

# Tectonic geomorphology of High Zagros Ranges, SW Iran: an initiative towards seismic hazard assessment

Ali Faghih<sup>1</sup> · Akbar Esmailzadeh Soudejani<sup>1</sup> · Ahmad Nourbakhsh<sup>1</sup> · Sara Rokni<sup>1</sup>

Received: 10 August 2014 / Accepted: 21 March 2015 / Published online: 28 March 2015  
© Springer-Verlag Berlin Heidelberg 2015

**Abstract** The High Zagros Ranges, SW Iran is considered to be tectonically active where damaging earthquakes have occurred. These ranges were uplifted by approximately 4550 m with respect to sea level following the collision between the Afro-Arabian and Central-Iranian plates. The Plio-Quaternary active tectonics was assessed through a detailed quantitative geomorphological study of fault-generated mountain fronts and alluvial/fluviol systems of the High Zagros Ranges. Quantitative measurement of geomorphological indices such as the stream-gradient index (SL), drainage basin asymmetry (Af), hypsometric integral (Hi), valley floor width–valley height ratio (Vf), drainage basin shape (Bs), and mountain-front sinuosity (Smf) and field data suggests a relatively medium to high degree of tectonic activity along the High Zagros Ranges. The obtained results from these indices were combined to yield an index of active tectonics (Iat). The indicative values of this index are consistent with the landforms and geology of the study area. The Iat is low to moderate in northern part of the study area which corresponds to the inactive Main Zagros Reverse Fault. The high values of Iat mainly occur in southern parts of the study area where straight mountain fronts and triangular facets along the Dena Fault suggest high tectonic activity. Moreover, the data plotted for earthquakes occurrences are consistent with morphotectonic map of relative tectonic activity and can be used as an initiative towards seismic hazard assessment. Most of the major faults are considered to be active and have potential to generate large earthquake in

future and need to be evaluated more carefully for the regional seismic hazard.

**Keywords** Geomorphological indices · Active tectonics · Earthquake · Zagros · Iran

## Introduction

Tectonic geomorphology investigations are important because the results of regional studies on neotectonics are significant to assessment natural hazards in populated areas (Cloetingh et al. 2006; Gomes et al. 2007; Pedrera et al. 2009; Rockwell et al. 2009a; Pérez-Peña et al. 2010; Mahmood and Gloaguen 2011). In geomorphological sense, natural hazards must be regarded as the suite of threats to human resources arising from instability of the surface features of the Earth. The threat arises from landform response to surficial processes, although the initiating processes may originate at great distances from the surface (Gares et al. 1994). Geomorphological hazards can be categorized as endogenous (volcanism, earthquake and neotectonics), exogenous (floods, karst collapse, snow avalanche, channel erosion, sedimentation, mass movement, tsunamis, coastal erosion), and those induced by climate and land-use change (e.g., desertification, permafrost, degradation, soil erosion, salinization, floods) (Slaymaker 1996; Alcántara-Ayala 2002). Geomorphological hazards would generally have slower speed of onset, longer duration, more widespread areal extent, more diffuse spatial dispersion and more regular temporal spacing (Gares et al. 1994).

Recent and active tectonic structures may affect the topographic surface, interacting with geomorphological processes during landscape evolution. Geomorphological indices are indicators capable of detecting landform

✉ Ali Faghih  
afaghih@shirazu.ac.ir

<sup>1</sup> Department for Earth Sciences, College of Sciences, Shiraz University, Shiraz, Iran

responses to recent deformation processes and, therefore, have been broadly used as a recognition tool to characterize sectors deformed by active faults (Pedrera et al. 2009). The analysis of tectonic activity has been used as a key element for seismic hazard assessment (Galadini and Galli 2000), and such earthquake assessment has also been applied to environmental planning (Panizza 1981).

The application of digital elevation data through geographical information systems (GIS) is a powerful approach in geomorphological analysis of landscapes, since the ability to create, manipulate, store, and use spatial data much faster and at a rapid rate, with both operational and quality advantages. Moreover, it made the quantitative approach for surface characterization and the mechanism for the interpretation and manipulation of the quantitative data sets easy. The coupling of Digital Elevation Models (DEMs) and GIS enables the extraction essential derivatives of DEM for geomorphometric analysis, which is offered by standard GIS platforms (Kamberis et al. 2012; Thomas et al. 2012; Bathrellos et al. 2013; Viececi et al. 2014; Faghih and Nourbakhsh 2015).

Geomorphological studies of active tectonics in the late Pleistocene and Holocene are important to evaluate earthquake hazards in tectonically active areas such as the Zagros (Keller and Pinter 2002). The landforms and geology of the Zagros Mountains in southwest Iran such as fault scarps, triangular facets, truncated folds, and Quaternary deposits along folded/faulted mountain fronts reflect recent tectonics (Ramsey et al. 2008; Dehbozorgi et al. 2010; Bretis et al. 2011; Bahrami 2012, 2013; Faghih et al. 2012; Faghih and Nourbakhsh 2014). Despite the large number of indices proposed by various workers, often for different purposes and in different geographical areas and scientific disciplines, relatively few aspects of basin forms are measured by available indices (Migiros et al. 2011; Bali et al. 2012). Considering the diversity of the geomorphological features, six geomorphological indices: the stream-gradient index (SL), drainage basin asymmetry (Af), hypsometric integral (Hi), valley floor width–valley height ratio (Vf), drainage basin shape (Bs), and mountain-front sinuosity (Smf) were analyzed. The applied quantitative analysis of geomorphological indices combined with GIS methodologies allows producing maps showing relative tectonic activity of landscapes.

Since natural hazards must be regarded as the suite of threats to human resources arising from instability of the surface features of the Earth, the purpose of this work is to assess the level of seismic activity in the High Zagros Ranges by studying the effects of tectonic deformation on the landscape. To reach this goal, a quantitative geomorphological analysis was applied to evaluate relative rates of active tectonics in the High Zagros Ranges.

## Regional tectonic and geomorphological settings

The NW-trending Zagros Fold-Thrust Belt, one of the ranges of the Alpine-Himalayan Belt, extends for about 1800 km from East Anatolian Fault in north eastern Turkey to the Strait of Hormuz where the north trending Zendan-Minab-Palami Fault System separates the Zagros Belt from the Makran accretionary prism (Yaminifard et al. 2012). These ranges are formed by closure of the Neo-Tethys Ocean and then continental collision, starting in the Miocene between the Arabian plate and central Iran (McQuarrie et al. 2003; Yaminifard et al. 2012).

The northeastern boundary of the belt is marked by the suture zone that coincides with ophiolite complexes (e.g., Neyriz and Kermanshah ophiolites) and a major thrust, the Main Zagros Reverse Fault (MZRF), which is presently inactive (Stöcklin 1974; Stoneley 1981; Berberian 1995). The present-day deformation appears to be concentrated near the 1000 m elevation contour, supporting a thick-skinned model of southwestward propagation of deformation, starting from the Main Zagros Reverse Fault (Hatzfeld et al. 2010).

The High Zagros Ranges (or imbricate belt) is a narrow thrust belt up to 80 km wide, with an NW–SE trend between the MZRF to the northeast and the High Zagros Fault (HZF) to the southwest. The High Zagros Ranges is strongly dissected by numerous reverse faults and is up-thrusted to the southwest along different segments of the HZF. That major fault zone separates the thrust belt of the High Zagros in the northeast from the Simple Fold Belt in the southwest (Berberian and King 1981; Berberian 1995). In this part of the orogen, several thrust sheets expose Palaeozoic strata, indicating the accommodation of large displacements at the origin of the highest topography in the region. In the NW Zagros, the MZRF is cut by the Main Recent Fault (MRF) a major active strike-slip fault partitioning the N–S convergence into an NW–SE right-lateral strike-slip and NE–SW shortening.

The Main Recent Fault (MRF) is one of the major right-lateral faults of the Middle East collision belt, which stretches from easternmost Anatolia parallel to the Zagros suture zone (Talebian and Jackson 2002). The transition from oblique (western Zagros) to pure shortening (eastern Zagros) occurs in the vicinity of the junction between two major right-lateral strike-slip faults of the Middle-East collision belt and MZRF. The N-trending Kazerun Fault (KF) cuts across the entire width of the belt (Authemayou et al. 2009). The displacement accommodated along the MRF is currently being transferred in the central Zagros in N–S active right-lateral transpressional faults such as KF (Authemayou et al. 2005, 2006, 2009; Lacombe et al. 2006; Talebian and Jackson 2004). The study area is located at

the High Zagros Ranges where these three important crustal-deep faults (i.e., MZRF, HZF and KF) are linked together (Fig. 1).

**Materials and methods**

Geomorphological indices are useful tools for studying active tectonics because they provide rapid insights into specific area or sites in the study area that are adjusting to relatively rapid rate of active tectonic deformation (e.g., Bull and McFadden 1977; Rockwell et al. 1985, 2009a, b; Keller 1986; Ramirez-Herrera 1998; Silva et al. 2003). In this work, six geomorphological indices were used to evaluate relative tectonic activity in a large area in the High Zagros Ranges.

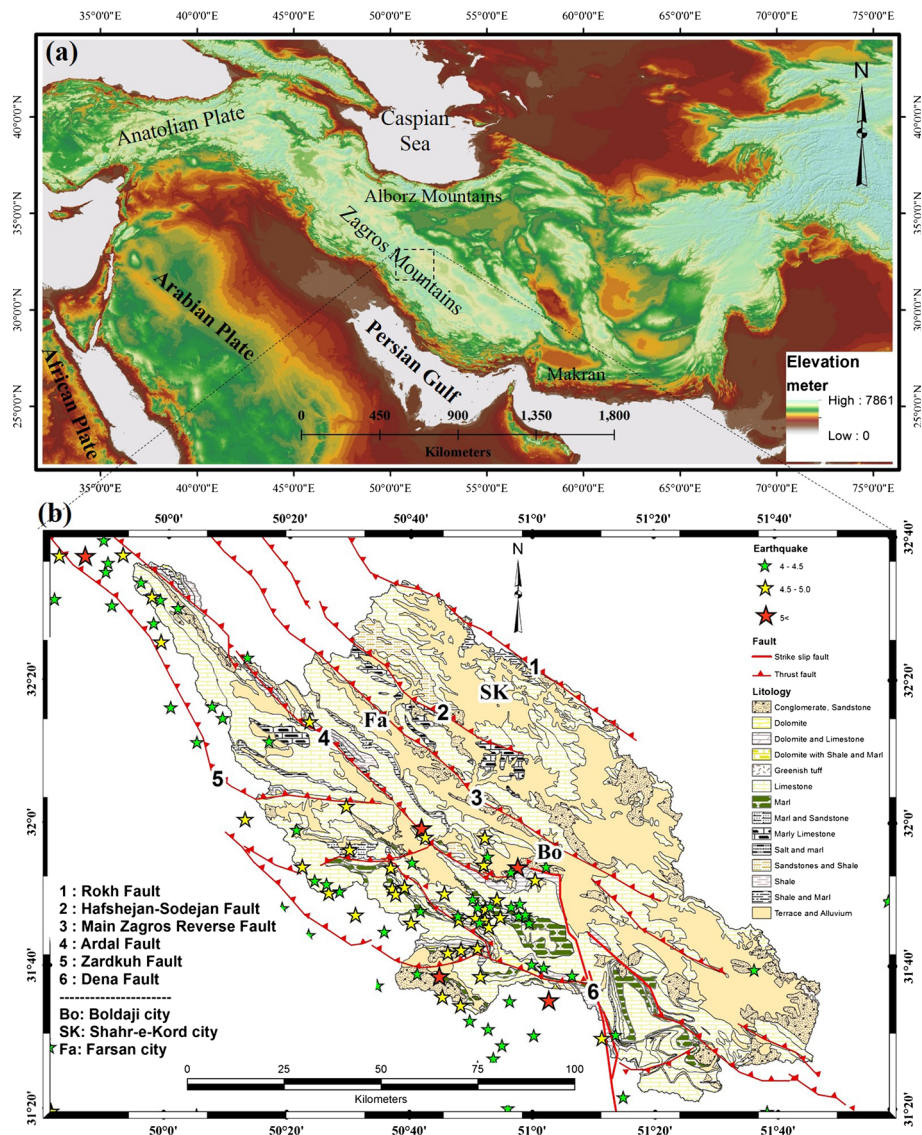
**Mountain-front sinuosity**

Mountain-front sinuosity is the ratio of the distance along the mountain front at the mountain-front piedmont intersection over the straight line distance of the same mountain front (Bull and McFadden 1977). This index is defined by.

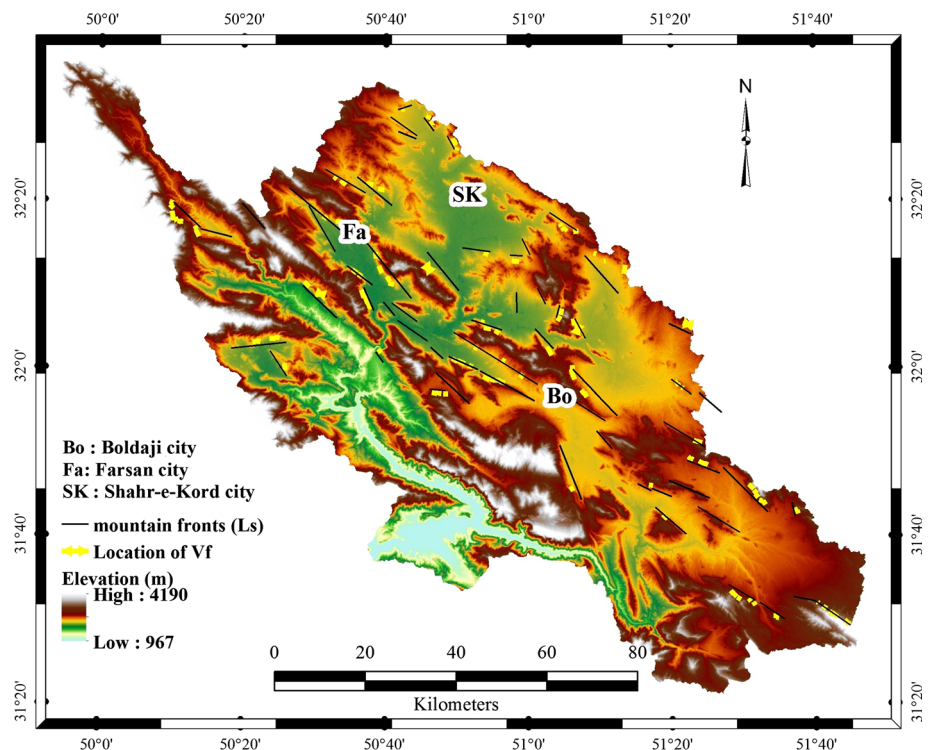
$$Smf = L_{mf}/L_s$$

where  $L_{mf}$  is the length of the mountain front along the foot of the mountain where a change in slope from the mountain to the piedmont occurs and  $L_s$  is the straightline length of the mountain front (Fig. 2).  $Smf$  represents a balance between erosive processes tending to erode a mountain front, making it more sinuous through streams that cut laterally and into the front and active vertical tectonics that tend to produce straight mountain fronts, often coincidental with

**Fig. 1** a Geographical position of the study area is marked by the black quadrangle within the Zagros Mountains and b geological map of the study area



**Fig. 2** Location of measured Smf and Vf indices is represented on the hillshade image of the study area



active faults or folds (Bull and McFadden 1977; Keller 1986). The mountain fronts associated with active tectonics and active uplift are relatively straight with low values of Smf. When the rate of uplift is reduced, the erosional processes along the mountain front produce a more sinuous front and thus higher value of Smf. Values of Smf approach 1.0 on the most tectonically active fronts, whereas Smf increases if the rate of uplift is reduced and erosional processes begin to form a front that becomes more irregular with time (Bull and McFadden 1977; Rockwell et al. 1985; Keller 1986).

### Stream-gradient index (SL)

Rivers flowing over rocks and soils of various strengths tend to reach equilibrium with specific longitudinal profiles and hydraulic geometries (Hack 1973; Bull 2007). Hack (1957, 1973, 1982) defined the stream-gradient index (SL) to discuss influences of environmental variables on longitudinal stream profiles, and to test whether streams has reached an equilibrium. The SL is defined as:

$$SL = (\Delta H / \Delta L_r \times L_{sc})$$

where  $\Delta H$  is change in altitude,  $\Delta L_r$  is length of a reach, and  $L_{sc}$  is the horizontal length from the watershed divide to midpoint of the reach. The SL index can be used to evaluate relative tectonic activity (Keller and Pinter 2002; Lee and Tsai 2010). Although an area on soft rocks with

high SL values indicates recent tectonic activity, anomalously low values of SL may also represent such activity when rivers and streams flow through strike-slip faults. The SL along the rivers was calculated using a digital elevation model and computed its average value for each sub-basin.

### Hypsometric integral (Hi)

The hypsometric integral 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 simple equation that may be used to calculate the index (Pike and Wilson 1971; Mayer 1990; Keller and Pinter 2002) is

$$Hi = (\text{average elevation} - \text{min elevation}) / (\text{max elevation} - \text{min elevation})$$

The values of elevation necessary for the calculation are obtained from a digital elevation model. The average elevation is from 50 points 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 SL index in that rock resistance, as well as other factors, affects the value. High values of the 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.

## Basin shape index (Bs)

The horizontal projection of a basin may be described by the basin shape index or the elongation ratio, Bs which defined as (Cannon 1976; Ramirez-Herrera 1998):

$$Bs = Bl/Bw$$

where Bl is the length of a basin measured from the highest point, and Bw is the width of a basin measured at its widest point. Relatively young drainage basins in tectonically active areas tend to be elongated in shape, normal to the topographic slope of a mountain (Bull and McFadden 1977; Ramirez-Herrera 1998). With continued evolution or less active tectonic processes, the elongated shape tends to evolve to a more circular shape (Bull and McFadden 1977). 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 (Ramirez-Herrera 1998).

## The ratio of valley floor width to valley height (Vf)

The Vf is defined as the ratio of the width of the valley floor to its average height (Bull and McFadden 1977; Bull 1978) and defined as:

$$Vf = 2V_{fw}/[(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})]$$

where Vf is the ratio of valley floor width to valley height;  $E_{ld}$  and  $E_{rd}$  are the elevations of the left and right sides of the valley, respectively;  $E_{sc}$  is the average elevation of the valley floor; and  $V_{fw}$  is the width of the valley floor. Generally, V- (steep) and U-shaped (wide) valleys show high and low values of the Vf indexes, respectively. Because uplift is associated with incision, the Vf index is thought to be a substitute for active tectonics where low values of this index are associated with higher rates of uplift and incision. The calculation of the index is done at a prescribed distance upstream from the mountain front (Silva et al. 2003) (Fig. 2). In general, values of Vf depend on basin size, stream discharge, and lithology of valleys.

## Asymmetry factor (AF)

The asymmetry factor (AF) is a way to evaluate the existence of tectonic tilting at the scale of a drainage basin. The method may be applied over a relatively large area (Hare and Gardner 1985). AF is defined by

$$AF = (A_r/A_t) \times 100$$

where  $A_r$  is the area of the basin to the right (looking downstream) of the stream trunk,  $A_t$  is the total area of the

drainage basin and both were measured in Arc GIS. AF is sensitive to change in inclination perpendicular to the stream direction. AF significantly greater or smaller than 50 shows influence of active tectonic/lithological control or differential erosion, as for example the stream slipping down bedding plains over time (El-Hamdouni et al. 2008). AF is close to 50, if there is no or a little tilting perpendicular to the direction of the trunk channel. In tectonically active topography, the landforms are characterized by relatively steep, mountainous sides and flat floors. The steep sides are created by displacement on faults such that the valley floor moves down relative to the surrounding margins, or, conversely, the margins move up relative to the floor. This movement results in basin tilting and causes the river to migrate latterly and deviate from the basin midline. Also, structural control of the orientation of bedding may play a vital role in the growth of basin asymmetry and tilting of bedding allows for preferred migration of the valley in the down-dip direction, producing an asymmetric valley (Cox 1994).

$$AF = |[ (A_r/A_t) \times 100 ] - 50|$$

The AF-50 value is the amount of difference between the neutral value of 50 and the calculated AF value.

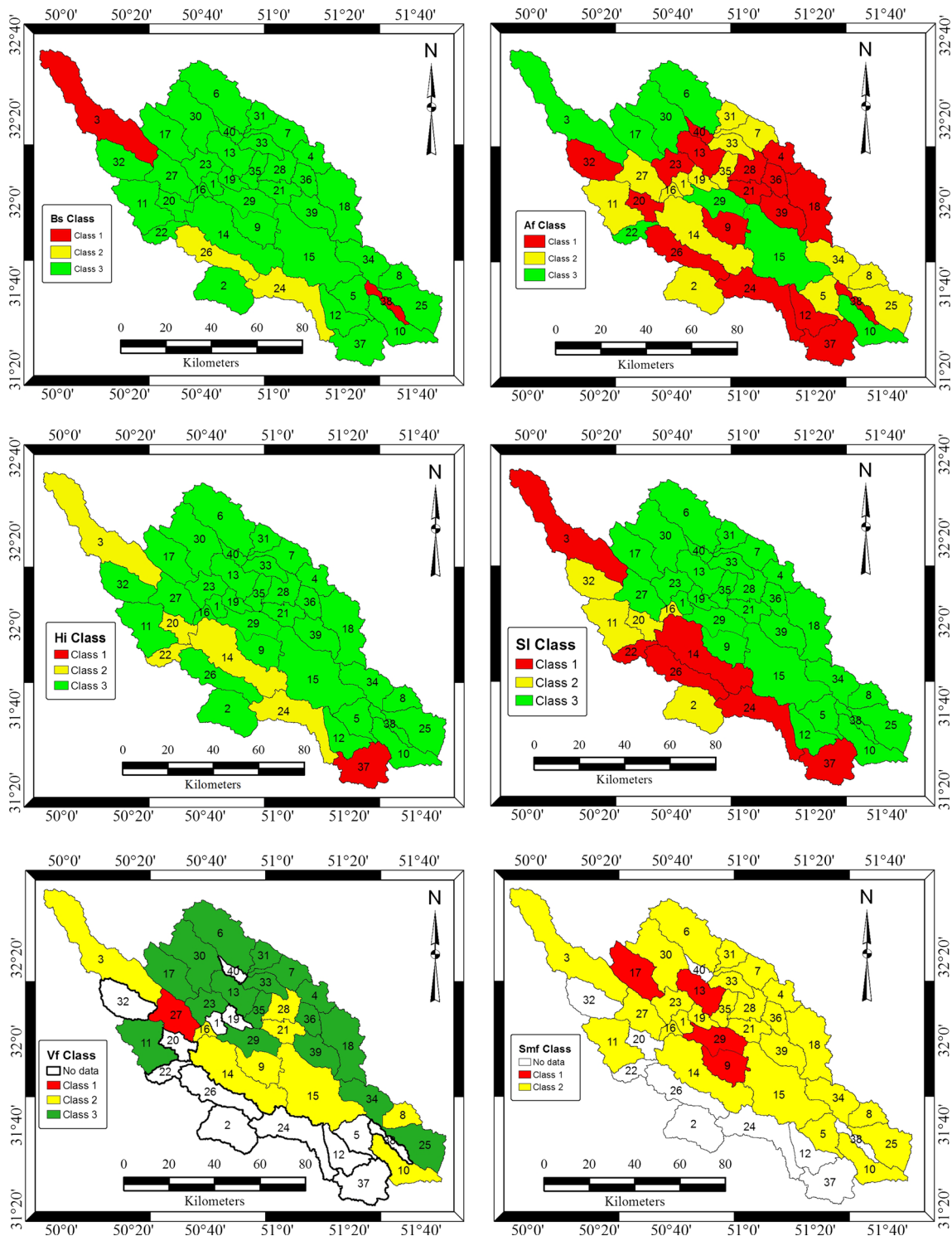
## Results

### Mountain-front sinuosity (Smf)

Some studies have proposed that the lower values of the Smf index (<1.4) are indicative of tectonically active fronts (Keller 1986; El-Hamdouni et al. 2008), while higher Smf values (>3) are normally associated with inactive fronts in which the initial range-front fault may be more than 1 km away from the present erosional front (Bull 2007). The values of Smf were calculated for the 49 mountain fronts using Lmf and Ls values measured from ASTER GDEM elevation model with a spatial resolution of 15 m and divided into three classes: class 1 (1.00–1.1), class 2 (1.1–1.5) and class 3 (>1.5) as shown in Fig. 3 and Table 1.

### Stream-gradient index (SL)

The SL values were computed along streams and rivers using ASTER GDEM V2 (Tachikawa et al. 2011) with spatial resolution of 15 m and GIS techniques and calculated its standardized average value for each sub-basin. The value ranges from 56 (sub-basin 36) to 847 (sub-basin 22). The values were classified into three classes: class 1 (SL > 500), class 2 (300–500) and class 3 (SL < 300) according to El-Hamdouni et al. (2008). The result of the classification is shown in Fig. 3 and Table 1.



**Fig. 3** Classification of sub-basins of the study area based on the measured indices. Stream-gradient index (SL), drainage basin asymmetry (Af), hypsometric integral (Hi), valley floor width–valley height ratio (Vf), drainage basin shape (Bs), and mountain-front sinuosity (Smf)

**Hypsometric integral (Hi)**

The Hi values were computed for each sub-basin. It ranges from 0.16 (sub-basins 36) to 0.52 (sub-basin 37). Then, Hi values were grouped into three classes with respect to the

convexity or concavity of the hypsometric curve: class 1 with convex hypsometric curves ( $Hi > 0.5$ ), class 2 with concave–convex hypsometric curves (0.4–0.5) and class 3 with concave hypsometric curves ( $Hi < 0.4$ ) as shown in Fig. 3 and Table 1.

### Basin shape index (Bs)

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. Therefore, Bs may reflect the rate of active tectonics. The Bs values were computed using the DEM and classified into three classes: class 1 (Bs > 4); class 2 (3–4) and class 3 (Bs < 3). The Bs values range from 1.36 (sub-basin 36) to 5.35 (sub-basin 3). More than two-thirds of the studied sub-basins belong to classes 2 and 3 and are elongated with lower Bs values as compared to class 1 with high Bs values and are nearly circular shapes (Fig. 3; Table 1).

### The ratio of valley floor width to valley height (Vf)

The Vf was calculated for the main valleys that cross mountain fronts of the study area using cross section drawn from the DEM. Then, Vf was classified into three classes: class 1 (Vf < 0.5), class 2 (0.5–1) and class 3 (Vf > 1) as shown in Fig. 3 and Table 1. The range of Vf is from 0.41 (sub-basin 27) to 3.07 (sub-basin 13). Vf is relatively low for V-shaped valleys but high for U-shaped valleys.

### Asymmetry factor (AF)

For the purpose of evaluating the relative active tectonics, the absolute difference is what is important, and values of AF-50 range from 0 (almost symmetric sub-basins 22 and 29) to 30 (highly asymmetric sub-basin 23). AF values were divided into three classes: class 1 (AF > 15), class 2: (7–15) and class 3 (AF < 7) as shown in Fig. 3 and Table 1.

### Discussion

In vulnerable locations, the natural hazards can cause extensive economic damage and loss of human life and property. To avoid these effects, during the planning process, it is necessary for the decision makers, engineers, planners, and managers to take into account the physical parameters of the urban area, as well as the susceptibility to the natural hazards. The geology and the geomorphology of an area are important in the assurance of sustainable land management and in the protection of human life (Bathrellos et al. 2012 and references therein).

Previous studies for the evaluation of relative active tectonics based on geomorphological indices mostly focused on a particular mountain front or small area (Bull and

**Table 1** Classification of the measured indices for the sub-basins of the study area

Basin	Smf	Vf	Hi	Bs	Af	Sl	S/n	Iat	Tectonic activity
1	2	–	3	3	2	3	2.60	4	Low active
2	–	–	3	3	2	2	2.50	3	Moderately active
3	2	2	2	1	3	1	1.83	2	Highly active
4	2	3	3	3	1	3	2.50	3	Moderately active
5	2	–	3	3	2	3	2.60	4	Low active
6	2	3	3	3	3	3	2.83	4	Low active
7	2	3	3	3	2	3	2.67	4	Low active
8	2	2	3	3	2	3	2.50	3	Moderately active
9	1	2	3	3	1	3	2.17	3	Moderately active
10	2	2	3	3	3	3	2.67	4	Low active
11	2	3	3	3	2	2	2.50	3	Moderately active
12	–	–	3	3	1	3	2.50	3	Moderately active
13	1	3	3	3	1	3	2.33	3	Moderately active
14	2	2	2	3	2	1	2.00	2	Highly active
15	2	2	3	3	3	3	2.67	4	Low active
16	2	2	3	3	2	2	2.33	3	Moderately active
17	1	3	3	3	3	3	2.67	4	Low active
18	2	3	3	3	1	3	2.50	3	Moderately active
19	2	–	3	3	2	3	2.60	4	Low active
20	–	–	2	3	1	2	2.00	2	Highly active
21	2	2	3	3	1	3	2.33	3	Moderately active
22	–	–	2	3	3	1	2.25	3	Moderately active
23	2	3	3	3	1	3	2.50	3	Moderately active
24	–	–	2	2	1	1	1.50	1	Very high active
25	2	3	3	3	2	3	2.67	4	Low active
26	–	–	3	2	1	1	1.75	2	Very high active
27	2	1	3	3	2	3	2.33	3	Moderately active
28	2	2	3	3	1	3	2.33	3	Moderately active
29	1	3	3	3	3	3	2.67	4	Low active
30	2	3	3	3	3	3	2.83	4	Low active
31	2	3	3	3	2	3	2.67	4	Low active
32	–	–	3	3	1	2	2.25	3	Moderately active
33	2	3	3	3	2	3	2.67	4	Low active
34	2	3	3	3	2	3	2.67	4	Low active
35	2	3	3	3	2	3	2.67	4	Low active
36	2	3	3	3	1	3	2.50	3	Moderately active
37	–	–	1	3	1	1	1.50	1	Very high active
38	–	–	3	1	1	3	2.00	2	Highly active
39	2	3	3	3	1	3	2.50	3	Moderately active
40	–	–	3	3	1	3	2.50	3	Moderately active

SL Stream-gradient index, Af drainage basin asymmetry, Hi hypsometric integral, Vf valley floor width–valley height ratio, Bs drainage basin shape, Smf mountain-front sinuosity

McFadden 1977; Rockwell et al. 1985; Azor et al. 2002; Silva et al. 2003). Numerous approaches used a combination of two or more than two indices to give semi-quantitative information regarding the relative tectonic activity in

active mountain ranges (Bull and McFadden 1977; Silva et al. 2003; El-Hamdouni et al. 2008; Rockwell et al. 2009a; Dehbozorgi et al. 2010; Mahmood and Gloaguen 2011). This investigation is an attempt to evaluate relative active tectonics in a large area based on several sub-basins and using a number of geomorphological indices. In this study, the data on geomorphological indices were presented that have been used in other studies to evaluate the landscape in terms of potential tectonic activity.

The proposed GIS methodology allows a map showing relative tectonic activity of the landscape to be produced. The average of the values of seven computed indices was combined to yield Iat (index of active tectonics) (El-Hamdouni et al. 2008) and was used to assess the spatial distribution of relative tectonic activity in the study area. Values of Iat would be different, as would the boundaries between classes of relative tectonic activity. However, this methodology would provide an index based on area that estimates relative tectonic activity as it has for the study area in High Zagros Ranges. The values of the Iat were grouped into four classes to define the degree of relative tectonic activity following (El-Hamdouni et al. 2008) as class 1: very high (1.0–1.5); class 2: high (1.5–2); class 3: moderate (2–2.5); and class 4: low (2.5–3) relative tectonic activity, respectively. The distribution of the four Iat classes is shown in Fig. 4 and Table 1, and Table 1 shows the results of all the six geomorphological indices and their classification for all 40 sub-basins. About 5 % of the study area belongs to class 1; 12.5 % to class 2; 45 % to class 3; and 37.5 % to class 4.

The utilization of the six geomorphological indices as well as Iat exhibits change mostly corresponding to the distribution of the prominent fault zones in the study area. Neotectonics movements in the High Zagros Ranges and the dynamic characters of the resulting structures indicate north–south compression, dextral transpression, approximately N–S strike-slip faults and NW–SE trending reverse faults. In addition, neotectonics movements show strong vertical uplifting, total rising, differential tilting that have created steepest slopes, highly asymmetric valleys, elongated basins, V-shaped valleys, linearized drainages, active mountain fronts, high stream-length gradients and hypsometric integrals. The geomorphological indices for most of sub-basins show Iat classes 3 and 4 within most of the study area and Iat classes 1 and 2 in the adjacent regions where the relative tectonic activity is assumed to be very high or high. Iat for areas along northern part of the study area is low to moderately active which is close to inactive Main Zagros Reverse Fault, while Iat is high to very high for southern part of the study area that is situated around conjunction of Dena Fault (northern segment of Kazerun Fault Zone) with Main Recent Fault.

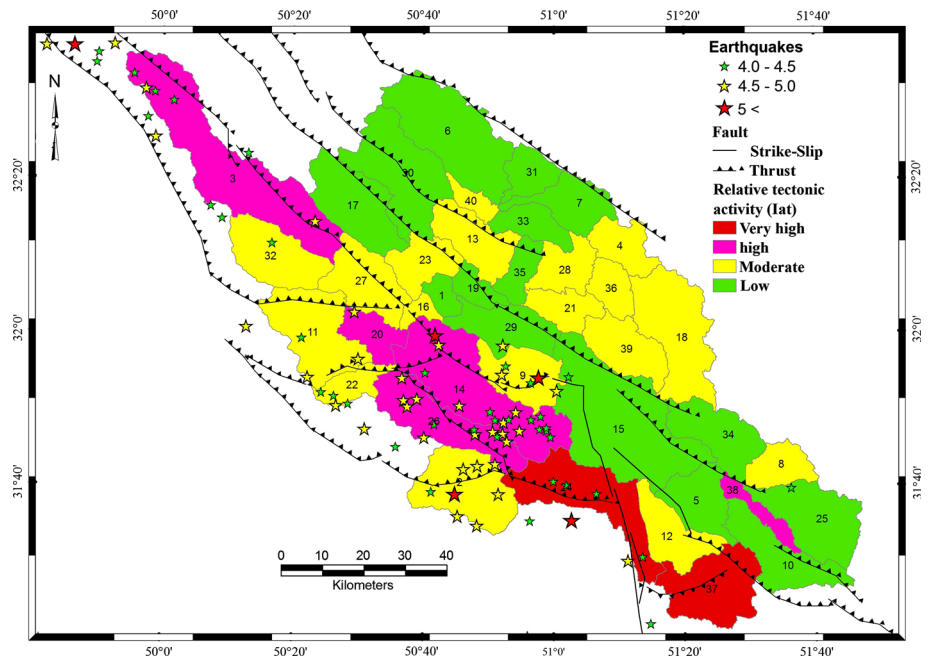
Several devastating earthquakes (historical and/or instrumental) that occurred in the last decades in this area, such as 6.4 magnitude Ardal earthquake of 1666, 6.8 magnitude Naghan earthquake 1977 and 6.4 magnitude Boldaji earthquake 2012, have caused a severe damage to life and property (Amrei et al. 2011; Oveisi and Tajik 2012). Nearly, 80 earthquakes with  $M > 4$  have been acquired as recorded by the International Seismological Centre (ISC) and USGS in the study area for the past 100 years. These earthquakes were plotted on the morphotectonic map which classifies the area into relative tectonic activity classes based on inputs from morphometric analysis, and they show a reasonable correlation. Out of these earthquakes, 11.5 % occurred over 5 Mb magnitude, 44.9 % of earthquakes happened between 4.5 and 5 Mb magnitude and 43.6 % of earthquakes with magnitude of 4–4.5 Mb within the study area (Fig. 4). Approximately, most of the earthquakes occurred in the southern part of the study area that shows the extent of faults activity within this part. The lack of earthquake epicenters in northern part of the study area is consistent with prominent distribution of sub-basins with classes 3 and 4 of Iat which exhibit low to moderate tectonic activity. Most of the earthquake epicenters are concentrated at the south central part of the study area where the sub-basins of 14, 20 and 26 with class 2 of high relative tectonic activity affected by the activities of intersected thrust and strike-slip faults. Also, earthquakes with magnitude of greater than 5 occurred within sub-basins of 24 and 3 with Iat classes of 1 (very high) and 2 (high), respectively. Thus, the morphotectonic map prepared is well consistent with the earthquake occurrences in this region. The pattern of tectonic deformation in the study area remained the same over the last 5 million years (Allen et al. 2004; Talebian and Jackson 2004). An  $N20^{\circ}$ – $30^{\circ}$  compression prevailed (Molinario et al. 2005; Lacombe et al. 2006), and the oblique Arabia–Eurasia convergence has been accommodated by both shortening and strike slip (Lacombe et al. 2006). The  $N20^{\circ}$ – $30^{\circ}$  compression is also consistent with dextral motions along the other NW–SE trending faults.

## Conclusion

Tectonic geomorphology investigations guide us for further research, such as paleoseismological surveys to reveal specific slip and recurrence rates and to better understand fault behavior to eventually quantify seismic hazard. Tectonic geomorphology of orogenic belts has become one of the principal tools in the identification of active faults, seismic hazard assessment and the study of landscape evolution. This study provides geomorphological analyses of fault-generated mountain fronts and



**Fig. 4** Iat classification of sub-basins of the study area based on the measured index



channel gradient that cross the High Zagros Ranges. The results of channel gradient analysis reveal that the most part of the High Zagros Ranges is active and the results of mountain-front sinuosity and valley-width ratio analyses imply that their degree of activity is moderate to high. Morphometric analyses revealed that the High Zagros Ranges is a moderately to highly active region in Iran. The obtained results from geomorphological indices were combined to yield an index of active tectonics (Iat). The indicative values of this index are consistent with the landforms and geology of the study area. The Iat is low to moderate in northern part of the study area which corresponds to inactive Main Zagros Reverse Fault. The high values of Iat mainly occur in southern parts of the study area where straight mountain fronts and triangular facets along the Dena Fault suggest high tectonic activity. Most of the earthquake epicenters are concentrated where the majority of sub-basins of class 1 and class 2 suggest high tectonic activity. The lack of earthquake epicenters in some parts of the study area is consistent with prominent distribution of sub-basins with classes 3 and 4 of Iat index which exhibits low to moderate tectonic activity. High relative tectonic activity mostly corresponds to the distribution of prominent strike-slip and thrust faults in the study area. These areas are among populated places of this region and these factors threaten the lives and property of the people residing there.

**Acknowledgments** The authors would like to thank Editor-in-Chief, Professor Dörhöfer for his editorial authority and valuable comments. The constructive suggestions and comments of two anonymous reviewers improved the content of the manuscript.

Important support by the research council of Shiraz University is gratefully acknowledged.

## References

- Alcántara-Ayala I (2002) Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology* 47(2):107–124
- Allen M, Jackson J, Walker R (2004) Late Cenozoic reorganization of the Arabia-Eurasia collision and the comparison of short-term and long-term deformation rates. *Tectonics* 23:TC2008
- Amrei SR, Amiri GG, Rezaei D (2011) Evaluation of horizontal seismic hazard of Naghan Iran. *World Acad Sci Eng Technol* 5:1456–1458
- Authemayou C, Bellier O, Chardon D, Malekzade Z, Abbasi M (2005) Role of the Kazerun fault system in active deformation of the Zagros fold-and-thrust belt (Iran). *CR Geosci* 337:539–545
- Authemayou C, Chardon D, Bellier O, Malekzadeh Z, Shabanian E, Abbassi MR (2006) Late Cenozoic partitioning of oblique plate convergence in the Zagros fold-and-thrust belt (Iran). *Tectonics* 25:TC3002
- Authemayou C, Bellier O, Chardon D, Benedetti L, Malekzade Z, Claude C, Angeletti B, Shabanian E, Abbassi MR (2009) Quaternary slip-rates of the Kazerun and the main recent faults: active strike-slip partitioning in the Zagros fold-and-thrust belt. *Geophys J Int* 178(1):524–540
- Azor A, Keller EA, Yeats RS (2002) Geomorphic indicators of active fold growth: South Mountain-Oak Ridge Ventura basin, southern California. *Geol Soc Am Bull* 114:745–753
- Bahrami S (2012) Morphotectonic evolution of triangular facets and wine-glass valleys in the Noakoh anticline, Zagros, Iran: implications for active tectonics. *Geomorphology* 159:37–49
- Bahrami S (2013) Analyzing the drainage system anomaly of Zagros basins: implications for active tectonics. *Tectonophysics* 608:914–928
- Bali R, Agarwal KK, Ali SN, Rastogi SK, Krishna K (2012) Drainage morphometry of Himalayan Glacio-fluvial basin, India:

- hydrologic and neotectonic implications. *Environ Earth Sci* 66(4):1163–1174
- Bathrellos GD, Gaki-Papanastassiou K, Skilodimou HD, Papanastassiou D, Chousianitis KG (2012) Potential suitability for urban planning and industry development using natural hazard maps and geological–geomorphological parameters. *Environ Earth Sci* 66(2):537–548
- Bathrellos GD, Gaki-Papanastassiou K, Skilodimou HD, Skianis GA, Chousianitis KG (2013) Assessment of rural community and agricultural development using geomorphological–geological factors and GIS in the Trikala prefecture (Central Greece). *Stoch Env Res Risk Assess* 27(2):573–588
- Berberian M (1995) Master “blind” thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. *Tectonophysics* 241:193–224
- Berberian M, King GCP (1981) Towards a paleogeography and tectonic evolution of Iran. *Can J Earth Sci* 18:210–265
- Bretis B, Bartl N, Grasemann B (2011) Lateral fold growth and linkage in the Zagros fold and thrust belt (Kurdistan, NE Iraq). *Basin Res* 23(6):615–630
- Bull WB (1978) Geomorphic tectonic activity classes of the south front of the San Gabriel Mountains. Geosciences Department, University of Arizona, California
- Bull WB (2007) Tectonic geomorphology of mountains: a new approach to paleoseismology. Wiley, Oxford
- Bull WB, McFadden LD (1977) Tectonic geomorphology north and south of the Garlock fault, California. In: Doehring DO (Ed.), *Geomorphology in Arid Regions*. Proceedings of the Eighth Annual Geomorphology Symposium. State University of New York, Binghamton, pp 115–138
- Cannon PJ (1976) Generation of explicit parameters for a quantitative geomorphic study of the Mill Creek drainage basin. *Okla Geol Notes* 36:3–16
- Cloetingh S, Cornu T, Ziegler PA, Beekman F (2006) Neotectonics and intraplate continental topography of the northern Alpine Foreland. *Earth Sci Rev* 74(3):127–196
- Cox RT (1994) Analysis of drainage-basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: an example from the Mississippi Embayment. *Geol Soc Am Bull* 106(5):571–581
- Dehbozorgi M, Pourkermani M, Arian M, Matkan AA, Motamedi H, Hosseiniasl A (2010) Quantitative analysis of relative tectonic activity in the Sarvestan area, central Zagros Iran. *Geomorphology* 121:329–341
- El-Hamdouni R, Irigaray C, Fernández T, Chacón J, Keller EA (2008) Assessment of relative active tectonics, southwest border of the Sierra Nevada (southern Spain). *Geomorphology* 96:150–173
- Faghih A, Nourbakhsh A (2014) Appraisal of relative tectonic activity along the Kazerun Fault Zone, Zagros Mountains, Iran: insight from spatial analysis of geomorphic indices. *Geol J*. doi:10.1002/gj.2597
- Faghih A, Nourbakhsh A (2015) Implication of surface fractal analysis to evaluate the relative sensitivity of topography to active tectonics, Zagros Mountains Iran. *J Mt Sci* 12(1):177–185
- Faghih A, Samani B, Kusky T, Khabazi S, Roshanak R (2012) Geomorphologic assessment of relative tectonic activity in the Maharlou Lake Basin, Zagros Mountains of Iran. *Geol J* 47:30–40
- Galadini F, Galli P (2000) Active tectonics in the central Apennines (Italy)—input data for seismic hazard assessment. *Nat Hazards* 22(3):225–268
- Gares PA, Sherman DJ, Nordstrom KF (1994) Geomorphology and natural hazards. *Geomorphology* 10(1):1–18
- Gomes A, Chamini HI, Teixeira J, Fonseca PE, Gama Pereira LC, Pinto de Jesus A, Pérez Alberti A, Araújo MA, Coelho A, Soares de Andrade A, Rocha F (2007) Late Cenozoic basin opening in relation to major strike-slip faulting along the Porto-Coimbra-Tomar fault zone (northern Portugal). In: Nichols G, Williams E, Paola C (Eds), *Sedimentary processes, environments and basins: a tribute to Peter Friend*. Special Publications of the International Association Sedimentologists (IAS), Blackwell Publishing, pp 38:137–153
- Hack T (1957) Submerged river system of Chesapeake Bay. *Geol Soc Am Bull* 68(7):817–830
- Hack JT (1973) Stream-profile analysis and stream-gradient index. *J Res US Geol Surv* 1(4):421–429
- Hack JT (1982) Physiographic divisions and differential uplift in the Piedmont and Blue Ridge
- Hare PW, Gardner TW (1985) Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula Costa Rica. Allen and Unwin, Boston, pp 75–104
- Hatzfeld D, Authemayou C, Van Der Beek P, Bellier O, Lavé J, Oveisi B, Tatar M, Tavakoli F, Walpersdorf A, Yamini-Fard F (2010) The kinematics of the Zagros Mountains (Iran). *Geol Soc London Spec Publ* 330:19–42
- Kamberis E, Bathrellos G, Kokinou E, Skilodimou HD (2012) Correlation between the structural pattern and the development of the hydrographic network in the area of Western Thessaly basin (Greece). *Cent Eur J Geosci* 4(3):416–424
- Keller EA (1986) Investigation of active tectonics: use of surficial Earth processes. In: Wallace RE (ed) *Active tectonics, studies in geophysics*. National Academy Press, Washington, pp 136–147
- Keller EA, Pinter N (2002) *Active tectonics: earthquakes, uplift, and landscape*. Prentice Hall, New Jersey
- Lacombe O, Mouthereau F, Kargar S, Meyer B (2006) Late Cenozoic and modern stress fields in the western Fars (Iran): Implications for the tectonic and kinematic evolution of central Zagros. *Tectonics* 25:TC1003
- Lee CS, Tsai LL (2010) A quantitative analysis for geomorphic indices of longitudinal river profile: a case study of the Choushui River Central Taiwan. *Environ Earth Sci* 59(7):1549–1558
- Mahmood SA, Gloaguen R (2011) Fractal measures of drainage network to investigate surface deformation from remote sensing data: a paradigm from Hindukush (NE-Afghanistan). *J Mt Sci* 8(5):641–654
- Mayer L (1990) *Introduction to quantitative geomorphology: an exercise manual*. Prentice-Hall International, Inc
- McQuarrie N, Stock JM, Verdel C, Wernicke BP (2003) Cenozoic evolution of Neotethys and implications for the causes of plate motions. *Geophys Res Lett* 30:2036
- Migiros G, Bathrellos GD, Skilodimou HD, Karamousalis T (2011) Pinios (Peneus) River (Central Greece): hydrological–geomorphological elements and changes during the quaternary. *Central Eur J Geosci* 3(2):215–228
- Molinario M, Leturmy P, Guezou JC, Frizon de Lamotte D, Eshraghi SA (2005) The structure and kinematics of the southeastern Zagros fold-thrust belt, Iran: From thin-skinned to thick-skinned tectonics. *Tectonics* 24:TC3007
- Oveisi B, Tajik R (2012) The report of Boldaji 2012 earthquake of Chaharmahal-o-Bakhtiari, Zagros. Geological survey of Iran, Iran
- Panizza M (1981) Geomorphology and earthquake hazard in environmental planning. In: *Proceedings of the International Conference on Seismic Zones in the Mediterranean Area*. Basilicata, Italy pp 203–207
- Pedraza A, Pérez-Peña JV, Galindo-Zaldívar J, Azañón JM, Azor A (2009) Testing the sensitivity of geomorphic indices in areas of low-rate active folding (eastern Betic Cordillera, Spain). *Geomorphology* 105(3):218–231
- Pérez-Peña JV, Azor A, Azañón JM, Keller EA (2010) Active tectonics in the Sierra Nevada (Betic Cordillera, SE Spain): insights from geomorphic indexes and drainage pattern analysis. *Geomorphology* 119(1):74–87

- Pike RJ, Wilson SE (1971) Elevation-relief ratio, hypsometric integral and geomorphic area-altitude analysis. *Geol Soc Am Bull* 82:1079–1084
- Ramirez-Herrera MT (1998) Geomorphic assessment of active tectonics in the Acambay Graben, Mexican volcanic belt. *Earth Surf Proc Land* 23:317–332
- Ramsey LA, Walker RT, Jackson J (2008) Fold evolution and drainage development in the Zagros Mountains of Fars province, SE Iran. *Basin Res* 20:23–48
- Rockwell TK, Keller EA, Johnson DL (1985) Tectonic geomorphology of alluvial fans and mountain fronts near Ventura, California. In: Morisawa M (Ed.), *Tectonic Geomorphology. Proceedings of the 15th Annual Geomorphology Symposium*. Allen and Unwin Publishers, Boston pp 183–207
- Rockwell TK, Ragona D, Akbalic B, Aksou ME, Barka AA, Ferry M, Klinger Y, Langridge R, Meghraoui M, Meltzner AJ, Satir D, Seitz G, Ucarukus G (2009a) Palaeoseismology of the north Anatolian fault near the Marmara sea: implications for fault segmentation and seismic hazard. In: Reicherter K, Michetti AM, Silva PG (eds), *Palaeoseismology: historical and prehistorical records of earthquake ground effects for seismic hazard assessment*. The Geological Society, London, Special Publications 316:31–54
- Rockwell TK, Fonseca J, Madden C, Dawson T, Owen LA, Vilanova S, Figueiredo P (2009b) Paleoseismology of the Vilarica segment of the Manteigas-Bragança fault in Northeastern Portugal. In: Reicherter K, Michetti AM, Silva PG (eds), *Palaeoseismology: historical and prehistorical records of earthquake ground effects for seismic hazard assessment*. The Geological Society, London, Special Publications 316:237–258
- Silva PG, Goy JL, Zazo C, Bardajm T (2003) Fault generated mountain fronts in Southeast Spain: geomorphologic assessment of tectonic and earthquake activity. *Geomorphology* 250:203–226
- Slaymaker O (1996) Introduction. In: Slaymaker O (ed) *Geomorphic Hazards*. Wiley, Chichester, pp 1–7
- Stöcklin, J (1974) Possible ancient continental margins in Iran. In *The geology of continental margins* Springer Berlin Heidelberg, New York, pp 873–887
- Stoneley R (1981) The geology of the Kuh-e Dalneshin area of southern Iran, and its bearing on the evolution of southern Tethys. *J Geol Soc* 138(5):509–526
- Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography. *Geol Soc Am Bull* 63:1117–1142
- Tachikawa T, Hato M, Kaku M, et al. (2011) Characteristics of ASTER GDEM version 2. In: *Geoscience and Remote Sensing Symposium (IGARSS) IEEE International*, pp 3657–3660
- Talebian M, Jackson J (2002) Offset on the main recent fault of NW Iran and implications for the late Cenozoic tectonics of the Arabia-Eurasia collision zone. *Geophys J Int* 150:422–439
- Talebian M, Jackson J (2004) A reappraisal of earthquake focal mechanisms and active shortening in the Zagros mountains of Iran. *Geophys J Int* 156:506–526
- Thomas J, Joseph S, Thirvikramji KP, Abe G, Kannan N (2012) Morphometrical analysis of two tropical mountain river basins of contrasting environmental settings, the southern Western Ghats India. *Environ Earth Sci* 66(8):2353–2366
- Vieceli N, Bortolin TA, Mendes LA, Bacarim G, Cemin G, Schneider VE (2014) Morphometric evaluation of watersheds in Caxias do Sul City, Brazil, using SRTM (DEM) data and GIS. *Environ Earth Sci*. doi:10.1007/s12665-014-3823-3
- Yaminifard F, Sedghi MH, Gholamzadeh A, Tatar M, Hessami K (2012) Active faulting of the southeastern-most Zagros (Iran): microearthquake seismicity and crustal structure. *J Geodyn* 55:56–65