Estimating rate of tectonic activity in central Kopeh dagh using morphometric indices

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Abstract

In central part of Kopeh dagh there is an array of active right-lateral strike-slip faults that obliquely cut the range and produce offsets of several kilometers in the geomorphology and geological structure. Geomorphic indices indicate the presence of differential uplifting in history of this area. Tectonic activity of the study area is investigated by a large number of DEM derived catchments and drainage lines using GIS: ratio of valley floor width to valley height, stream length-gradient index, transverse topographic system, hypsometric integral, drainage basin shape and sinuosity. The recent investigations show that west part of Yekehshakh basin is active part and morphotectonism has played a key role in the geomorphic evolution of this part of the Kopeh dagh mountain range. Low value of Vf index and high value of SL index is related to west of basin. Calculating morphometric indixes for Yekehshakh basin's show that, value of T index is 0.25 and direction of tilting is toward S. Geomorphic indices indicate the presence of differential uplifting was happened in past. The west of study area shows very high relative tectonic activity.

Keywords: Kopeh dagh, Tectonic activity, Drainage basin, Morphometric indices.

1–Introduction

In central part of Kopeh dagh there is an array of active right-lateral strike-slip faults that obliquely cut the range and produce offsets of several kilometers in the geomorphology and geological structure. They are responsible for major destructive earthquakes in the 19th and 20th centuries and represent an important seismic hazard for this now-populous region of NE Iran (Hollingsworth *et al*., 2006). Recent GPS (Global Positioning System) measurements (McClusky *et al*., 2003) indicate that Arabian plate moves approximately northwards, with respect to Eurasian plate, at ~23 mm/yr at the longitude of the Kopeh dagh, which is oblique to the NW–SE trend of the Kopeh dagh range. Lyberis *et al*. (1999) have calculated 75 km shortening in N-S direction comprising the Western part of Kope dagh using balanced geological section during last five million years. This value proposed 16 mm/y shortening rate in the Kope dagh belt. The high rate of shortening and convergence, results to the morphotectonic active features in the study area. The folds and faults are the important structural elements, formed by tectonic activities (Ramazani, 2008). The study of tectonic activity, and in particular those areas with relatively high activity, in the Holocene and late Pleistocene is important to evaluate the earthquake hazard (Keller and Pinter, 2002). On a regional scale, obtaining rates of tectonic activity is difficult or even knowing where to go in a particular region for quantitative studies to obtain rates. The approach of this paper is to provide a quantitative method to focus on areas for more detailed work to establish rates of active tectonics in regional scale. We use geomorphic indices such as ratio of valley floor width to valley height (Vf), stream length-gradient index (SL), transverse topographic system (T), hypsometric integral (Hi), drainage basin shape (Bs) and sinuosity (S) of tectonic activity, known to be useful in tectonic activity studies. This methodology has been previously tested as a valuable tool in different tectonically active areas, such as SW USA (Rockwell *et al*., 1985), the Pacific coast of Costa Rica (Wells *et al*., 1988), and the Mediterranean coast of Spain (Silva, 1994). (Bull and McFadden, 1977; Azor *et al*., 2002; Keller and Pinter, 2002; Silva *et al*., 2003; Molin *et al*., 2004). Active tectonic in the Acambay Graben, Mexican Volcamic belt (Ramirez- Herrera, 1998). Southern Sierra Nevada Mountains (Califonia) (Figueroa and Knott, 2010). Bolu pull-apart basin, western section of North Anatolian Fault System, Turkey (Sarp and Duzgun, 2012). Western section of the North Anatolian Fault System, Turkey (Sarp *et al*., 2014).

2- Regional geology

The Kopeh dagh trends at 120°-300° for 700 km through northeast Iran and Turkmenistan between the Caspian Sea and the Afghanistan border. The northern limit of the Kopeh dagh is marked by a fault zone called the "Main Fault Zone" which separates the Kopeh dagh from the stable Turan shield (Fig. 1) (Tchalenko, 1975).

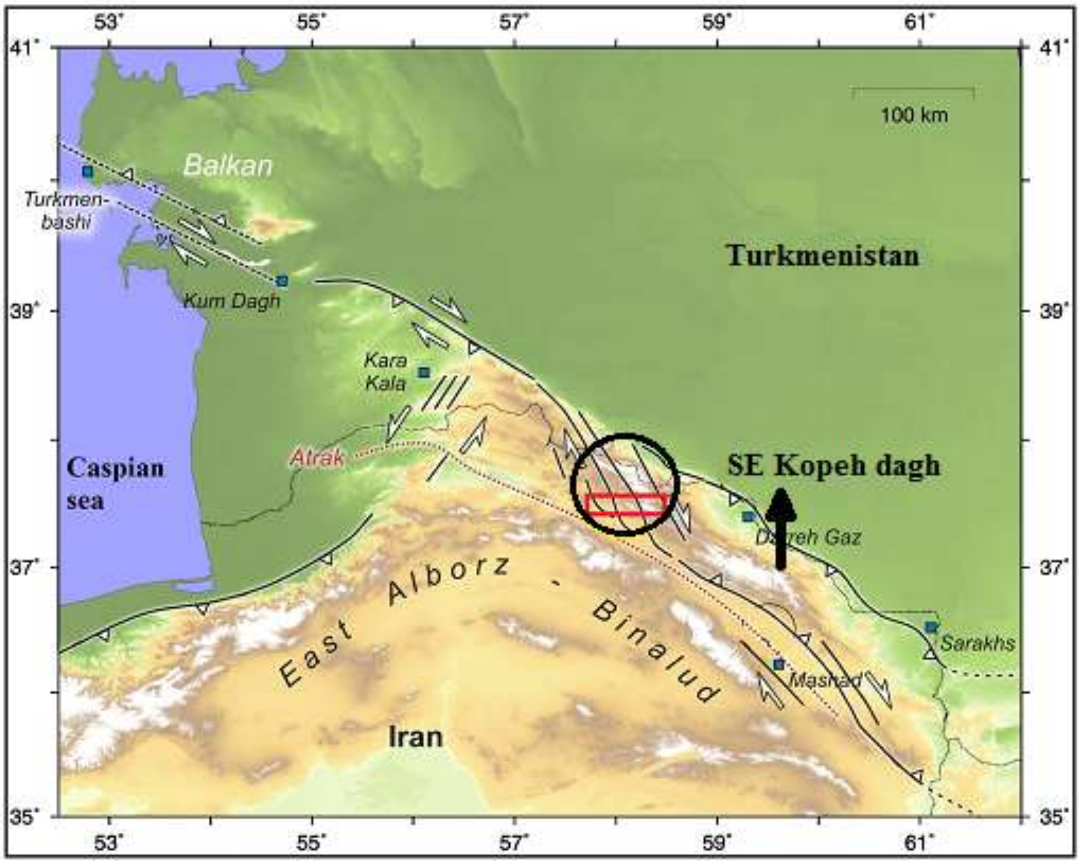

Figure 1) Geological setting of the study area (Hollingsworth, 2007), black circle shows central Kopeh dagh and red rectangular shows study area.

In the eastern Kopeh dagh, Tchalenko (1975) describes SSE faults that splay off the Main Fault Zone, possibly with a right-lateral component of motion (Fig. 1). In the western Kopeh dagh there are many NE-trending faults, which do not cross the Main Fault Zone but continue SW into Iran and eastern Alborz (Jackson and McKenzie, 1984).

The Kopeh dagh is made up of a sequence of mostly conformable and complete Mesozoic–Tertiary sedimentary rocks (Berberian 1976). These consist of limestone, marl and sandstone sequences, which have been shortened into open symmetric folds, with typical wavelengths of 5–20 km (Afshar *et al*., 1987, Hollingsworth, 2007). In this way, the resistant Cretaceous limestones form the characteristic linear peaks of the mountain belt, while the softer sandstones and marls form the low, intervening valleys. The rocks of the Kopeh dagh represent a closing ocean basin (Lyberis and Manby 1999), as NE Iran became sutured to the Turan platform of Eurasia (Hollingsworth *et al*., 2006).

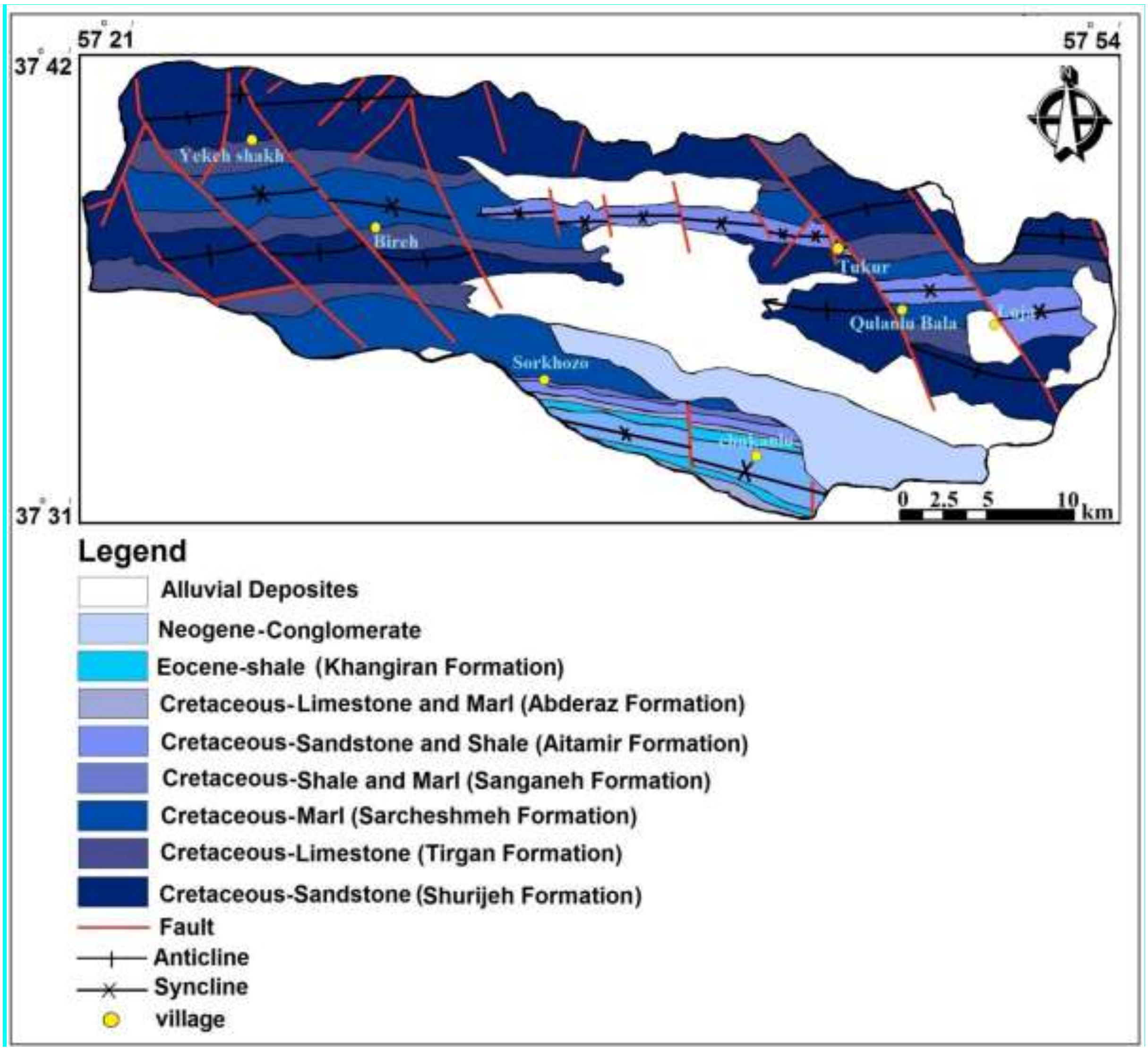

Figure 2) Geological map of the Yekehshakh basin area.

Structurally, the rocks of the Kopeh dagh are distinct from those of Central Iran, and belong to the Turan platform (Stocklin, 1974; Alavi, 1996). Study area is located in the central kopeh dagh north of Bojnurd city (Fig. 1). The morphotectonic evaluations confirm that the structural elements like (fold and fault) are the main controlling factors of the geomorphology of the region. According to geological map of Yekehshakh basin alluvial deposit is highly concentrated in central part (Fig. 2).

The 1997 February 4 (10:37am GMT (Greenwich Mean Time)) earthquake of Mw 6.4 near Bojnurd was the biggest earthquake to occur in the Kopeh Dagh in the last 50 yr (Hollingsworth, 2006). The epicentral region was 30 km north of Bojnurd (Fig. 3). It was preceded by a foreshock of Mw 5.4 at 09:53 am GMT. The villages of Naveh, Yekehshakh, Qezelqan, and Sheikh were completely destroyed on earthquake, Field view of sheikh village which was destroyed during the Bojnurd earthquake shows in Fig. 4. Rose diagram of study area shows that main orientation of fault lines is NW-SE. Focal Mechanism of 1997 Bojnurd earthquake mainshock is shown in Fig. 3, Body-wave analysis for the main shock indicates a strike-slip fault, with a small vertical displacement (strike: 326◦, dip: 75◦, rake: 173◦) (Fig. 5) and centroid depth of 8 km (Jackson *et al*. 2002). The teleseismic epicentre is shown in Fig. 3, and is slightly west of the region of surface rupture of the 1997 earthquake (Hollingsworth, 2006).

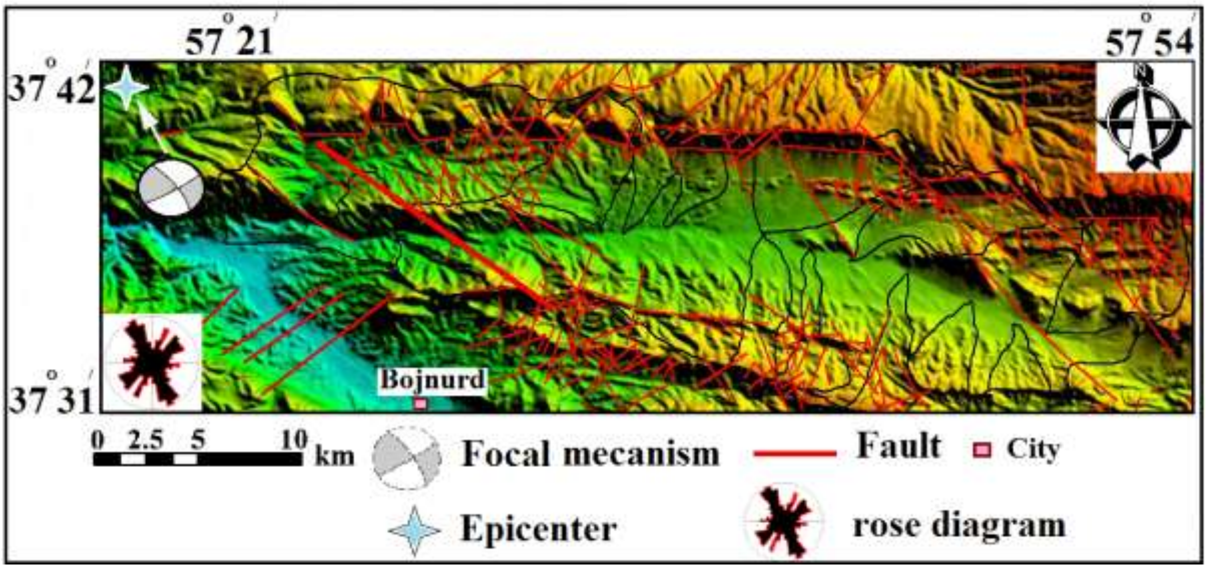

Figure 3) Lineament extracted of study area, the heavy line shows the mapped surface rupture of the 1997 earthquake.

Figure 4) West part of this image is field view of sheikh village which was destroyed during the Bojnurd earthquake and east part of this image is field view of reconstructed sheikh village.

Figure 5) Field view of fault responsible of the 1997 Bojnurd's earthquake.

3- Material and methods

The indices represent a quantitative approach to differential geomorphic analysis related to erosion and depositional processes that include the river channel, long profile, and valley morphology as well as tectonically derived features, such as fault scarps. Indices of active tectonics may detect anomalies in the fluvial system or along mountain fronts. These anomalies may be produced by local changes from tectonic activity resulting from uplift or subsidence (El Hamdouni *et al*., 2008). In this research, in order to evaluate rate of tectonic activity morphometric indices such as ratio of valley floor width to valley height (Vf), stream length-gradient index (SL), transverse topographic system (T), hypsometric integral (Hi), drainage basin shape (Bs) and sinuosity (S) in Yekehshakh basin were calculated.

3.1- Ratio of Valley Floor Width to Valley Height (Vf)

Ratio of valley floor width to valley height (Vf) is defined as the ratio of the width of the valley floor to its average height (Bull and McFadden, 1977; Bull, 1978) and is computed by equation (1):

Vf = 2 valley floor width / [(elevation of left side divide – elevation of the valley floor average)] + (elevation of right side divide – elevation of the valley floor average)] (1)

Where ratio of valley floor width to valley height (Vf) is the ratio of valley floor width to valley height; valley floor width (Vfw) is the width of the valley floor; elevation of left side divide (Eld) is the elevation of the divide on the left side of the valley; elevation of right side divide (Erd) is the elevation on the right side; and elevation of the valley floor average (Esc) is the average elevation of the valley floor. This index differentiates between valleys with a wide floor relative to the height of valley walls with a U shape compared to narrow, steep valleys with a V shape. Valleys with a U shape generally have high values of Vf, whereas V-shaped valleys with relatively low values (Bull and McFadden, 1977). Because uplift is associated with incision, the index is thought to be a surrogate for active tectonics where low values of ratio of valley floor width to valley height (Vf) are associated with higher rates of uplift and incision. The index is a measure of incision and not uplift; but in an equilibrium state, incision and uplift are nearly matched (Keller and Pinter, 2002).

3.2- Stream Length-gradient Index (SL)

Development of topography results from an adjustment between processes of erosion such as streams and rivers flow over rocks and soils of variable strength (Hack, 1973). The adjustment eventually reaches a dynamic equilibrium. The stream length-gradient index was defined by Hack (1973) in a study of the role of rock resistance in streams of the Appalachian Mountains of the southeastern United States. The SL index is computed by equation (2):

$$SL = (\Delta h/\Delta l)l \quad (2)$$

Where $\Delta h/\Delta l$ is the local slope of the channel segment being evaluated and l is the channel length from the divide to the midpoint of the channel reach for which the index is calculated. The stream length-gradient index can be used to evaluate relative tectonic activity. The stream length-gradient index will increase in value as rivers and streams flow over active uplifts and may have lesser values when flowing parallel to features such as valleys produced by strike–slip faulting (Keller and Pinter, 2002).

3.3- Hypsometric Integral (Hi)

The hypsometric integral (Hi) is an index that describes the distribution of elevation of a given area of a landscape (Strahler, 1952). The integral is generally derived for a particular drainage basin and is an index that is independent of basin area. The index is defined as the area below the hypsometric curve and thus expresses the volume of a basin that has not been eroded. A simple way to calculate the Hi index is using equation (3) (Pike and Wilson, 1971; Keller and Pinter, 2002):

Hi = (average elevation – min. elevation) / (max. elevation – min. elevation) (3)

The values of elevation necessary for the calculation are obtained from a digital elevation model. The average elevation is from 50 points (Keller and Pinter, 2002) of elevation taken at random from the drainage basin. The hypsometric integral does not relate directly to relative active tectonics. This index is similar to the stream length-gradient index in that rock resistance as well as other factors affects the value.

3.4- Transverse topographic symmetry factor (T)

The transverse topographic symmetry factor is a method that evaluates the amount of asymmetry of a river within a basin and the variation of this asymmetry in different segments of valley. The basin midline would be the location of a river that is symmetrically placed with regard to the basin divide. It is calculated regarding the larger axis of the basin. For each segment, transverse topographic symmetry factor is the ratio of the distance from the basin midline to the active meander-belt midline (Da) and to the basin divide (Dd). The transverse topographic symmetry factor is defined by equation (4):

$$T = Da/Dd \qquad (4)$$

This value varies between 0 and 1, which represent the minimum and maximum asymmetry of a segment, respectively. It can be represented as a tow-dimensional vector with a length equivalent to Da/Dd and a direction perpendicular to the segment with regard to the basin midline (Salvany, 2004).

3.5- Index of Drainage Basin Shape (Bs)

Relatively young drainage basins in active tectonic areas tend to be elongated in shape normal to the topographic slope of a mountain. With continued evolution or less active tectonic processes, the elongated shape tends to evolve to a more circular shape (Bull and McFadden, 1977). Horizontal projection of basin shape may be described by the elongation ratio, Bs (Ramirez-Herrera, 1998) expressed by the equation (5):

$$Bs = Bl / Bw \qquad (5)$$

Where Bl is the length of the basin measured from the headwaters to the mouth, and Bw is the width of the basin measured at its widest point. High values of Bs are associated with elongated basins, generally associated with relatively higher tectonic activity. Low values of Bs indicate a more circular-shaped basin, generally associated with low tectonic activity. Rapidly uplifted mountain fronts generally produce elongated, steep basins; and when tectonic activity is diminished or ceases, widening of the basins occur from the mountain front up (Ramirez-Herrera, 1998).

3.6- Sinuosity (S)

Even small amounts of deformation can change the sinuosity of a meandering river. The sinuosity is computed by equation (6):

$$S = C/V \qquad (6)$$

C is channel length and Vis valley length, in the conceptual framework of a graded system rivers meander in order to maintain a channel slope in equilibrium with discharge and sediment load.

Table 1) Geomorphic indices classifications used in this study (EL Hamdouni et al., 2008).

Class	Vf	SL	Bs
1	< 0.5	SL≥500	(Bs≥٤)
2	0.5 - 1	300≤SL<500	(٣<Bs<٤)
3	> 1	SL<300	(Bs≤٣)

Any tectonic deformation that changes the slope of a river valley results in a corresponding change in sinuosity to maintain the equilibrium channel slope. A secondary effect of this adjustment is that, as a river switches from one sinuosity to another, the rates of meander migration and floodplain reworking accelerate accordingly; this secondary effect itself has proved to be a diagnostic tool in identifying areas of active tectonic (Hack, 1973). The classification used in this paper for each geomorphic index is based upon EL Hamdouni *et al*. (2008) (Table 1).

4- Results and Discussion

In this study, we have used 1: 25,000 topographic maps with 50 m contour intervals. This projection was the UTM (Universal Transverse Mercator) zone 40 N. The Yekehshakh drainage basin of the Central kopeh dagh in northern khorasan has an area about 602.15 km^2, and a length and width, 47.96 km and 17.81 km respectively (Fig. 6).

Table 2) Classification of the geomorphic indices in the subbasins of the Yekehshakh basin (Vf: ratio of valley floor width to valley height; SL: stream length gradient index; Bs: index of drainage basin shape).

Sub basin	Vf	Vf class	T	S	Bs	Bs class
1	1.04	3	0.33	1.26	1.97	3
2	1.2	3	0.34	1.14	2.26	3
3	1.5	3	0.24	1.24	2.2	3
4	0.68	2	0.46	1.08	2.85	3
5	0.62	2	0.40	1.2	6.36	1
6	0.39	1	0.25	1.15	2.19	3
7	0.32	1	0.68	1.09	2.18	3
8	0.47	1	0.66	1.1	2.26	3
9	4.84	3	0.32	1.04	3.89	2
10	3.49	3	0.34	1.14	4.02	1
11	3.03	3	0.33	1.09	3.53	2
12	1.79	3	0.05	1.18	2.9	3
13	1.52	3	0.05	1.1	2.6	3

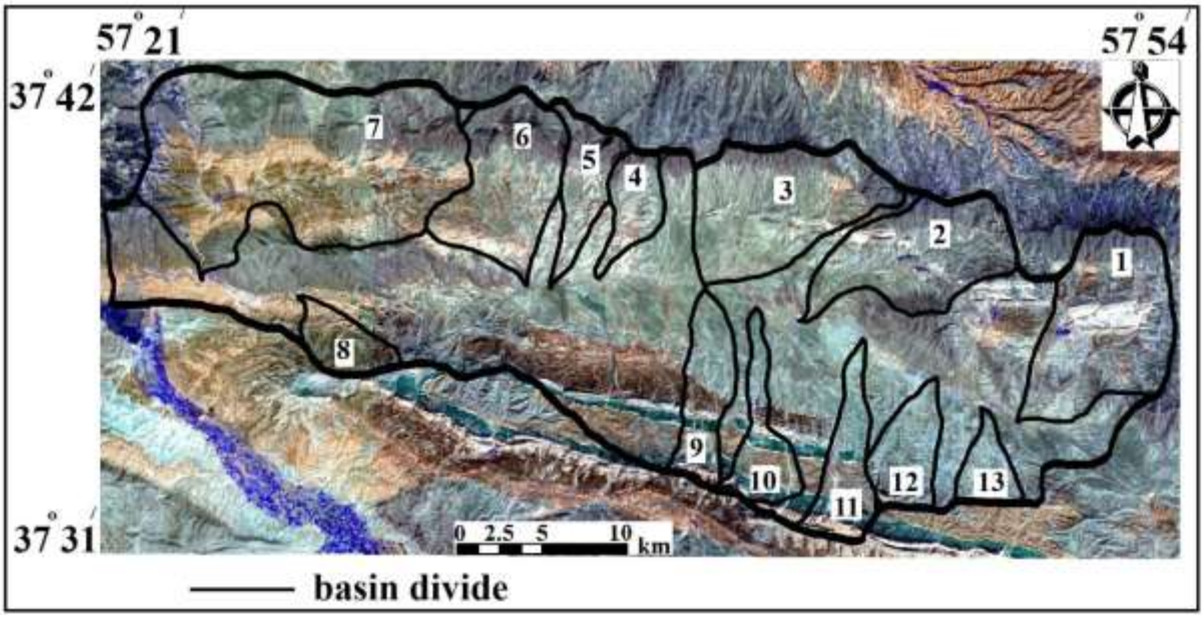

Figure 6) Aster image of study area, and referenced number sub basins of study area.

For calculation of Vf, 3 to 6 ordered rivers was calcified and pointed, Vf index was calculate for each point. Numbers from the calculation of valley floor area to valley height Vf were contoured and Vf index map were drawn. Values of Vf vary from a low of 0.2 for the west part of Yekehshakh basin, where it is deeply incised into hard bedrock, to a high of 3.6 at east part of Yekehshakh basin (Fig. 7). In general, the values of Vf are relatively high in east part of study area. Therefore, values of Vf should be compared for similar geologic conditions. Values of Vf for the study area are shown in Table 2. Classification of the index is based upon the Hamdouni *et al*., 2008. In general, the values of Vf are relatively high for most of the study area (Fig. 8), with the exception of the lower amount in western part of Yekehshakh basin.

In this study the SL index was calculated by placing topographic maps and river of the region in GIS software then calculated values were contoured and its map was drawn. A map of SL index was created using values for all segments on stream channels crossing the 50 m contours on the1: 25,000 topographic maps (Fig. 9). Values of the SL index over the study area, determined from digital elevation models and geographic information system (GIS), according to EL Hamdouni *et al* 2008. SL indices were calculated on stream segments between the 50 m contour lines. Four SL categories were distinguished: 0-300, 300-500, 500-950 and 950-1550. Low value of Vf index and high value of SL index is related to western part of Yekehshakh basin. Based upon the quantitative SL index linked to relative rock resistance (geology map) described with field observations suggest that: on the western part of the study area high indices are associated with particularly resistant rocks (Fig. 10).

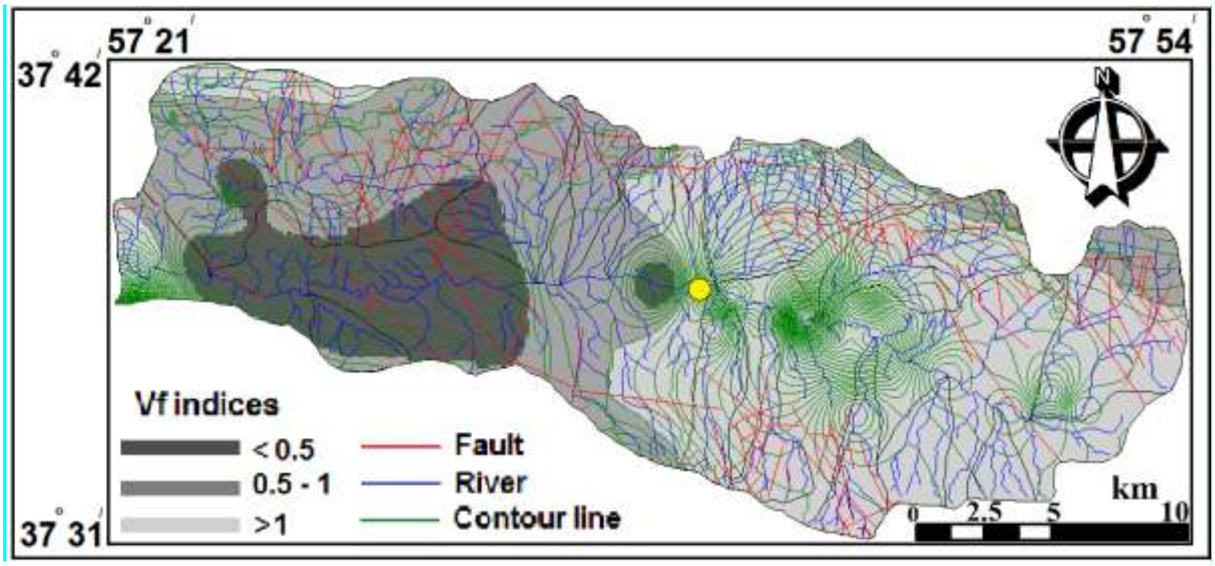

Figure 7) Ratio of valley floor width to valley height for the study, yellow circle is the location of figure 8.

Figure 8) Field view of U shape valley in central part of study area.

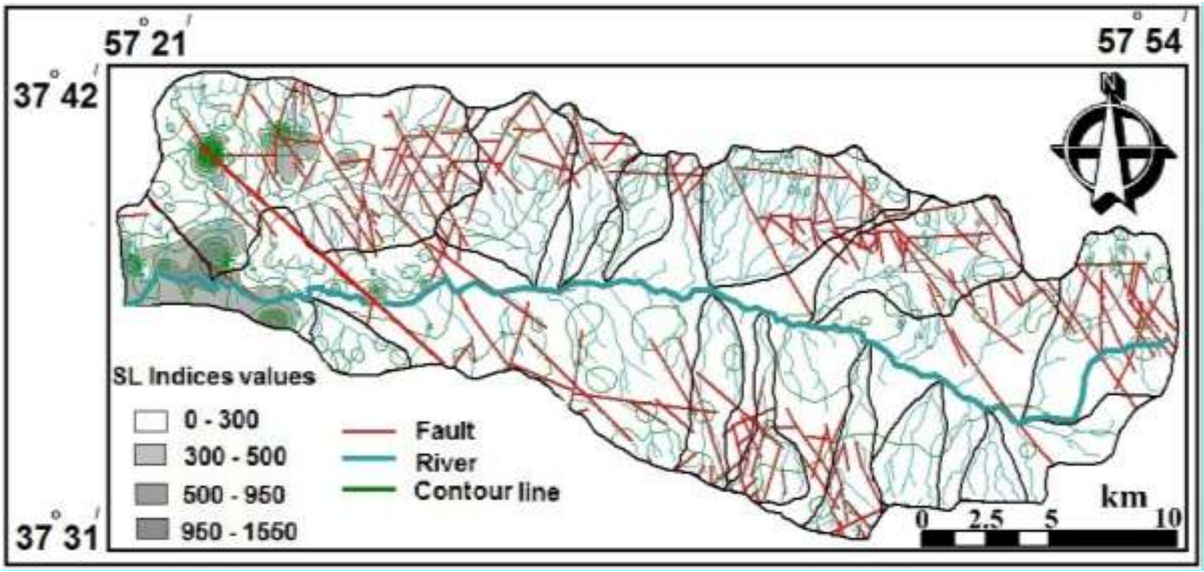

Figure 9) Map of Stream length- gradient (SL) index for the study area.

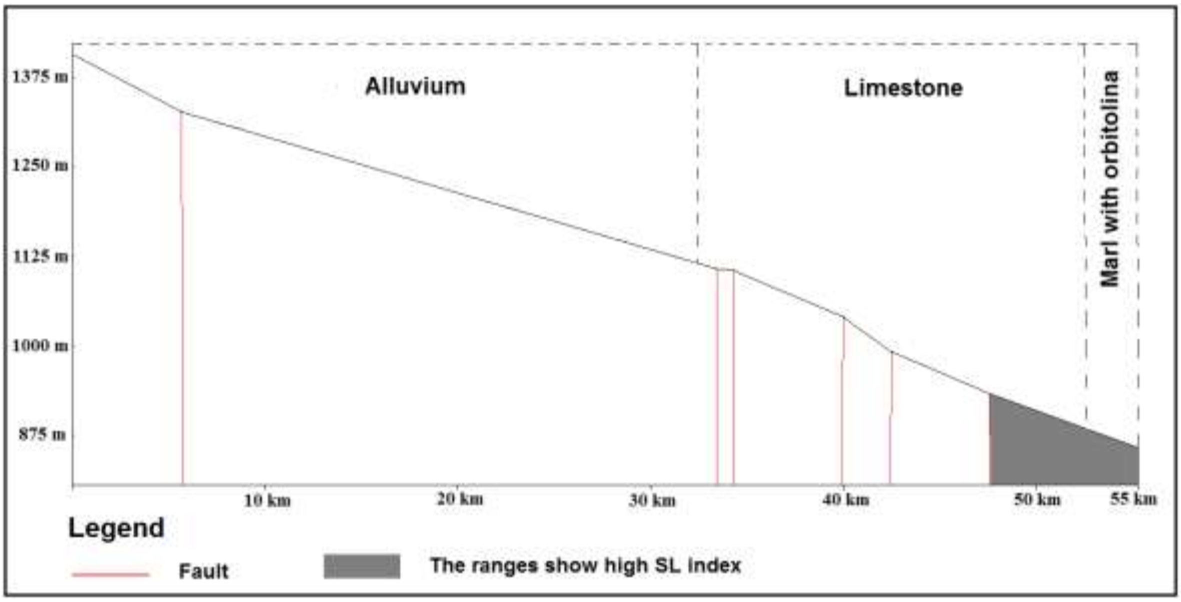

Figure 10) Longitudinal rivers profile of Yekehshakh basin is belonging to heavy blue river in figure 9 that showing the relationship between the slope and the bedrock lithology.

High values of Hi index are possibly related to young active tectonic and low values are related to older landscapes that have been more eroded and less impacted by recent active tectonics (El Hamdouni *et al*., 2008). In general, high values of the Hi are convex, and these values are generally > 0.55. Intermediate values tend to be more concave–convex or straight, and generally have values between 0.45 and 0.55. Finally, lower values (< 0.45) tend to have concave shapes. Analysis of the Hi in the study area was based upon digital elevation models utilizing GIS applications, Results are shown on figure 11. Main basin is in mature stage caused by intermediate values of Hi index is concentrating alluvial deposits in middle side of study area. Reason of high values of the Hi index in western part of study area is concentrating high resistance rock in this part of study area.

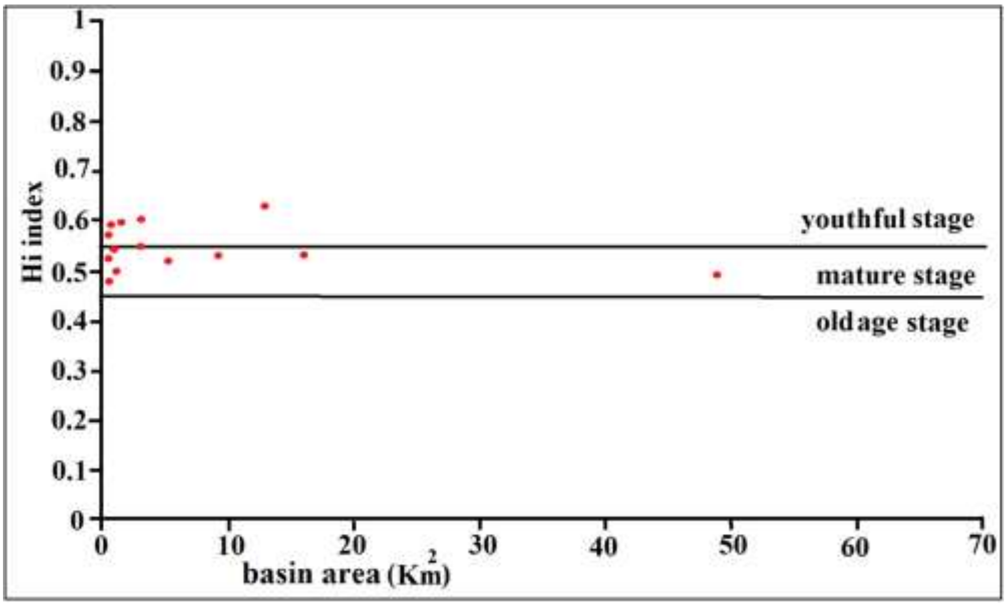

Figure 11) Hypsometric integral of the Yekehshakh basin and its sub basins.

The transverse topographic symmetric factor (T) applied in these research. Existing anticline at the north side of study area caused river tilting toward S (Fig. 12). Calculated morphometric indices for Yekehshakh basin's show that, value of T index is 0.25 and direction of tilting is toward S. It seems that folds and trusts parallel to the basin caused such tilting. In central part of dringe basin because of high concentration alluvial deposites and low rivers tilting values of T index is near to 0.

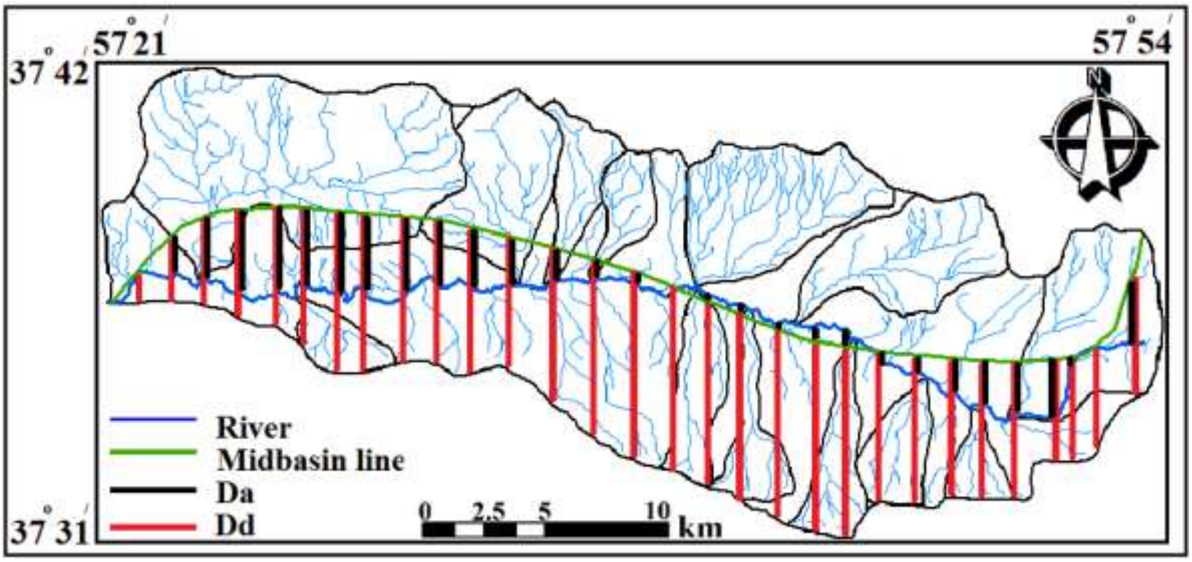

Figure 12) Transverse topographic symmetry factor for the study area.

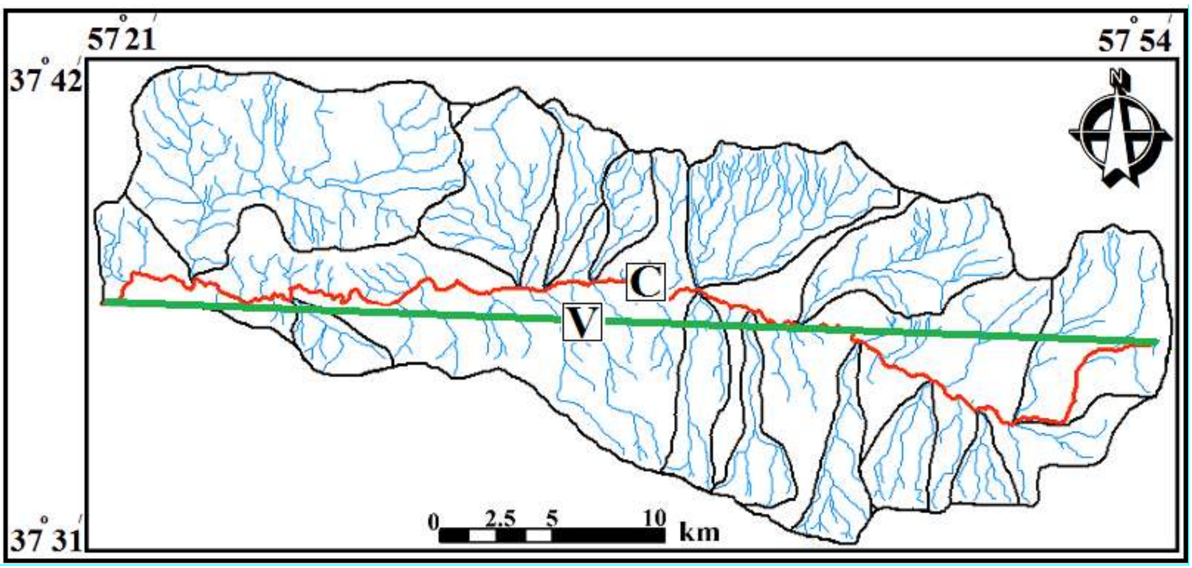

Figure 13) Map of S index in study area.

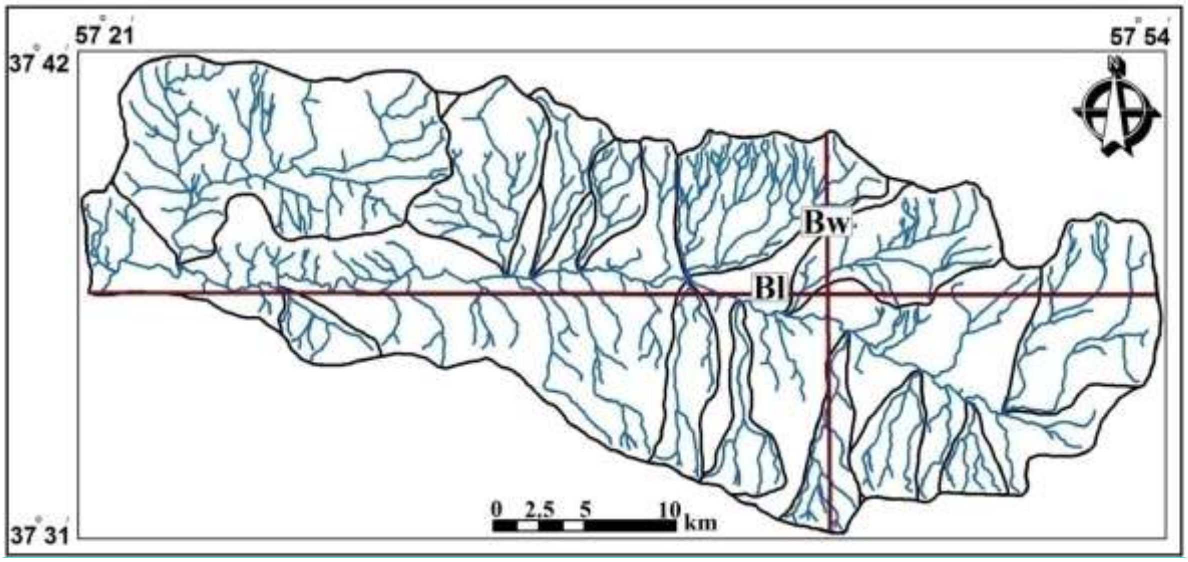

Fig 14. Index of Drainage Basin Shape (Bs) for the study area.

Values of Sinuosity (S) index in Yekehshakh basin is 1.22 and show high tectonic activity in study area (Fig. 13). Amount of (S) index in western subbasin is near to 1, in high tectonically active area values of (S) index is near to 1. Bs was calculated for main basin and 13 subbasins of study area. The results are shown in Table 2 and values range from 1. 97 to 6.36. The highest values are along the S border of the Yekehshakh basin. Bs index in main basin is 2.69 (Fig. 14), low values of Bs index is associated with low tectonic activity and low uplifting in central and east part of study area.

4- Conclusions

The values of morphometric indices including ratio of valley floor width to valley height (Vf), stream length-gradient index (SL), transverse topographic system (T), hypsometric integral (Hi), drainage basin shape (Bs) and sinuosity (S) compared with extracted lineament and geological map. Most valleys in east part of study area are U shape, U shape valleys in east part of study area are associated with low rate of incision in this part of study area, and V shape valleys in west part of study area are associated with high rate of incision and tectonic uplift. Calculating transverse topographic system index shows that tilting direction has changed along main river by differentiation of tectonic activity in Yekesheikh basin. The data are consistent with S tilting where the orientations of folds are parallel to main river. On the contrary, tectonics seems to explain the stream migration reasonably. Calculating all indices show that, the west part of Yekesheikh basin is more active than east side. West side of this basin is coincide with location of 1997 Bojnurd earthquak's. Result of this research shows that rate of tectonic activity in west part of study area is more than east part.

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