Open Journal of Geology, 2015, 5, 309-324
Published Online May 2015 in SciRes. http://www.scirp.org/journal/ojg
http://dx.doi.org/10.4236/ojg.2015.55028

Neotectonics of Boroujerd Area, SW Iran by Index of Active Tectonics

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Received 14 April 2015; accepted 11 May 2015; published 15 May 2015

Abstract

Boroujerd area has located in the border zone of Zagros mountain and Sanandaj-Sirjan belt in the southwest Iran. Six geomorphic indices were calculated in the study area. Through averaging these indices we obtain index of active tectonics (Iat). The values of the index were divided into classes to define the degree of active tectonics. Therefore, relative tectonic activity was calculated and their values were classified and analyzed in two groups. Regions were identified as low and moderate levels. In analyzing data and combining them with tectonic setting the results were often associated and justified with regional geology. Our results show that the highest value has located along faulted area, which shows 3 classes of relative tectonic activity (moderate level). Also, other values have located along folded area (low level). Therefore, middle part of study area (sub-basin No. 4) is showing the more active uplifting related to surroundings region (sub-basin No. 1, 2 and 3). In other words, sub-basin No. 4 has got the more active uplifting by quaternary movements of several faults such as Doroud fault.

Keywords

Neotectonics, Geomorohic Index, Boroujerd, Zagros, Iran

1. Introduction

The study area is around Boroujerd city in the border zone of Zagros hinterland and Sanandaj-Sirjan belt in the south west Iran (**Figure 1**). This area is structurally and geographically belonging to Zagros Mountain. Its northeastern margin belongs to Sanandaj-Sirjan zone and its rest belongs to Zagros Mountain. These two zones have no similar geologic history. Sanandaj-Sirjan zone has comprised from some intrusive bodies in this area.

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How to cite this paper: Omidali, M., Arian, M. and Sorbi, A. (2015) Neotectonics of Boroujerd Area, SW Iran by Index of Active Tectonics. *Open Journal of Geology*, **5**, 309-324. http://dx.doi.org/10.4236/ojg.2015.55028

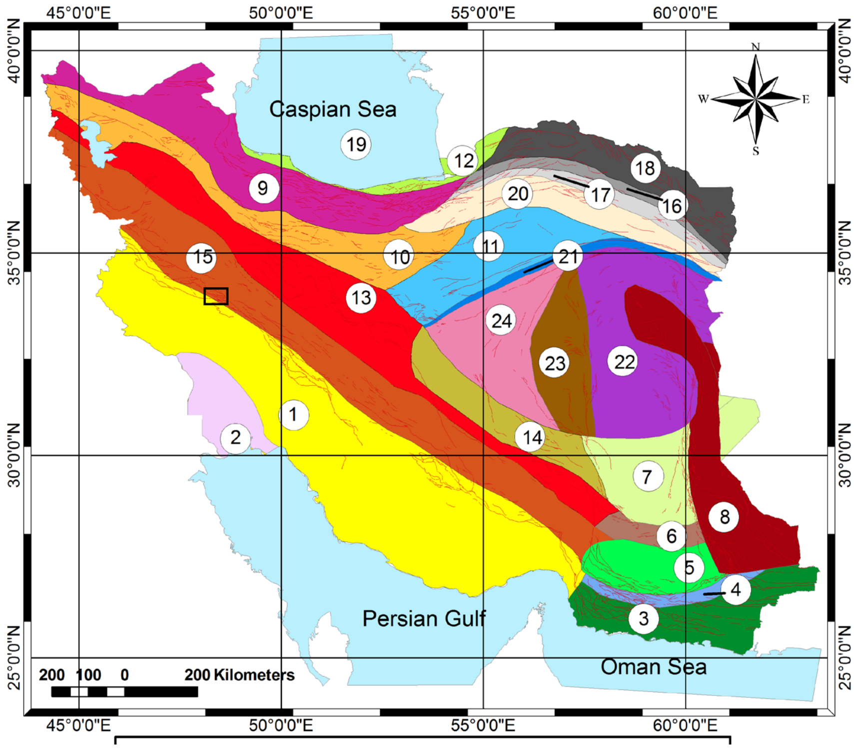

Figure 1. Physiographic-tectonic zoning map of Iran's sedimentary basins Iran modified from [1]. Numbers in this figure are, 1: Zagros-East Taurus hinterland, 2: Persian Gulf-Mesopotamian foreland basin, 3: Makran accretionary prism, 4: Bashagard Mountains, 5: Jazmorian-Mashkel fore arc basin, 6: Shahsavaran-Soltan magmatic arc, 7: South Lut-South Helmand back arc basin, 8: East Iran Mountain belt, 9: West-Central Alborz and lesser Caucasus hinterland, 10: Great Kavir-Nor-thenUr- mieh lake foreland basin, 11: South Great Kavirfold and thrust belt, 12: South Caspian-Black sea foreland basin, 13: Urmieh-Dokhtar Magmatic Arc, 14: Naien-Kerman retro arc foreland basin, 15: Sanandaj-Sirjanover thrust belts, 16: East Alborz or Binalod hinterland, 17: Torbat-e am-Neyshabour retro arc foreland basin, 18: KopetDagh hinterland, 19: South Caspian remnant basin, 20: Maiamay-Taibad Inverted back arc basin, 21: Khaf-Kavir Plain Magmatic Arc, 22: Lut Plain-Gonabad back arc basin, 23: Tabas hinterland, 24: Yazd-Khour Piggy back basin. The study area is shown in the black rectangle.

The southwestern part is a folded mountain belt in which lies the highest parts of the mountain. The boundary of these two different zones is Silakhor plains covered by alluvium.

These two structural zones have structural, metamorphic, magmatic contrasts so that this province can be divided into two contrasting domains: The north-eastern parts of this area are territories defined by magmatic, thermic, metamorphic features and most of the rock sequences are metamorphic. Pellitic metamorphic rocks constitute low lands while marbles are feature forming. The south-western parts of this area are platform sequences of Paleozoic to Triassic that they are composed of sandstone, limestone. Rock sequences younger than Triassic are limited to Plio-Quaternary conglomerates which are formed as post-orogenic deposit. Dominant structural trends in Zagros are NW-SE in this area. From tectonics view, it contains the over thrust and simple fold belts of Zagros that formed on the northeastern part of Arabian plate's passive margin. Zagros hinterland is external platform (fold and thrust belt) of north margin of Arabian Craton (**Figure 1**). Vergence of folding in this hinterland is toward south and southwest. But, Sanandaj-Sirjan overthrust belt has been formed by metamorphic rocks of the northeastern part of Arabian plate. Late Cretaceous-Paleogene sequences in this belt have piled up on a wedge top part of Zagros, before regional metamorphism. Recently, pre-Cretaceous deformed and metamorphic rocks have exposed in this province by upthrusting of basement wedges [1]-[3]. In this research, area is divided into 4 sub-basins and the following indices are calculated: stream-gradient index (Sl), valley floor width-valley height ratio (Vf), and mountain-front sinuosity (Smf), drainage basin asymmetry (Af), hypsometric integral (Hi) and drainage basin shape (Bs). We use geomorphic indices of active tectonics, known to be useful in active tectonic studies [4]-[7]; methodology has been previously tested as a valuable tool in different tectonically active areas, namely SW USA [8], the Pacific coast of Costa Rica [9], central Zagros, Iran [10].

2. Materials and Methods

The calculated geomorphic indices are suitable for assessment of tectonic activity of the study area. The geomorphic indices such as: stream-gradient index (*Sl*), valley floor width-valley height ratio (Vf), mountain-front sinuosity (*Smf*), drainage basin asymmetry (Af), hypsometric integral (Hi) and drainage basin shape (*Bs*) are calculated in Boroujerd area by using of topographic data and DEM (**Figure 2**). On the other hand, the area was divided to four sub-basins tructural and for each one, indices were calculated, then all of the indices were combined to obtain index of active tectonics (Iat) by new method [11]. Therefore, sub-basins can be compared together. The study area is located between longitudes E48˚30' - 49˚ and latitudes N33˚45' - 34˚ in the Louristan province, south west Iran. Based on previous work on the salt diapirism [12]-[21] and neotectonics regime in Iran [22]-[26], Zagros in south Iran is the most active zone [27]-[36]. Then, Alborz [37]-[69] and Central Iran [70]-[82] have been situated in the next orders.

Altitudes in this area reach to 3645 m on Garin mountain in the western part of Boroujerd, which it have about 2100 m difference respect to the Silakhore plain in the south eastern part of it. Geomorphologically, the ridges and valleys in the area under study are mainly due to the rocks variations in the lithology and assisted by faults presence in the area that offer varying degrees of resistance to the degradation processes. Topographically, the down faulted. Silakhore plain is quaternary alluvium covered (**Figure 3**).

3. Results and Discussion

To study the indices, there is a formula which we turn to describe each one of indices; It is necessary to have some primary maps to calculate the indices, and the most important of which are: Digital Elevation Model (DEM), the drainage network and the sub-basins map of the Boroujerd area that have been extracted from DEM (**Figure 4**). DEM extracted from a digitized topographic map (with 10 m intervals).

3.1. The Stream-Gradient Index (SL)

The rivers flowing over rocks and soils of various strengths tend to reach equilibrium with specific longitudinal profiles and hydraulic geometrics [83] [84]. [85] defined the stream-gradient index (*SL*) to discuss influences of environmental variables on longitudinal stream profiles, and to test whether streams has reached equilibrium. The calculation formula is in this manner:

$$SL = \left(\Delta H / \Delta L\right) L$$

where ($\Delta H/\Delta L$) is local slope of the channel segment that is located between two contours and L is the channel length from the division to the midpoint of the channel reaches for which the index is calculated. This index is

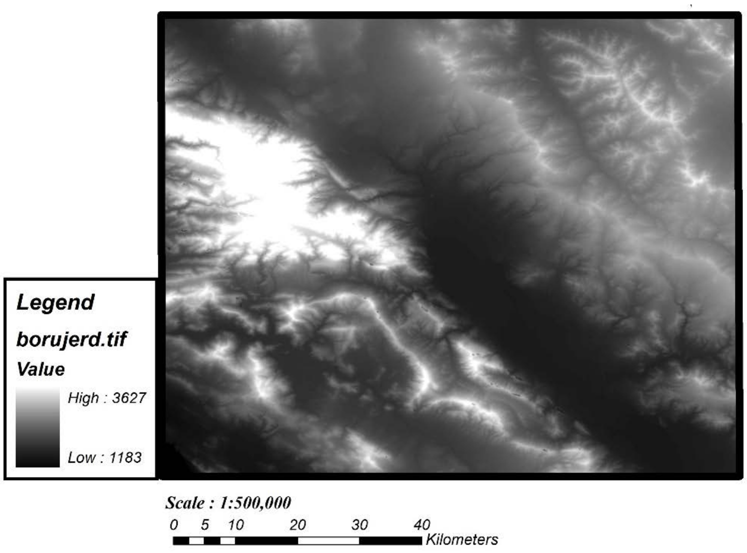

Figure 2. Digital elevation model of the Boroujerd area.

Figure 3. The Ghaleh Hatam fault (boundary of mountain and plain) in the north eastern part of Boroujerd city, view to the east.

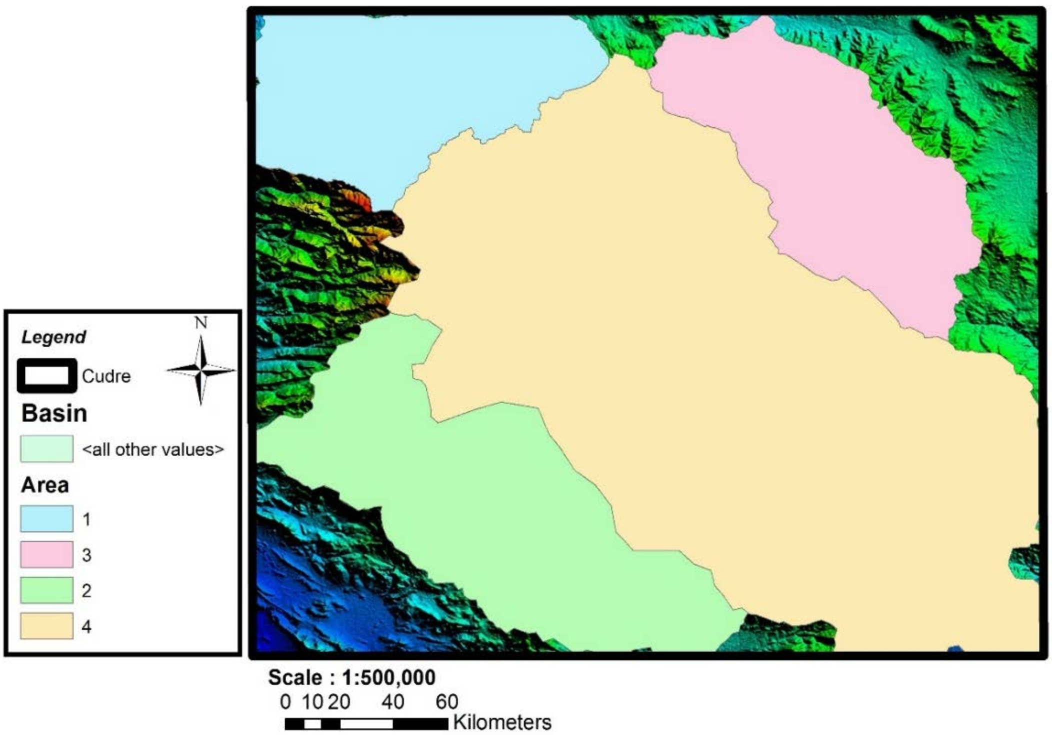

Figure 4. Determination of sub-basins in the Boroujerd area based on Digital Elevation model (DEM).

calculated along the four master rivers (**Table 1**) and then SL graphs have prepared for them (**Figure 5**). The SL index can be used to evaluate relative tectonic activity. An area on soft rocks with high *SL* values can be indicated for active tectonics. Based on our results, there are in 2 and 3 classes.

3.2. Valley Floor Width-Valley Height Ratio (*Vf*)

Another index sensitive to tectonic uplift is the valley floor width to valley height ratio (Vf). This index can separate v-shaped valleys with small amounts from u-shaped valleys with greater amounts. The calculation formula is in this manner:

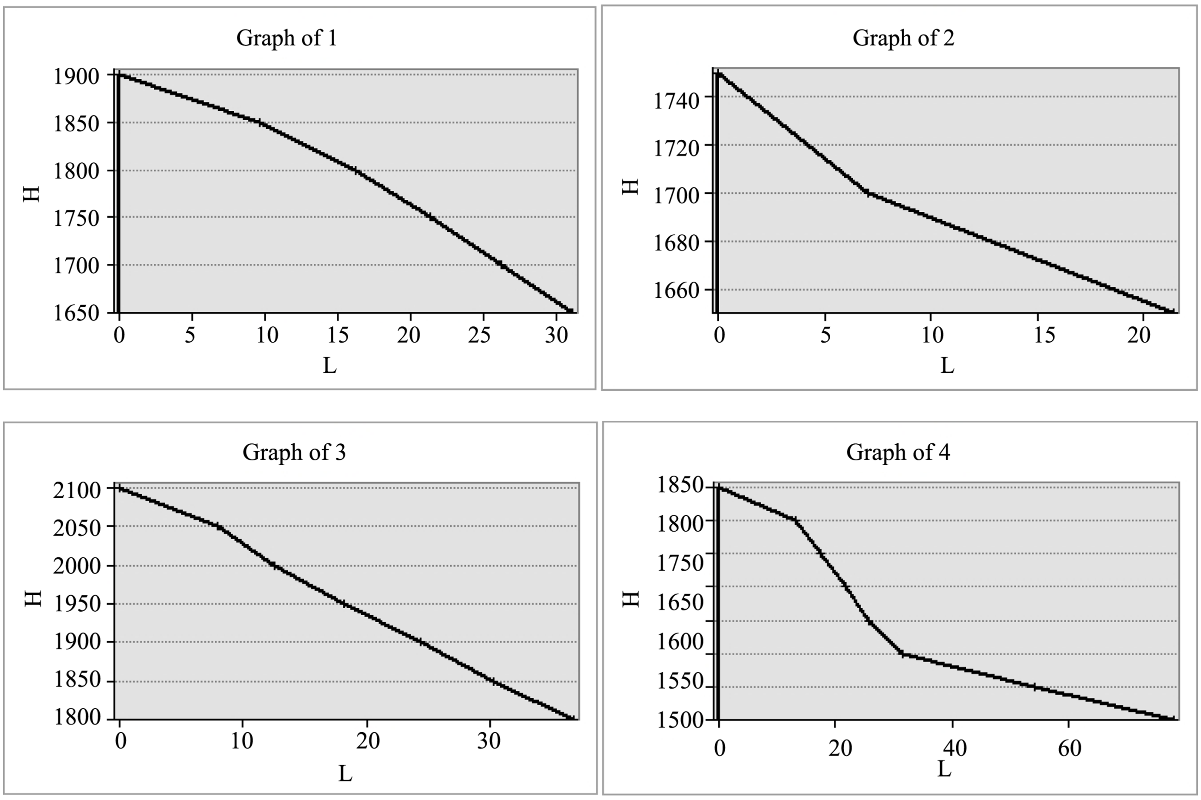

Figure 5. Graphs of stream length-gradient index for 4 rivers.

Table 1. Values of stream length-gradient index.

SL(1)	L	ΔL	ΔH/Δh	Δh2	ΔH
12.06	31.08	4.38	50	1650	1700
8.56	26.21	5.36	50	1700	1750
8.81	21.35	4.36	50	1750	1800
4.99	16.17	6	50	1800	1850
2.62	9.67	7	50	1850	1900
Class 2					

SL(2)	L	ΔL	ΔH/Δh	Δh2	ΔH
1.88	21.39	19.30	50	1650	1700
1.30	7.02	9.44	50	1700	1750
Class 3					

SL(3)	L	ΔL	ΔH/Δh	Δh2	ΔH
8.92	36.78	7.63	50	1800	1850
8.90	30.36	6.48	50	1850	1900
8.48	24.32	5.59	50	1900	1950
5.6	18.2	6.5	50	1950	2000
5.47	12.6	4.72	50	2000	2050
3.5	7.9	4.7	50	2050	2100
Class 3					

SL(4)	L	ΔL	ΔH/Δh	Δh2	ΔH
13.82	78.12	8.76	50	1500	1550
22.25	54.24	3.9	50	1550	1600
7.94	31.47	6.54	50	1600	1650
9.39	25.86	4.68	50	1650	1700
9.79	21.26	3.80	50	1700	1750
6.83	17.42	4.59	50	1750	1800
1.7	13.1	14.06	50	1800	1850
Class 2					

$$Vf = 2Vfw/\left(Eld + Erd - 2Esc\right)$$

where Vfw is the width of the valley floor, and Eld, Erd and Esc are the altitudes of the left and right divisions (looking downstream) and the stream channel, respectively [84]. [4] found significant differences in Vf between tectonically active and inactive mountain fronts. Also, they found significant differences in Vf between tectonically active and inactive mountain fronts, because a valley floor is narrowed due to rapid stream down cutting.

So, we have considered suitable valleys in the study area (**Figure 6**).

Vfw value is obtained by measuring the length of a line which cuts the river and limits to two sides of a contour through which the river crosses (**Table 2**). Based on [11], Vf values are divided into 3 classes: 1 ($Vf < 0.3$), 2 ($0.3 < Vf < 1$), and 3 ($Vf > 1$). Therefore, all of the valleys are in 2 and 3 classes and show U shape valleys.

3.3. Mountain-Front Sinuosity Index (*Smf*)

This index represents a balance between stream erosion processes tending to cut some parts of a mountain front and active vertical tectonics that tend to produce straight mountain fronts. Index of mountain front sinuosity [3] is defined by:

$$Smf = Lj/Ls$$

where Lj is the planimetric length of the mountain along the mountain-piedmont junction, and Ls is the straight-line length of the front. The Mountain fronts of the study area have drawn in **Figure 7** by and one of them in sub-basin No. 2 has shown in **Figure 8**. *Smf* is commonly less than 3, and approaches 1 where steep mountains rise rapidly along a fault or fold [84]. Therefore, this index can play an important role in tectonic activity. Considering that mountain fronts sites are independent from basins places, chances are some of them have various fronts (**Table 3**). Values of *Smf* are readily calculated from topographic maps for 4sub-basins.

Based on [11], *Smf* values are divided into 3 classes: 1 ($Smf < 1.1$), 2 ($1.1 < Smf < 1.5$), and 3 ($Smf > 1.5$) and in the study area most of the obtained values are between 1.1 to 1.5 (class 2).

3.4. Asymmetry Factor (Af)

This index is related to two tectonic and none tectonic factors. None tectonic factors may relate to lithology and rock fabrics. It is a way to evaluate the existence of tectonic tilting at the scale of a drainage basin. The index is defined as follows:

$$Af = \left(Ar/At\right)100$$

where Ar is the right side area of the master stream basin (looking downstream) and At is the total area of the basin that can be measured by GIS software. To calculate this index in the area At and Ar are obtained using the sub-basins and the master river maps. Af is close to 50 if there is no or little tilting perpendicular to the direction of the master stream. Af is significantly greater or smaller than 50 under the effects of active tectonics or strong lithologic control. The values of this index are divided into three categories. 1: ($Af < 35$ or $Af > 63$) 2: ($57 < Af < 65$) or ($35 < Af < 43$) and 3: ($43 < Af < 57$), based on [11].

Among the obtained values (**Table 4**), the minimum value belongs to sub-basin No. 4 with 41.96 and the maximum value belongs to sub-basin No. 2 with 61.81 percents. Also, a map has prepared that it shows Asymmetry factor of study area (**Figure 9**).

Table 2. Values of *Vf* index.

Basin	Sub-Basin	V_{fw}	E_{ld}	E_{sc}	E_{rd}	V_f	Average	Class
1	1a	150	1930	1750	1930	0.83	8.08	3
	1b	600	2020	1820	1940	3.75		
	1c	200	1910	1760	1970	1.11		
	1d	800	1920	1810	1848	10.81		
	1e	1910	1910	1880	2010	23.88		
2	2a	70	2100	1610	2000	0.16	1.64	3
	2b	800	2000	1610	2050	1.93		
	2c	800	2600	1620	2400	0.91		
	2d	150	1810	1740	1970	1.00		
	2e	700	1930	1700	2400	1.51		
	2f	200	2050	1650	2300	0.38		
	2g	100	2000	1800	2080	0.42		
	2h	800	1980	1610	2080	1.90		
	2i	400	1810	1680	2040	1.63		
	2j	800	1760	1660	1860	5.33		
	2k	500	1850	1690	1940	2.44		
	2l	500	1850	1680	1980	2.13		
3	3a	2000	2100	1810	2040	7.69	2.35	3
	3b	200	2160	2050	2390	0.89		
	3c	1500	1980	1880	2350	5.26		
	3d	700	2280	2050	2440	2.26		
	3e	200	2170	2010	2250	1.00		
	3f	200	2250	2000	2400	0.62		
4	4a	300	2700	2510	2900	1.03	0.80	2
	4b	100	2100	1750	2000	0.33		
	4c	500	1790	1710	1800	5.88		
	4d	1000	2050	1650	1850	3.33		
	4e	200	1840	1710	2000	0.95		
	4f	150	1930	1610	1880	0.51		
	4g	800	1690	1960	1900	4.85		
	4h	400	2690	1800	2700	0.45		
	4i	150	2750	1700	2600	0.15		
	4j	100	2400	1720	2150	0.18		

Table 3. Values of *Smf* index.

Sub-Basin	L_s	L_{mf}	S_{mf}	Class
1	24	26	1.08	1
2	23	26	1.13	2
3	28	34	1.21	2
4	21	30	1.42	2

Table 4. Values of *Af* index.

Sub-Basin	*Ar*	*At*	*Af*	Class
1	233.7	538	43.44	3
2	501.9	812	61.81	2
3	297.2	585	50.8	3
4	1049	2500	41.96	2

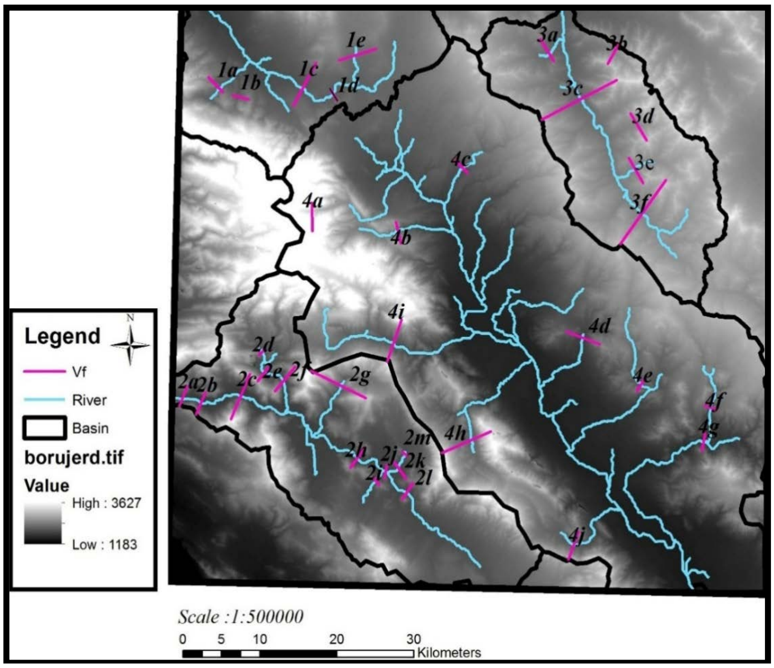

Figure 6. Position map for measurement of the valley floor width to valley height ratio.

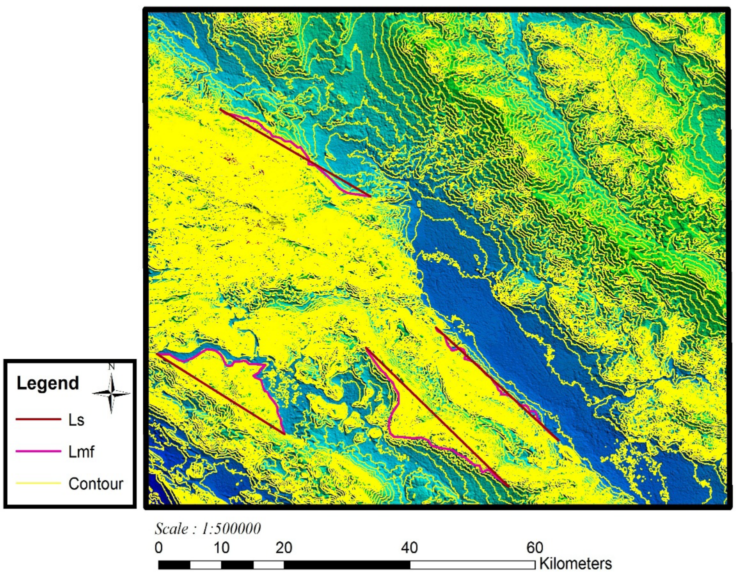

Figure 7. Position map for measurement of mountain-front sinuosity index.

Figure 8. A Mountain-front in the south western part of Boroujerd city (sub-basin No. 2), view to the SW.

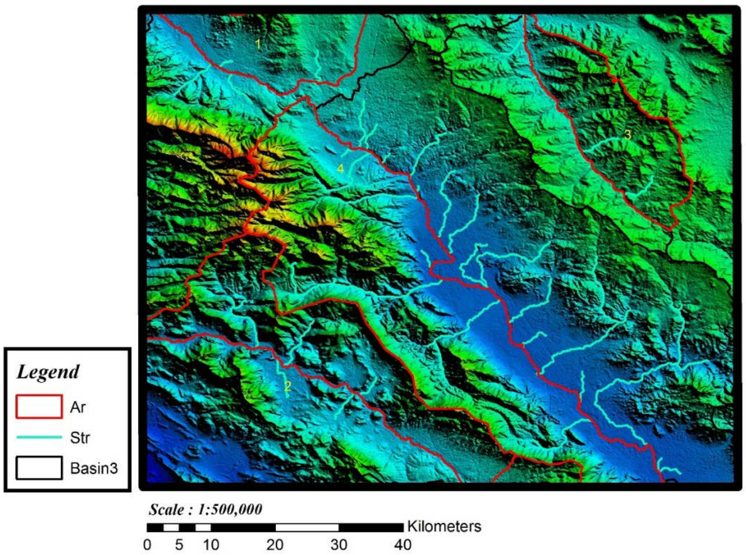

Figure 9. Asymmetry factor map of study areas.

3.5. Basin Shape Index (*Bs*)

Relatively young drainage basins in active tectonic areas tend to be more elongated than their normal shape to the topographic slope of a mountain. The elongated shape tends to evolve into a more circular shape [4]. The horizontal projection of the basin shape may be described by the basin shape index or the elongation ratio, Bs [7]. The calculation formula is:

$$Bs = Bl/Bw$$

where *Bl* is the length of the basin measured from the headwater to the mount, and *Bw* is basin width in the widest point of the basin *Bl*.

To calculate this index in the area, *Bl* and *Bw* are obtained using the sub-basins and the master river maps then the values are divided into 3 classes: 1: ($Bs > 4$) 2: ($3 < Bs < 4$) 3: ($Bs < 3$), based on [11]. According to **Figure 10** and **Table 5**). The minimum value belongs to sub-basin No. 1 with 1 and the maximum value belongs to sub-basin No. 2 with 2.4 (Class 3).

3.6. Hypsometric Integral Index (*Hi*)

The hypsometric integral (*Hi*) describes the relative distribution of elevation in a given area of a landscape particularly a drainage basin. The index is defined as the relative area below the hypsometric curve and it is an important indicator for topographic maturity. H_{max}, H_{min} and H_{ave} are calculated on DEM. This index is calculated to all sub-basins in the area and the minimum value is 0.19 for sub-basin No. 2 and maximum value is 0.50 for sub-basin No. 3 (**Table 6**). The hypsometric integral reveals the maturity stages of topography that can, indirectly, be an indicator of active tectonics. In general, high values of the hypsometric integral are convex, and these values are generally > 0.5. Intermediate values tend to be more concave-convex or straight, and generally have values between 0.4 and 0.5. Finally, lower values (<0.4) tend to have concave shapes [11]. We can consider class 1 for Hi > 0.5, class 2 for Hi between 0.4 and 0.5 and class 3 for Hi < 0.4 and so, sub-basin No. 3 shows younger topography.

4. Results and Discussion

The average of the six measured geomorphic indices (*Vf*, *Smf*, *SL*, *Af*, *Bs* and *Hi*) was used to evaluate the distribution of relative tectonic activity. Through averaging these six indices (**Table 7**). we obtain one index that is known index of active tectonics (*Iat*). The values of the index were divided into four classes to define the degree of active tectonics: 1-very high ($1 < Iat < 1.5$), 2-high ($1.5 < Iat < 2$), 3-moderate ($2 < Iat < 2.5$), 4-low ($2.5 < Iat$) [11].

Thus, there are low relative tectonic activities in sub-basin No. 1, 2 and 3 and moderate relative tectonic activities in sub-basin No. 4 (**Figure 11**). The sub-basin No. 4 has situated in the middle part of study area and it has got several faults that shown in **Figure 12**.

Also, based on [23], this area is a high seismic risk zone with following seismicity parameter: b = 1.06, M max = 7.2. Focal mechanisms of several earthquakes are dextral strike slip in relation to main recent faults of Zagros such as Doroud (*Ms* = 6.1, 2006).

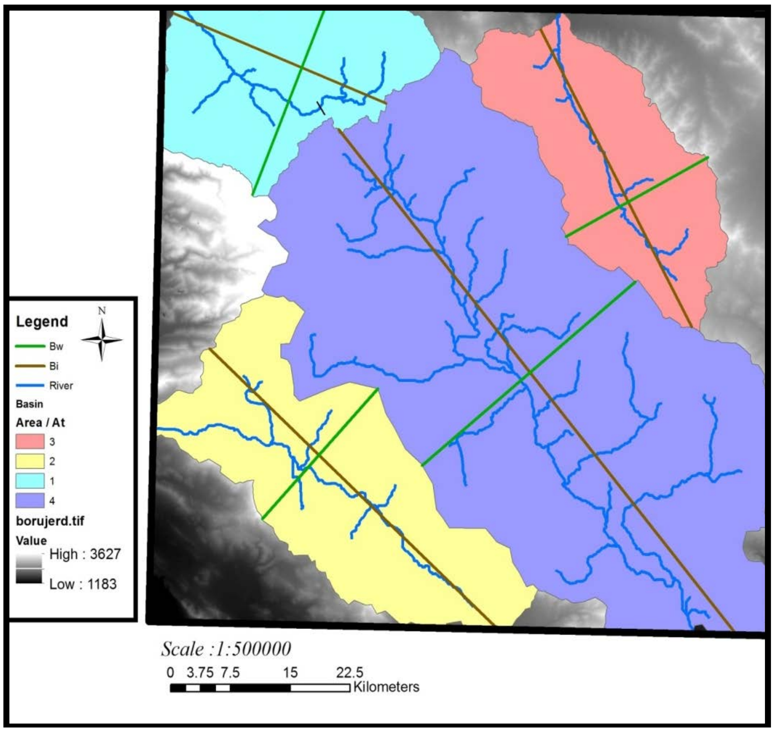

Figure 10. Basin shape map of study area.

Table 5. Values of Bs index.

Sub-Basin	B_i	B_w	B_s	Class
1	30.71	30.68	1	3
2	51.86	21.05	2.4	3
3	41.25	19.56	2.1	3
4	74.09	36.24	2.04	3

Table 6. The hypsometric integral (Hi).

Sub-Basin	H_{ave}	H_{max}	H_{min}	H_i	Class
1	2044.54	3036	1609	0.30	3
2	1884.70	2932	1631	0.19	3
3	2131.58	2425	1838	0.50	2
4	1868.98	3250	1440	0.23	3

Table 7. Relative Tectonic activity classification.

Sub-Basin	S_{mf}	V_f	S_l	A_f	B_s	H_i	s/n	IAT
1	1	3	2	3	3	3	2.5	4
2	2	3	3	2	3	3	2.6	4
3	2	3	3	3	3	2	2.6	4
4	2	2	2	2	3	3	2.3	3

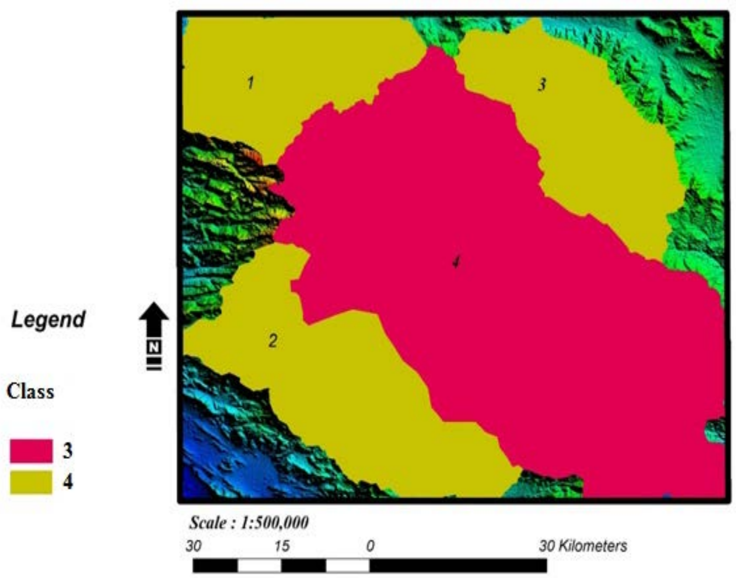

Figure 11. Relative Tectonic activity classification map of study area.

This area is struck by moderate to high earthquakes with low frequency, long repeat time and 10 - 15 Km focal depth. Intensity of earthquakes is in high levels. Sometimes, focal depths exceed to 70 Km which is an indication of initial stages of thick-skinned tectonics. The most serious seismic hazards in the study area are landslide in high regions, settlement in plain, surface faulting (**Figure 13**).

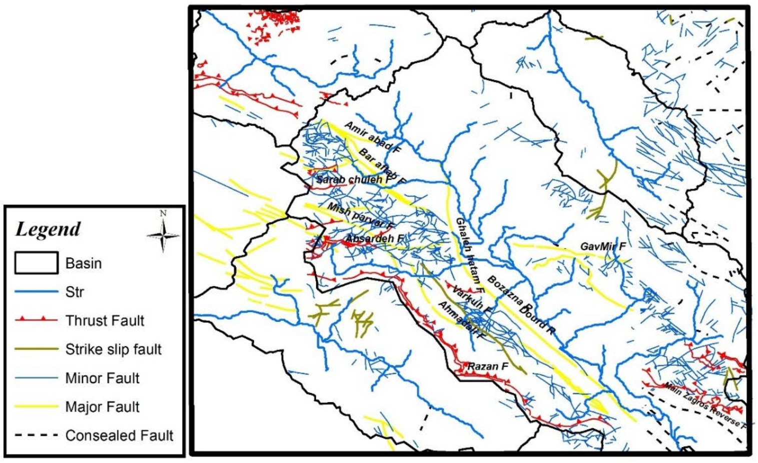

Figure 12. Fault map of study area.

Figure 13. The Doroud fault, view to the south.

5. Conclusions

The calculated geomorphic indices are suitable for assessment of tectonic activity of the study area. The six geomorphic indices; stream-gradient index (*Sl*), valley floor width-valley height ratio (Vf) and mountain-front sinuosity (*Smf*), drainage basin asymmetry (Af), hypsometric integral (*Hi*) and drainage basin shape (*Bs*) have been calculated in Boroujerd area.

Therefore, firstly the area was divided to sub-basins and for each one, indices were calculated, then all of the indices were divided into relative tectonic activity classes. Afterwards, the six measured indices for each sub-basin were compounded and a unit index obtained as index of active tectonics (*Iat*). According to this index, there are both low and moderate relative tectonic activities levels.

Low relative tectonic activities level has been found in sub-basin No. 1, 2 and 3 and moderate relative tectonic activities level, has been found in sub-basin No. 4. It means that sub-basin No. 4 has got the more active uplifting by movements of several faults such as Doroud fault.

Acknowledgements

This work has funded by the Department of geology, Islamic Azad University, Science and Research branch, Tehran, Iran. Also, Special thanks to vice-president for research in Science and Research branch, Tehran.

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