setting

The study area is the Rahmat Anticline part of the Simply Folded Zagros Belt Different tectonic phases and neotectonic activities and earthquakes in recent years are intensively affected this belt (Motiei, 1992), which is only briefly treated here as it has been dealt with in numerous publications (Molinaro *et al.*, 2005; Sherkati *et al*., 2006; Sepehr and Cosgrove 2005; Alavi, 2004; Casciello *et al*., 2009; Farzipour-Saein, et al 2009). It is dominated by elongate anticlines and synclines along with associated thrust and reverse faults (Mohajjel and Fergusson, 2014).

The folds pattern in the Simply Folded Belt is open anticlines. These folds probably mainly result from buckling and subsequent detachment folding of the 10–12 km thick sedimentary cover above a single master décollement lying within the Hormuz salt (Berberian, 1995; Jackson, 1980). Second-order intermediate décollement levels are, however, required to account for shorter fold wavelengths typically of 15–20 km and lengths of 100 km and more (Moutherau *et al*., 2006).

The Rahmat Anticline is located 70 Km northeast of Shiraz (Fars region). This anticline includes faults with combined normal, reverse (Rahmat Fault Zone in the south of anticline) and strike–slip movements (Fig. 1c).

Based on geological facie, Fars region is subdivided into different structural zones including sub-basins; Interior Fars, Coastal Fars and Sub-Coastal Fars. The Rahmat Anticline is located in the Interior Fars (Simply Folded Belt, Afghah and Shaabanpour, 2014). According to James and Wynd (1965), the Kuh-e- Rahmat section locality is assigned to the Interior Fars area, Kuh-e- Rahmat is an anticline with a NW-SE trend, composed of Aptiane Cenomanian succession. The exposed Cretaceous sequence of the Kuh-e- Rahmat section consists of the Dariyan (Aptian), Kazhdumi (Albian) and Sarvak (Cenomanian) formations. The basal part of the Dariyan Formation is not exposed in the Kuh-e- Rahmat region, but marly limestone of the Kazhdumi Formation (Albian) covers Dariyan limestone. An oxidized zone is distinguishable in the lithostratigraphic contact between the Dariyan and Kazhdumi formations. Marly limestone of the Kazhdumi terminates at the thick to massive grey limestone of the Sarvak Formation. (Afghah and Shaabanpour, 2014; Fig. 2).

3- Materials and Methods

3.1- Determining morphotectonic indices

Morphometric analysis is the basis for relative adjustments between local base-level processes (tectonic uplift, stream downcutting, basin sedimentation and erosion) and the fluvial systems, which cross structurally controlled topographic mountain fronts (Bull and McFadden, 1977). Therefore, manual sampling of drainage network was again adopted from topographic maps (1:25000) in combination with computerized tools and certainly the Geographic Information System (GIS), which were of great significance in this application. The study area, comprising mountain fronts and drainage basin associated with the systems of faults constituting the Rahmat Anticline were selected for morphometric analysis (Table 1). Mountain fronts were selected for this study on the basis of topographic, lithological, geomorphological and structural continuity. Drainage basin was given to each stream by following Strahler stream ordering technique (Strahler, 1952; Fig. 3). The attributes were assigned to create the digital data base for the drainage layer of the river basin. The map shows the drainage pattern in the study area (Fig. 3). Sample selection was determined according to particular geomorphological criteria that provided high reliability and confidence in the representativeness of the morphometric data produced.

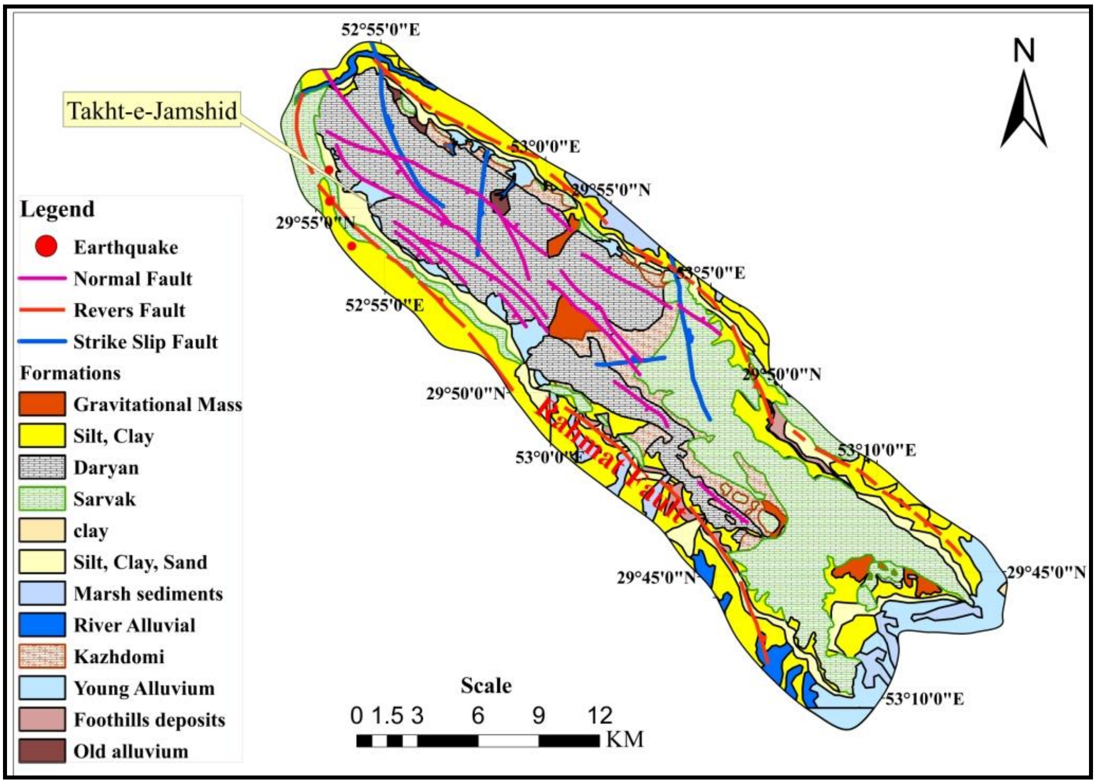


Figure 2) Geological map of the study area based on the geological map (1:100000) Shiraz and Arsanjan (Andalibi et al., 2004; Yousefi et al., 2006).

3.2- Determining stress Regime from Inversion of Fault Slip Data

The kinematics of a fault population is defined using striations observed on mesoscale fault planes at many sites. For each fault, strike, dip, slickenside, rake and polarity of movement are measured and determined in the field. The main objective is to define the successive Cenozoic states of stress the related faulting events and their probable significance in relation to regional tectonic events. The methodology of fault kinematic studies to determine paleostress fields and identify temporal and spatial changes in stress states has been used in many areas worldwide over the past 30 years (Molinaro *et al*., 2005; Moutherau *et al*., 2006).

To determine the stress fields responsible for Cenozoic deformation in the investigated area, we have carried out a quantitative inversion of distinct families of slip data determined at each individual site using the method proposed by Angelier (Burbank and Anderson, 2000). Fault slip inversion method assumes that:

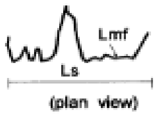
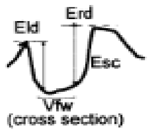
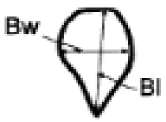
1) The analyzed body of rock is physically homogeneous and isotropic, and if prefractured, it is also mechanically isotropic, i.e., the orientation of fault planes is random (Twiss and Unruh, 1998).

2) The rock behaves as a rheologically linear material (Twiss and Unruh, 1998).

3) Displacements on the fault planes are small with respect to their lengths, and there is no ductile deformation of the material, and thus, no rotation of fault planes. Moreover, the computation assumes that (Twiss and Unruh, 1998).

4) A tectonic event is characterized by a single homogeneous stress tensor (Twiss and Unruh, 1998).

Table 1) Summary of the morphotectonic indices used in analysis of tectonic activity in the study area (Ramirez-Hererra, 1997; Cannon, 1976; Falcon 1974).

Morphometric parameter	Mathematica l derivatio*	Measurement Procedure	Purpose	Significance
Smf= Mountain frontsinuosity	$Smf = \frac{Lmf}{Ls}$		Reflect a balance between the tendency of stream and slope processes to produceirregular (sinuous) mountain front and vertical active tectonics that tend to produce a prominent straight front (Keller, 1986)	*Smf* = 1·0 – most tectonic activity Smf > 1·0 – less tectonic activity
Vf = Valley floor –valley height ratio	$V_f = \frac{2V_{fw}}{(E_{ld}-E_{sc})+(E_{rd}-E_{sc})}$		Define the ratio of the width of the valley floor to the mean height of two adjacent divides	The index reflects differences between broad-floored canyons with relatively high values of *Vf*, and V-shaped canyons with relatively low *Vf* values
Bs= Drainage basin shape ratio	$B_s = \frac{Bl}{Bw}$		Define the planimetric shape of a basin	High *B*s values = elongated basins and,. high tectonic activity; low *Bs*values = circular basins, i.e. low tectonic activity

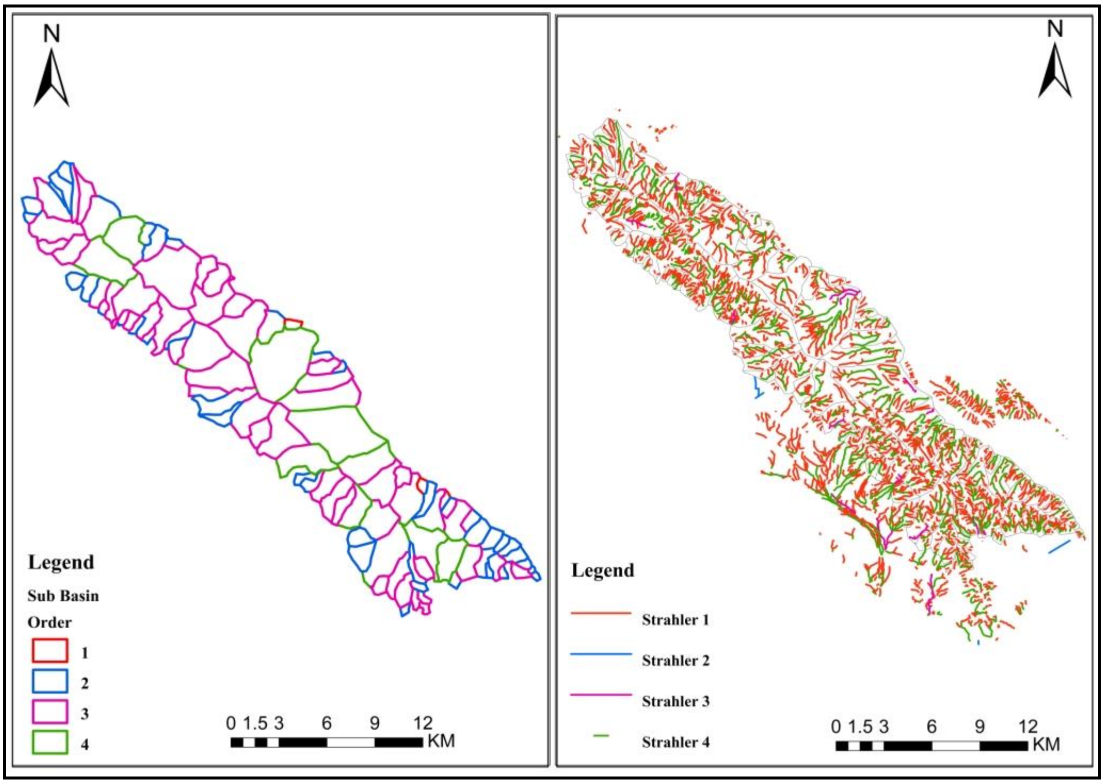


Figure 3) Drainage map of basins 1 to 4. The hydrographic network is represented according to Strahler's ordering system.

5) The slip responsible for the striation occurs on each fault plane in the direction and the sense of the maximum resolved shear stress on each fault plane (Wallace-Bott principle), the fault plane being the preexisting fractures.

6) The slip on each of the fault planes is independent of each other (Lacombe, 2006). Because in the cover of the SFB of Fars region, the train of folds is regular and almost devoid of major thrust zones at least reaching the surface, in the study area, along the major faults,

geological features such as slickensides along fault planes, crushed zones, and offsets of rock units including strike separations, were analyzed.

4- Results and Discussion

4.1- Morphotectonic Indices

The stream order is the first step in drainage basin analysis for classifying relative location of a reach (a stream segment) within the river basin. The stream order method followed the procedure method modified by Stahler. Stream order 1 has one connected edge, and then at the confluence of two1st order streams assigns the downstream reach of order 2, and so on for the other orders. Study basin system has 4-stream orders, and thus a map was obtained using GIS system (Fig. 3).

4.1.1- Drainage basin shape Index

The basin in the tectonically active mountain range is elongate, and basin shapes become progressively more circular with time after cessation of mountain uplift (Colman-Sadd 1978; Ramirez-Hererra, 1997; Bahrami, 2013). Thus, the planimetric shape of a basin may be described by an elongation ratio of the diameter of a circle with the same area as the basin to the distance between the two most distant points in the basin (Berberian and King, 1981). The elongation ratio Bs defined as where Bl is the length of the basin, measured from its mouth to the most distant drainage divide, and Bw is the width of the basin measured across the short axis (Bahrami 2013; Table 1). The index reflects differences between elongated basins with high values of Bs (high tectonic activity) and more circular basins with low values (low tectonic activity). The drainage basin shape was calculated for the 40 drainage basins of streams that cross the main faults of the Rahmat Anticline (Fig. 4). The purpose of calculating the drainage basin shape (Bs) index was to identify elongated basins which reveal primarily downcutting in areas of continuing rapid uplifts. Results indicate that high values of dissection and elongated drainage basins characteristically occur in the N part of the Rahmat Anticline (Fig. 5).

$$(B_s = \frac{Bl}{Bw}) \quad (1)$$

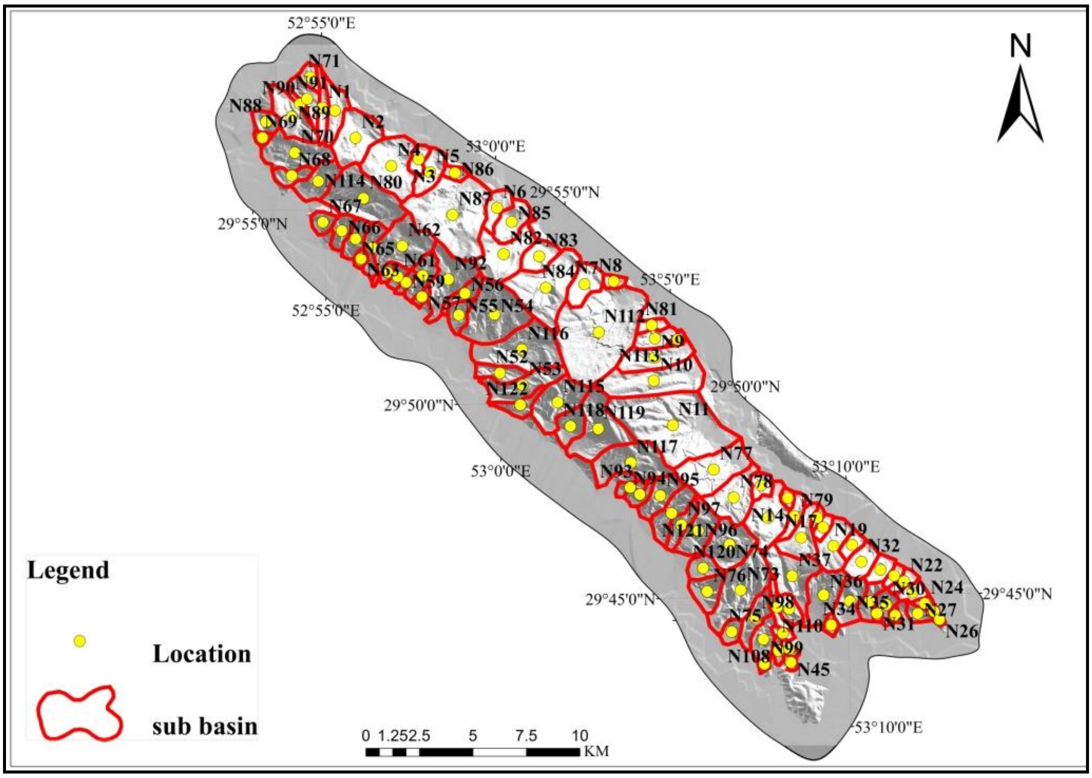


Figure 4) Location of sections for Bs calculation in the study area.

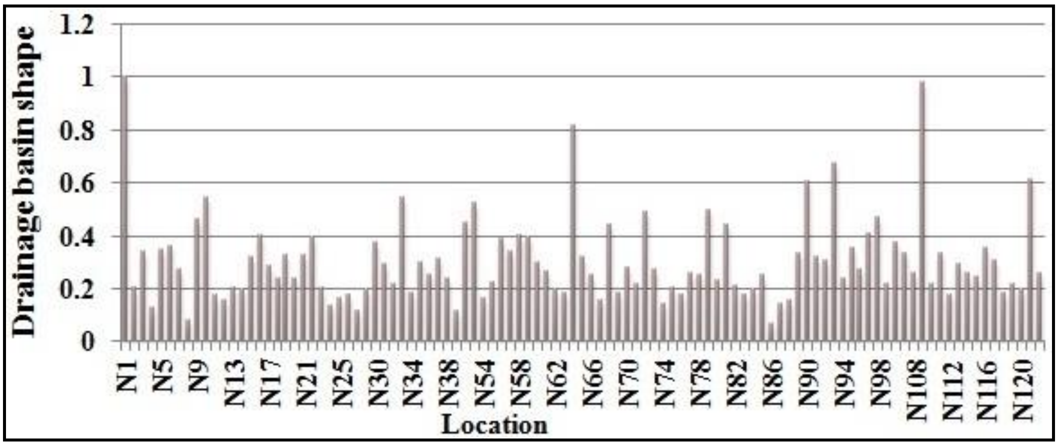


Figure 5) The measured values of Bs index in the study area.

4.1.2- Mountain front sinuosity Index

The mountain front sinuosity index (Smf) is defined as the ratio length of mountain front along the mountain–piedmont junction (Lmf) and the straight-line length of the front. (L) (Bull and McFadden 1977; Fig. 6). The Smf index reflects a balance between the tendency of stream and slope processes to produce an irregular (sinuous) mountain front and vertical active tectonics to produce a prominent straight front (Keller, 1986). Values of Smf approach 1 on the most tectonically active fronts, whereas Smf increases if the rate of uplift is reduced, and erosional processes begin to form a sinuous front that becomes more irregular over time (Table 1). However, values of mountain front sinuosity index depend on image scale, and small topographic maps produce only a rough estimate of mountain front sinuosity. Therefore, mountain front sinuosity and all morphometric variables were measured on small-scale topographic maps (1:25000, with 10m contour intervals). Results indicate low values of SMF characteristically occur in the N part of the Rahmat Anticline (Fig. 7).

$$(Smf = \frac{Lmf}{Ls}) \qquad (2)$$

4.1.3- The Valley floor width – height ratio Index

The Valley floor width – height ratio (*Vf*) is the width of valley floor, *E*ld and *E*rd are the respective elevations of the left and right valley divides and *E* is the elevation of the valley floor (Bull and McFadden, 1977). In this way the index reflects differences between broad-floored canyons (U shape) with relatively high values of *V*f, and V-shaped canyons with relatively low values (Keller, 1986; Table 1). Thus, in this study, transverse valley profiles were located 0.5 km upstream from the mountain front in smaller drainage basins; and in large drainage basins, transverse valley profiles were located 0.5 and 1km upstream from the mountain front. The reason for working with different ranges for the location of the cross valley transects is that valley floors tend to become progressively narrower upstream from the mountain front in larger drainage basins for a given mountain range. Values of *Vf* may also vary widely among streams with different drainage basin areas, discharges and underlying bedrock lithologies. Consequently *Vf* ratios were not used directly in this study to estimate the relative levels of tectonic activity of specific fronts, as this would require comparison of *Vf* values among streams of variable size and lithology. Instead, several *Vf* values were determined along the length of streams in each subarea with similar geological and morphological characteristics (Ramirez-Hererra, 1997; Fig. 8).

The data were combined with the longitudinal profile and valley morphology to indicate changes in valley and profile morphologies suggesting that localized uplift in channel reaches upstream from mountain fronts crossed by a given stream. Results indicate that low values of dissection and elongated drainage basins characteristically occur in the N part of the Rahmat Anticline (Fig. 9).

$$V_f = \frac{2V_{fw}}{(E_{ld}-E_{sc})+(E_{rd}-E_{sc})} \quad (3)$$

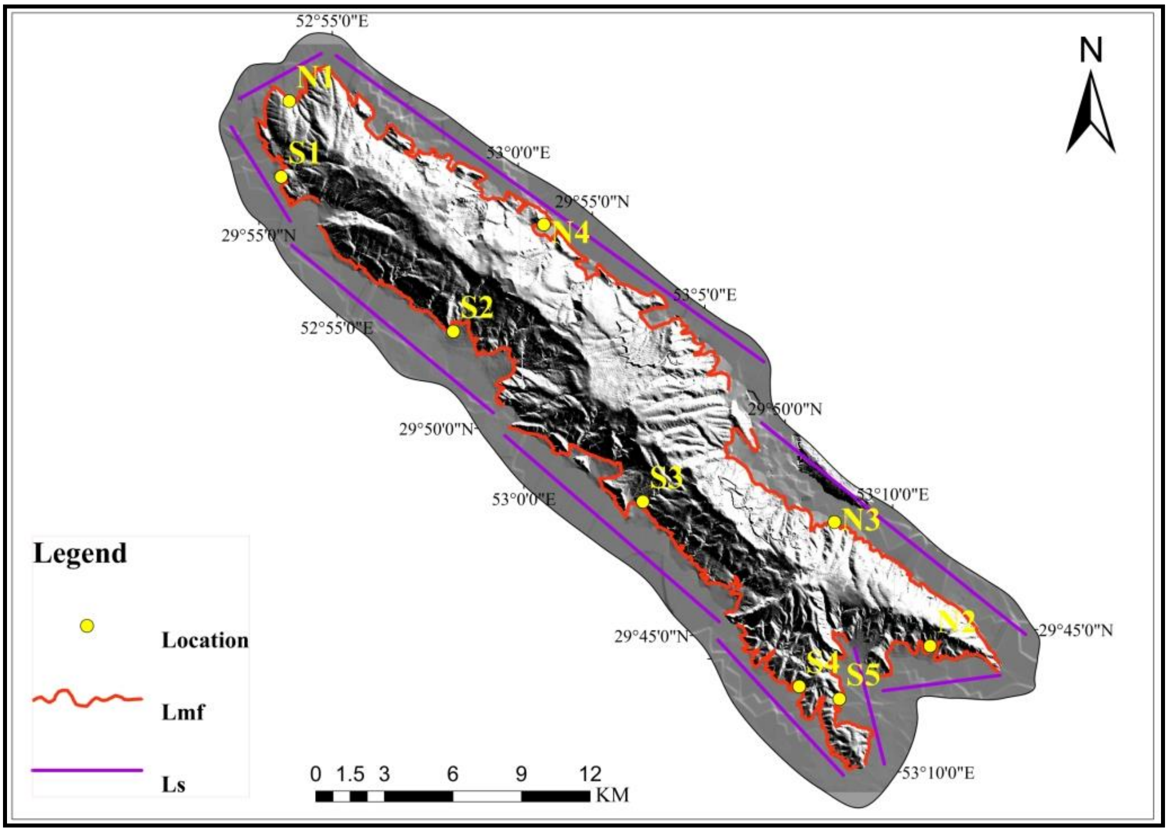


Figure 6) Location of sections for Smf calculation in the study area.

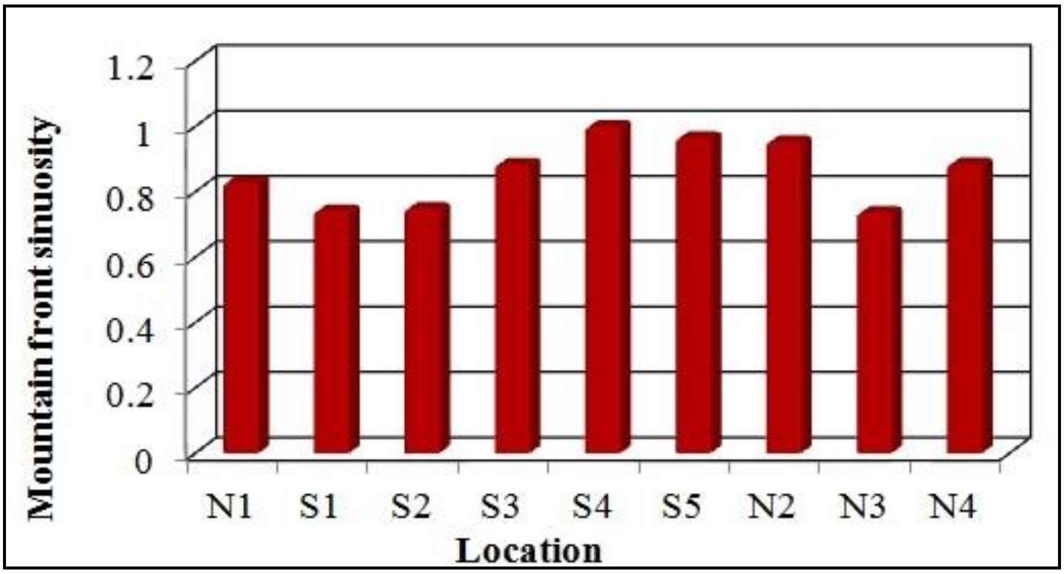


Figure 7) The measured values of smf index in the study area.

4.2- Stress Regime

To analyze the stress in the area, fault planes, the associated slickenside is measured. Numerous shear data are determined from historical locations in the study area and are categorized into 20 fault plane sites according to the inversion method (proposed by Angelier 1990, Fig. 10), which includes determination of the mean stress tensor orientation and sense of slip on numerous faults. Faults data are classified based on the principal stress axes, and corresponding compressional and extensional directions are calculated (by using tectonicsFp software).

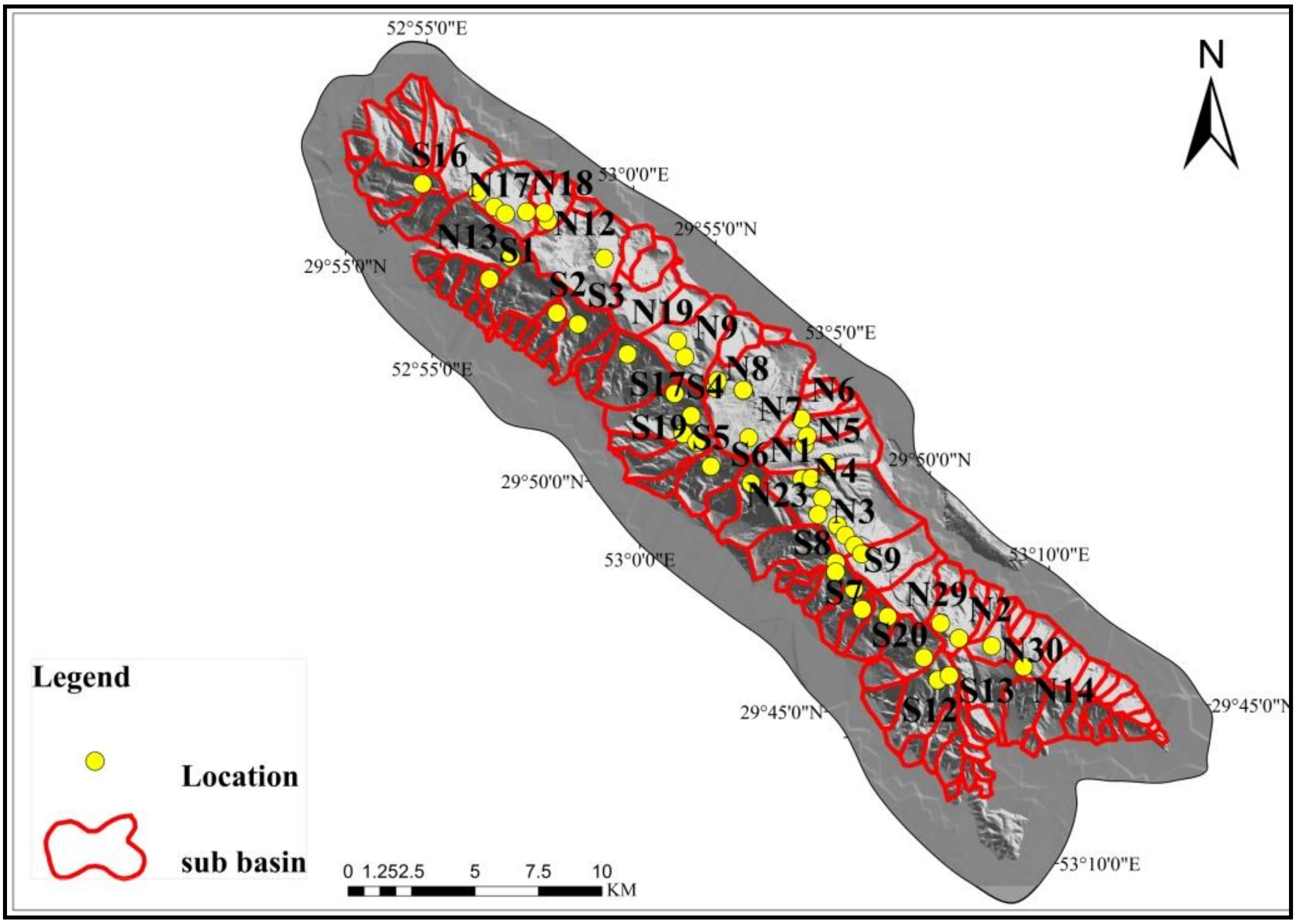


Figure 8) Location of sections for Vf calculation in the study area

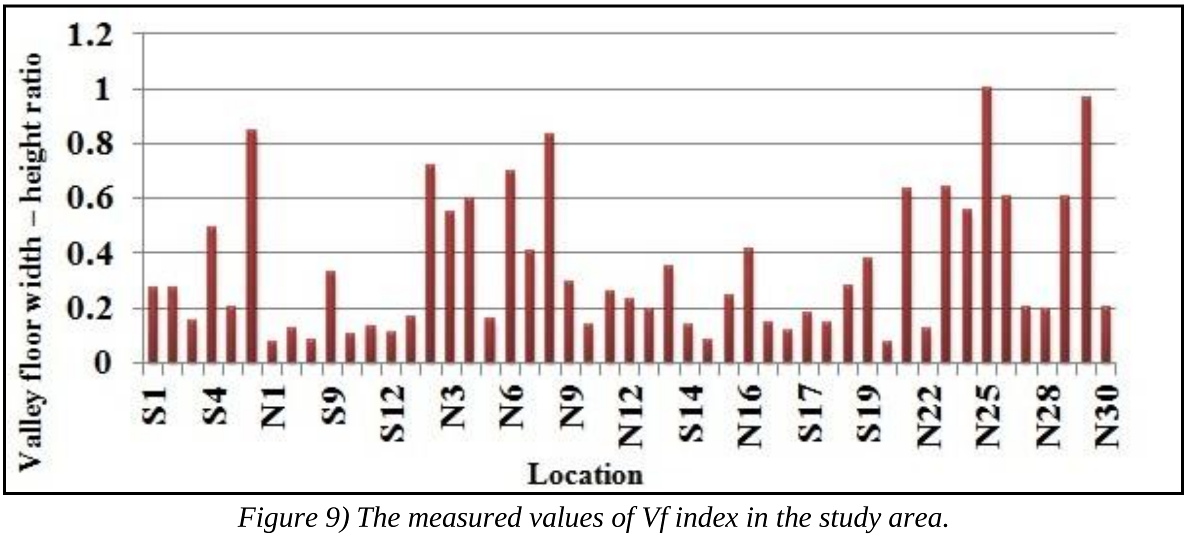


Figure 9) The measured values of Vf index in the study area.

Based on the results derived from the diagrams, suggested 3 stress directions NE-SW, N-S and NW-SE compressional stress directions, are obvious in study area. Fault slip analysis reveals two successive late Cenozoic regional compressional trends, NE-SW and N-S. The latter is in good agreement with the present-day stress. The significance of the NW-SE compression is discussed alternatively in terms of stress deviations or block rotations in relation to the strike-slip fault system (Fig. 11).

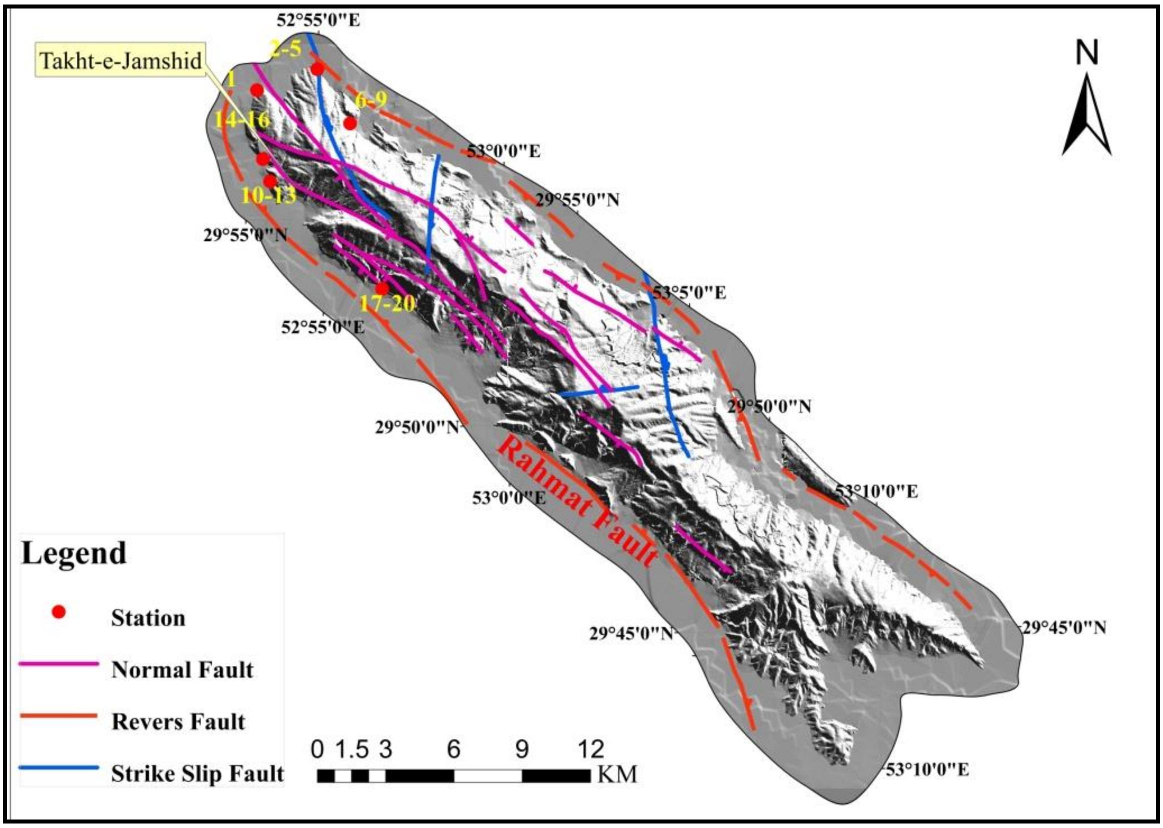


Figure 10) Location of sections for fault plane calculation in the study area.

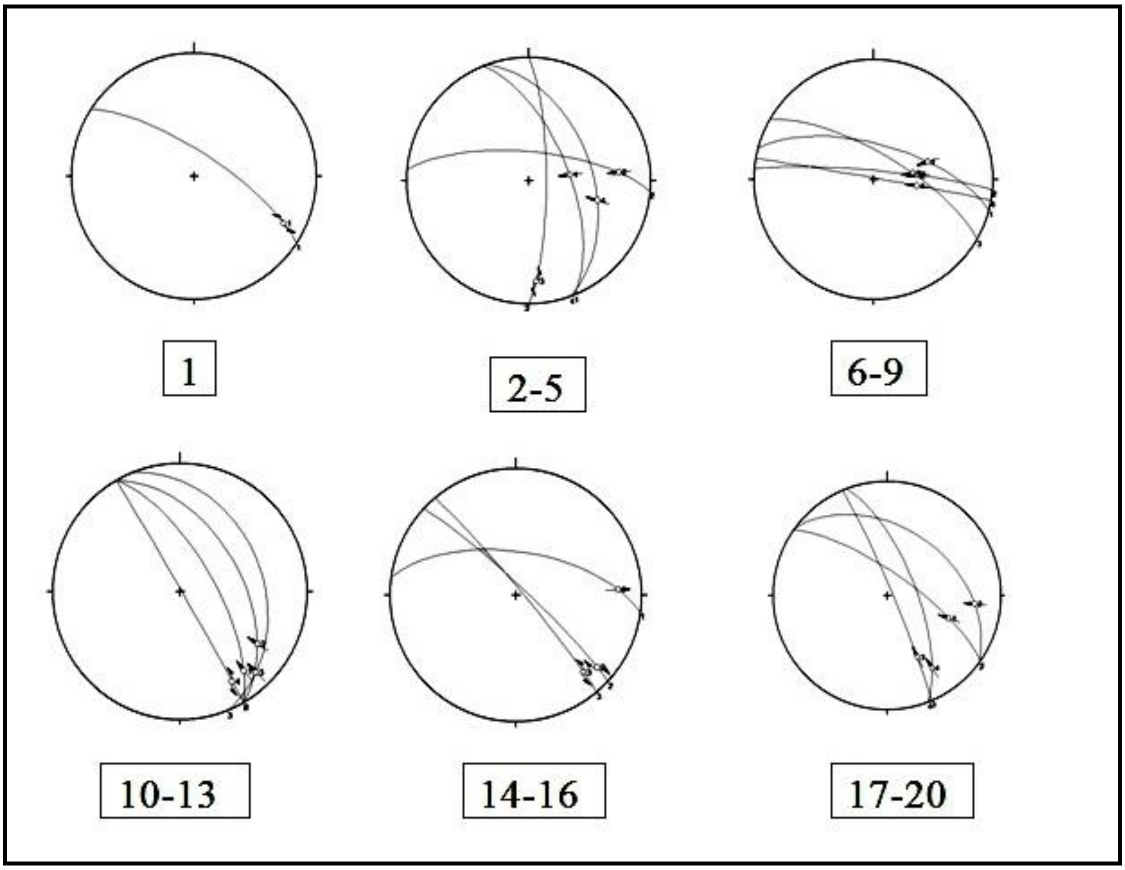


Figure 11) Diagrams of selected faults planes in the study area.

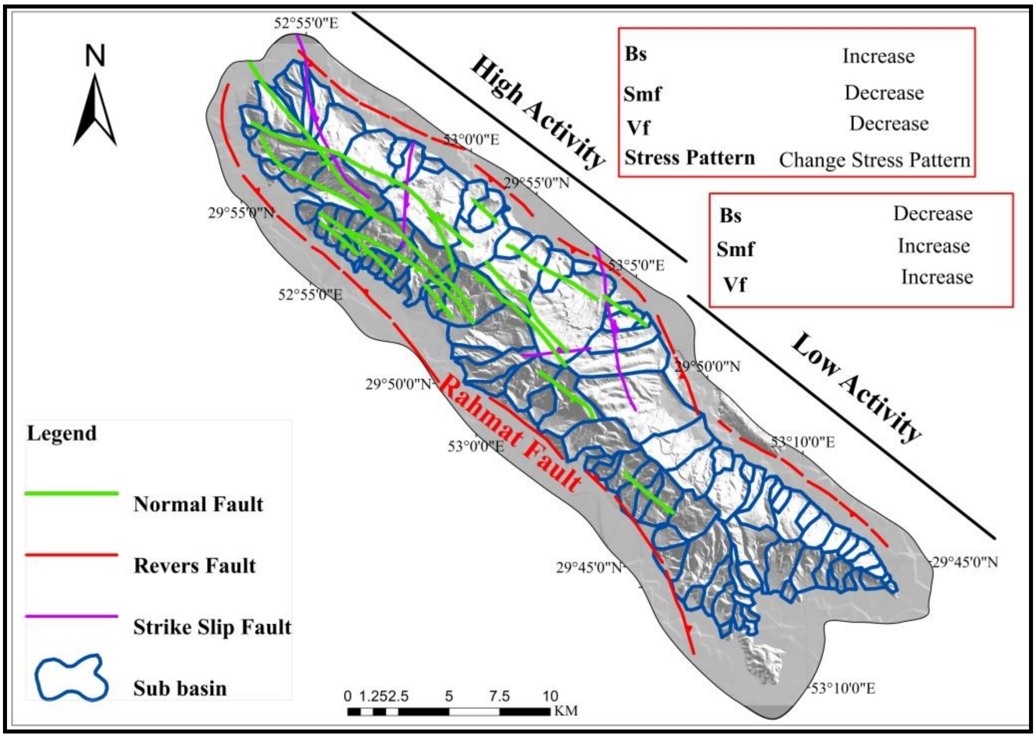


Figure 12) The results of the evaluation of morphotectonics and structural analysis in the study area.

5- Conclusions

The Rahmat Anticline is located 70 Km northeast of Shiraz (Fars Province). This anticline includes faults with combined normal, reverse (Rahmat Fault Zone in the south of anticline) and strike–slip movements. Takht-e-Jamshid (Perspolis) is located in the north anticline. The Kuh-e- Rahmat section locality is assigned to the Interior Fars area, Kuh-e-Rahmat is an anticline with a NW-SE trend. The aims of study are geomorphologic and structural assessment in the area.

Analyses of structural and morphometric data within the Rahmat Anticline allow interpretation of geomorphological anomalies in the investigation area. The results obtained from analysis of structural and morphometric indices indicated that:

1- Geomorphic indices computed using GIS are considered to be suitable for evaluating the effects of active tectonics over a large area. The method was applied to the study area to identify geomorphic anomalies, and to evaluate tectonic activity, we used three geomorphic indices: Drainage basin shape index (Bs), Mountain front Sinuosity Index (Smf) and valley floor width – height ratio (*Vf*). Low sinuosity (Smf) indicate that higher degree rate of uplift reduces erosional processes and begins to form a stright front. The higher values of dissection and elongated drainage basins (Bs) suggest relatively elongated drainage basins, and low (*Vf*) show that many valleys are narrow and deep, suggesting a higher rate of incision associated with tectonic uplift. The result of most active tectonics occurs mainly in the north part of the anticline. The result of graphs indicates that higher active tectonics occurs mainly in the north part of the anticline.(Fig. 12)

2- The reconstruction of the past kinematics and tectonic history and geomorphic investigation in area explain the history of the successive local/regional directions of stress and shortening and active tectonics through time. Based on the results derived from the diagrams in the area, it is suggested that there are 3 stress directions NE-SW, N-S and NW-SE compressional stress directions in the anticline, which is obvious in the study area. Fault slip analysis reveals two successive late Cenozoic regional compressional trends, NE-SW and N-S. The latter is in good agreement with the present-day stress. The significance of the NW-SE compression is discussed alternatively in terms of stress deviations or block rotations in relation to the strike-slip fault system. The change stress pattern can be seen in the northern part of the anticline . (Fig. 11)

3- In the end, based on the diagrams obtained from morphotectonic studies and structural analysis, the study area was divided into two classes of relative tectonic activities (Fig. 12). Class 1 is indicative of the most active tectonics, occurred mainly in the north part of the anticline. Class 2, corresponding to lowly active tectonics occurs mainly along south part of the anticline.

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