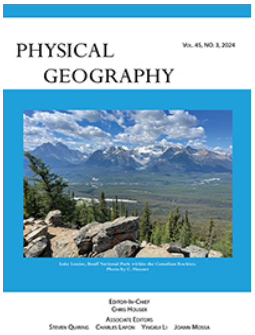

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Tectonic controls on the morphometry of alluvial fans in an arid region, northeast Iran

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ABSTRACT
The morphology of alluvial fans provides valuable information about changes in tectonic, climate, base level, and drainage basin characteristics. This study aims to evaluate the relationship between active tectonics and morphometric characteristics of alluvial fans in the less studied southern region of the Joghatay mountain, northeast Iran. The study area includes 13 alluvial fans and their corresponding catchment basins in a region with semi-arid climate. Morphometric characteristics of alluvial fans and their corresponding drainage basin including fan area, fan slope, sweep angle, fan toe length, fan radius, basin area, basin slope, fan's width-to-length ratio, asymmetry factor, and basin shape were measured. Our results revealed a negative relationship between the slope of alluvial fans and their corresponding basin area. The weak correlation between the drainage basin area and the fans area may be attributed to the lithology and active tectonics in the study area. The small sweep angle values of the studied alluvial fans can be attributed to the activity of thrust faults and presence of an uplifting anticline that resulted in formation of elongated alluvial fans in our study area. Analysis of the relationship between the morphometric characteristics of the fans and their corresponding basins indicated a negative correlation, which can be attributed to the sediment transport efficiency of the basins.

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Alluvial fan; tectonics control; morphometry; drainage basin; Joghatay range

Introduction

Alluvial fans are common depositional landforms in arid regions formed by fluvial aggradation processes (Ayaz et al., 2018; Fontana et al., 2008; Harvey, 2012; Li et al., 1999). Factors, including tectonic activity, climate, morphometric characteristics of the catchment area, and base-level changes, control the development of alluvial fans (Bahrami, 2013; Dorn, 1988; Hu et al., 2021; Spelz et al., 2008). By controlling the accommodation space (Bahrami, 2013), tectonic forces can influence the morphologic characteristics of alluvial fans (Barrier et al., 2010; Sarp, 2015). Faulting exerts a profound influence on the geometry and spatial distribution of alluvial fans through the generation of basins responsible for supplying sediment to the fans (Goswami & Mishra, 2012; Mack & Leeder, 1999). Additionally, fault-induced uplift or tilting of drainage basins contributes to alterations in the alluvial fan dynamics (Dehbozorgi et al., 2010; Goswami et al.,

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2009). The activity of faults can further result in deformation or offset occurring within the alluvial fans (Ridgway & Decelles, 1993), underscoring the significant role that tectonic processes play in shaping the geomorphology of alluvial fans. The characteristics of the catchment area, which plays a vital role in the size and slope of the alluvial fans (Bull, 1962; Goswami et al., 2009; Hooke, 1968; Hooke & Rohrer, 1977), are mainly controlled by tectonics (Dade & Verdeyen Meagan, 2007; Harvey et al., 2005; Mather Anne & Stokes, 2018; Salcher et al., 2010). Therefore, the geomorphology of alluvial fans is not only a suitable indicator to investigate previous tectonic activities but is also an outstanding geomorphic landform to indicate the interaction between the tectonic setting, Quaternary climate changes, and base-level changes (Viseras et al., 2003).

Relative tectonic activity indices have been widely employed to assess tectonic activity in mountainous catchment areas worldwide (S. A. Ali & Ikbal, 2020; U. Ali et al., 2021; Anand & Pradhan, 2019; Azor et al., 2002; Buczek & Górnik, 2020; Chang et al., 2015; El Hamdouni et al., 2008; A. M. Figueroa & Knott, 2010; Różycka & Migoń, 2021; Vijith et al., 2017). However, fewer studies have utilized these indices to examine the impact of tectonic activities on alluvial fans (Giano, 2011; Robustelli et al., 2005; Sarp, 2015). Notably, in Iran, the majority of studies employing active tectonic indices have concentrated on the Zagros Mountain Range (Alipoor et al., 2011; Alizadeh et al., 2022; Bahrami, 2013; Dehbozorgi et al., 2010; Ehsani & Arian, 2015), the Alborz Range (Alaei et al., 2017), and southern and central Iran (Ebrahimi et al., 2023; Mokarram et al., 2022).

To the best of our knowledge, there is a paucity of research utilizing the northeast region, specifically Joghatay mountain range, to investigate the influence of active tectonics on alluvial fans, including the examination of relative tectonic activity. Addressing this gap in knowledge and augmenting our understanding of relative tectonic activity in Iran, we have employed active tectonic indices in conjunction with morphometric indices to analyze alluvial fans located on the southern slopes of the Joghatay mountain range. Additionally, the study area holds significance due to the presence of rural settlements, agricultural lands, and infrastructure development. Consequently, the primary objective of this study is to elucidate the tectonic influences on the morphometric characteristics of a series of inhabited alluvial fans within an arid region, northeast of Iran. To achieve this objective, we systematically extracted morphological characteristics on the alluvial fans and conducted assessments of active tectonic parameters within the respective drainage basin areas. Subsequently, we undertook an exploration of the quantitative relationship between fan morphology and active tectonic indices, thereby contributing to a more comprehensive understanding of the interplay between tectonic forces and landscape evolution in the studied region.

Study area

The study area is located to the west of the city of Sabzevar, northeast of Iran (Figure 1). The studied alluvial fans are developed on the southern fronts of the Joghatay mountain range. According to the study area's digital elevation model (SRTM DEM with a 30 m spatial resolution), the maximum elevation in the basin area is about 2944 m a.m.s.l., and the minimum elevation is about 1046 m. The maximum elevation of the apex of studied alluvial fans is about 1194 m, while the minimum elevation at the toe of the fans is 844 m.

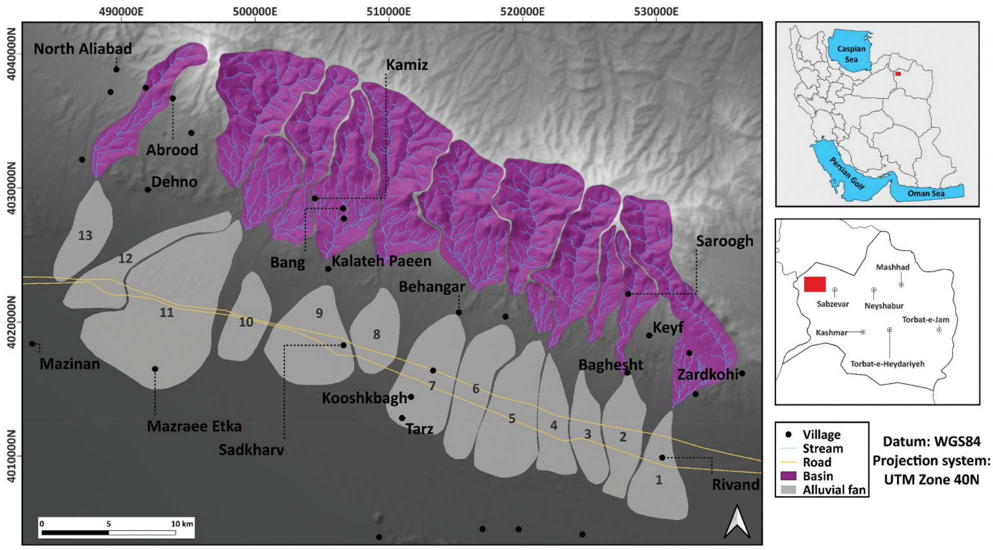

Figure 1. Location map of the studied alluvial fans, their corresponding basins, and the distribution of villages in the study area.

Climatically the study area is located in a warm semi-arid region with cold winters and warm summers (Bahrami & Ghahraman, 2019) with 150–200 mm annual precipitation. Wind erosion, arid and semi-arid climate, and the lack of precipitation have let the landforms such as barchans and nebkha emerge in the vicinity of the alluvial fans (in the playa).

The watershed basins corresponding to the investigated alluvial fans are exclusively situated within the Joghatay ophiolitic complex (Figure 2(a)). The Joghatay ophiolitic complex exhibits significant geological manifestations indicative of ancient plate margins, primarily dating back to the Upper Cretaceous and earlier periods (Rahmati & Niazi, 1986). The Joghatay range is bounded by multiple faults in the southern region (Figure 2(a)). The structural characteristics of the Joghatay range are notably defined by prominently inclined faults (Alavi-Tehrani, 1976; Rahmati & Niazi, 1986). The predominant orientation of these major faults is from east to west. Additionally, there exist a comparatively lesser number of minor faults in the central zones, aligning with a North-Northeast to South-Southwest strike direction (Rahmati & Niazi, 1986).

The active faulting observed in the Sabzevar range demonstrates a basinward progression of fault activity (Hollingsworth et al., 2010). The Sabzevar fault, situated at the base of the range, has uplifted a stratum of red Neogene conglomerates, forming a low topographic step. Ongoing uplift of this red Neogene formation along the Sabzevar fault has led to the incision of rivers through the Neogene deposits, resulting in the creation of a sequence of elevated Quaternary alluvial fan surfaces (Figure 2(b)). Major lithological units of the basins include light gray andesite, quartz trachyandesite (Da), diabase (Db), dunite (Du), cream bio-detrital limestone (E1), basal conglomerate (Ec), an association of sandstone, shale, and marl (E^{fsh}), yellowish marl and sandstone (E^{m}), gabbro (Gb), harzburgite (Hz), association of pillow lava and deep marine sediments (K^{vl}), gypsum bearing marl (Mm), red, pink marl with or without rock fragments (Plm),

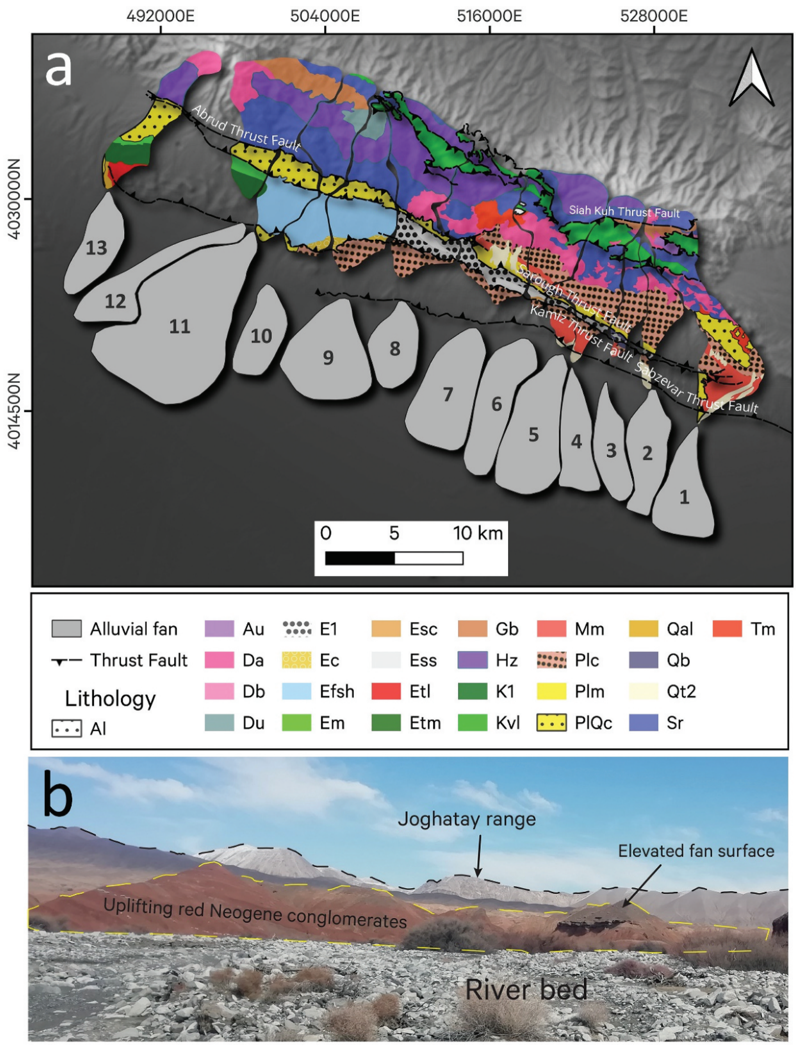

Figure 2. Geological map of the basin area shows the complex lithological units and the main thrust faults (a), and the impact of the tectonic activity on the incision of the Neogene conglomerate at the apex of alluvial fan number 1 (b).

pale gray poor sorted conglomerate (PlQ^c) and serpentinized harzburgite and dunite (Sr) (Figure 2(a)).

Materials and methods

In order to evaluate the relationship between active tectonics and quantitative characteristics of alluvial fans, first, we delineated the boundaries of 13 alluvial fans and their basin area using Sentinel-2 satellite imagery, topographic map and field survey as supplementary validation data. Field surveys helped us to better understand and identify the landforms and processes of the alluvial fans and the basins. To determine the morphological characteristics of the alluvial fans, such as fan area (FA), fan toe length (FT), fan width-to-length ratio (W/L), radius (R), and sweep angle (SA), we used ALOS PALSAR Digital Elevation Model (DEM) of the study area with a 12.5 m spatial resolution. Catchment basin parameters, including basin area (BA), asymmetry factor (AF), basin shape (Bs), were also obtained using DEM, GIS, and digitized shapefiles of the basins. Obtaining the slope raster layer from the DEM, the mean slope of each fan and its corresponding basin was calculated in QGIS. The geological data including faults and lithology of the basins were derived from the 1:100 000 geological maps of the geological survey of Iran (Figure 2). We used ArcMap to digitize the lithological units and major thrust faults.

Morphometric indices

Alluvial fan and drainage basin area

Using QGIS, we computed the planimetric area of each alluvial fan and its corresponding drainage basin. To maintain spatial accuracy and consistency, we adopted the Universal Transverse Mercator (UTM) coordinate system for area calculations, representing the results in square kilometers.

Alluvial fan and drainage basin slope

The slope of each alluvial fan and its respective drainage basin was determined by leveraging the DEM of the study area and the slope operator functionality within QGIS. Following the generation of a slope raster layer expressed in percentage gradient, the mean slope percentage for each fan and its associated basin was quantified using the zonal statistics tool in QGIS.

Alluvial fan toe length

The toe of an alluvial fan refers to the distal end where the fan deposits meet the surrounding landscape (Figure 3) (Hooke, 1967; Larson et al., 2015; Namy, 1971). To quantify the toe length of the studied fans, we employed the measure line tool in QGIS. The toe length of the fans was measured in meters.

Fan radius

The distance from the apex of an alluvial fan to its toe is commonly referred to as the fan radius (Moore & Howard, 2005; Moscariello, 2018). In our study, we utilized the shapefile of the fans and the line measure tool within QGIS to quantify the fan radius in kilometers. Figure 3 displays the fan radius of an alluvial fan.

Sweep angle

The sweep angle was obtained using the method suggested by Viseras and Fernández (1994), as shown in Figure 3. Sweep angle, also known as flow expansion angle, represents the angle between the two widest separated channels on the alluvial fan (Bowman, 2019). Following the delineation and digitization of the outermost channels of each alluvial fan, the calculation of the sweep angle was conducted in QGIS utilizing the angle measure tool, quantified in degrees.

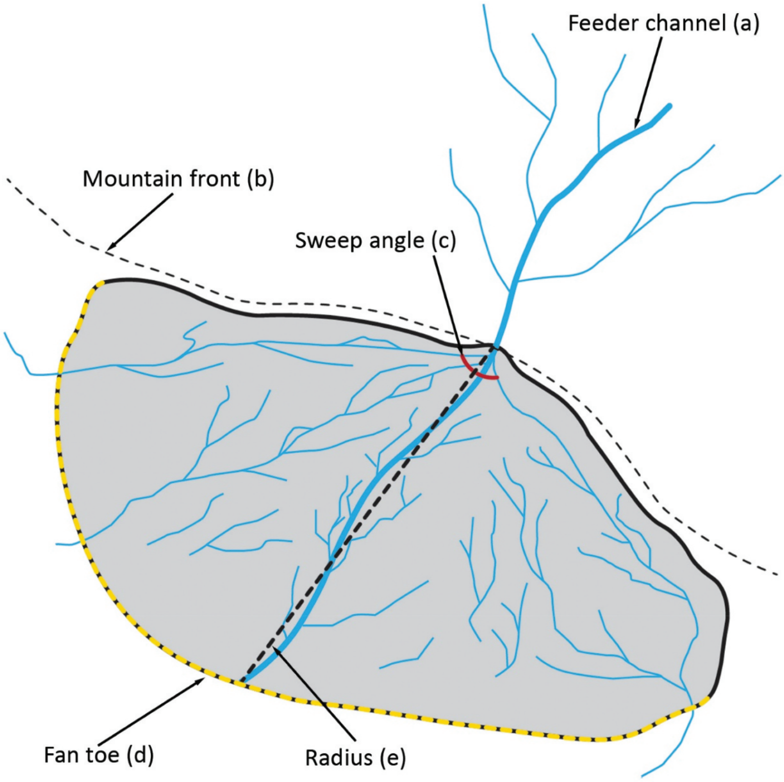

Figure 3. Schematics representation of the feeder channel (a), mountain front (b), sweep angle (c), fan toe (d), and radius (e) in an alluvial fan.

Asymmetry factor

The asymmetry factor (AF) is an index to detect tilting caused by tectonic activities in drainage basins (El Hamdouni et al., 2008). AF values greater or smaller than 50 show the basin's tilting and tectonic activity (Mokarram et al., 2022). The asymmetry factor was calculated using the following equation:

$$AF = (Ar/At) \times 100 \quad (1)$$

Where Ar represents the area of the drainage basin to the right of the main drainage channel, and At is the total area of the drainage basin. When the AF value is 50 or close to 50, it represents the little or no tilting in the drainage basin.

Basin shape

The basin shape (Bs) is a widely used index to show the activity of tectonics in a basin area (Alaei et al., 2017; Dehbozorgi et al., 2010; El Hamdouni et al., 2008). The higher the Bs value, the greater the tectonic impact on the basin area. Basins with higher basin shape values are usually elongated (Alaei et al., 2017), while circular basins represent the dominance of erosion and tectonic inactivity in the basin area (T. Zhang et al., 2019). Using the following equation, the basin shape index was calculated.

Table 1. Morphometric parameters of the alluvial fans and their basins.

Parameter	Symbol	Explanation
Alluvial fan area	FA	Total planimetric area of an alluvial fan
Alluvial fan slope	FS	Mean slope of an alluvial fan
Sweep angle	SA	The angle between the two widest separated channels on the alluvial fan
Alluvial fan toe length	FT	The length of the line at the base of a fan
Radius	R	The distance from the apex to the toe of an alluvial fan
Basin area	BA	Total planimetric area of a basin
Basin slope	BS	Mean slope of a basin
Width-to-length ratio	W/L	The ratio between the length and width of an alluvial fan
Asymmetry factor	AF	Values greater than 50 represent the influence of active tectonics
Basin shape	Bs	The ratio between the length and width of the basin. In basins with the influence of active tectonics the value is greater than 1

$$\mathrm{Bs} = \mathrm{Bl}/\mathrm{Bw} \tag{2}$$

Where Bs is the basin shape index, Bl is the basin length, and Bw is basin width. The measurement of Bs was conducted in QGIS.

Width-to-length ration

The width-to-length ratio of studied alluvial fans (W/L) is calculated by dividing the width of the fan by its length (Bahrami, 2013). This index provides insights into the spatial extent and shape of the fan deposit. Variations in the width-to-length ratio reflect differences in sediment transport dynamics, depositional patterns, and environmental factors.

Overall, the required data in this study were obtained by using Geographic Information Systems, specifically QGIS and ArcMap, satellite imagery, georeferenced topographic and geologic maps, and the Digital Elevation Model of the study area. To investigate the correlation between different parameters, we used Python and regression analysis. Table 1 represents the summary of morphometric parameters used in this study.

Results

Geomorphology

Geomorphologically, the study area can be classified into three distinct zones: mountainous, pediment, and playa. The mountainous zone's landforms are formed by the presence of the ophiolitic complex and Eocene-resistant rocks, while the pediment and playa zone's landforms are formed under the influence of younger deposits and Neogene marl. Alluvial fans in the area are valuable indicators of tectonic activity and erosion in the mountainous zone. Various alluvial fans of diverse ages and shapes have been formed as a result of tectonic activity and faulting in the area. To examine the area's tectonic activity, the study focused on 13 active alluvial fans connected to their corresponding drainage basin. The remaining alluvial fans became disconnected from their feeder channels and drainage basins due to ongoing tectonic activity and fault movements. Consequently, we made the decision in this study to exclude these disconnected fans from consideration. Excluding the disconnected fans from our analysis ensures the focus remains on contiguous and dynamically active fan systems, allowing for a more accurate assessment of geomorphic processes and landscape evolution associated with ongoing tectonic activity and fault movements. Field surveys and satellite imagery investigations showed that some alluvial fans in the area are telescopic or multi-staged (Figure 4(a,b)). Accordingly, inactive, relict, and active alluvial fans can be recognized in the area. Additionally, the presence of desert pavement and rock varnish (Figure 4(c)) on different fan surfaces suggests various geomorphic processes operating on alluvial fans.

Morphometric indices

This research investigated the morphometric properties of 13 alluvial fans and their corresponding basins located in an arid region in northeast Iran (Figure 1). Using morphometric indices, the role of relative active tectonics on alluvial fans can be analyzed. Table 2 summarizes the results of morphometric variables analyzed, including fan area (FA), fan slope (FS), fan toe length (FT), radius (R), sweep angle (SA), and width to length ratio (W/L) as well as basin characteristics such as basin area (BA), basin slope (BS), asymmetry factor (AF), and basin shape (Bs).

The results of alluvial fan area (FA) revealed notable variations in the size of alluvial fans within the study area. The largest alluvial fan, encompassing an area of 82.39 km^2, is situated in the western segment of the study area, designated as fan No. 11. Conversely, the smallest alluvial fan, measuring 15.25 km^2, is positioned in the eastern region (fan No. 3). The remaining alluvial fans exhibit a range in size from 16 km^2 to 35 km^2, with a mean value of 27.67 km^2, as detailed in Table 2. Of particular interest is the discrepancy observed in fan No. 11, where despite its substantial size (82.39 km^2), the corresponding basin is comparatively smaller, spanning an area of 20.37 km^2. Basin No. 8 emerges as the largest basin, with an area of 51.4 km^2, while basin No. 5 represents the smallest basin, with a modest area of 5.65 km^2. Notably, basins 1, 7, and 12 stand out among the larger basins, each surpassing 45 km^2 in area when compared with other basins. The mean basin area is calculated at 32.12 km^2.

The smallest alluvial fan slope (FS) value is 2.89% (fan No. 1), whereas fan number 11 is the steepest (6.37%). The slope percentage in fans 2, 5, 6, and 10 is greater than 4%; however, the slope in fans 1, 3, 4, 7, 8,9, and 12 is lower than 3.80%. The mean slope of alluvial fans at the study area is measured at 4.12%. The highest drainage basin slope (BS) value belongs to basin 6 (54.56%), and the lowest value belongs to basin 11, with a value of 23.9% (Table 2). The mean basin slope is calculated at 40.18%.

Alluvial fans 7, 9, and 11 have fan toe length (FT) values greater than 5 kilometers (5.06, 7.37, and 7.33, respectively), while FT values in fans 2 and 13 are smaller than 2 kilometers (1.84 and 1.97, respectively). The mean value of FT at the study area is measured at 3.97 km.

The highest radius value, recorded at 14.76 km, corresponds to fan 11, while the lowest radius value, measuring 6.50 km, is associated with fan 8. On average, the alluvial fans within the study area exhibit a mean radius value of 9.51 km. The sweep angle (SA) values display variability across the studied alluvial fans, ranging from approximately 43° to around 94°, with a mean value of 67.35°. Notably, fan 7 exhibits the highest sweep angle value, reaching 93.81°, while fan 12 demonstrates the lowest sweep angle, measuring 43.54°. The highest W/L value is 0.63 in fan 9, and the lowest is 0.16 in fan 12, with

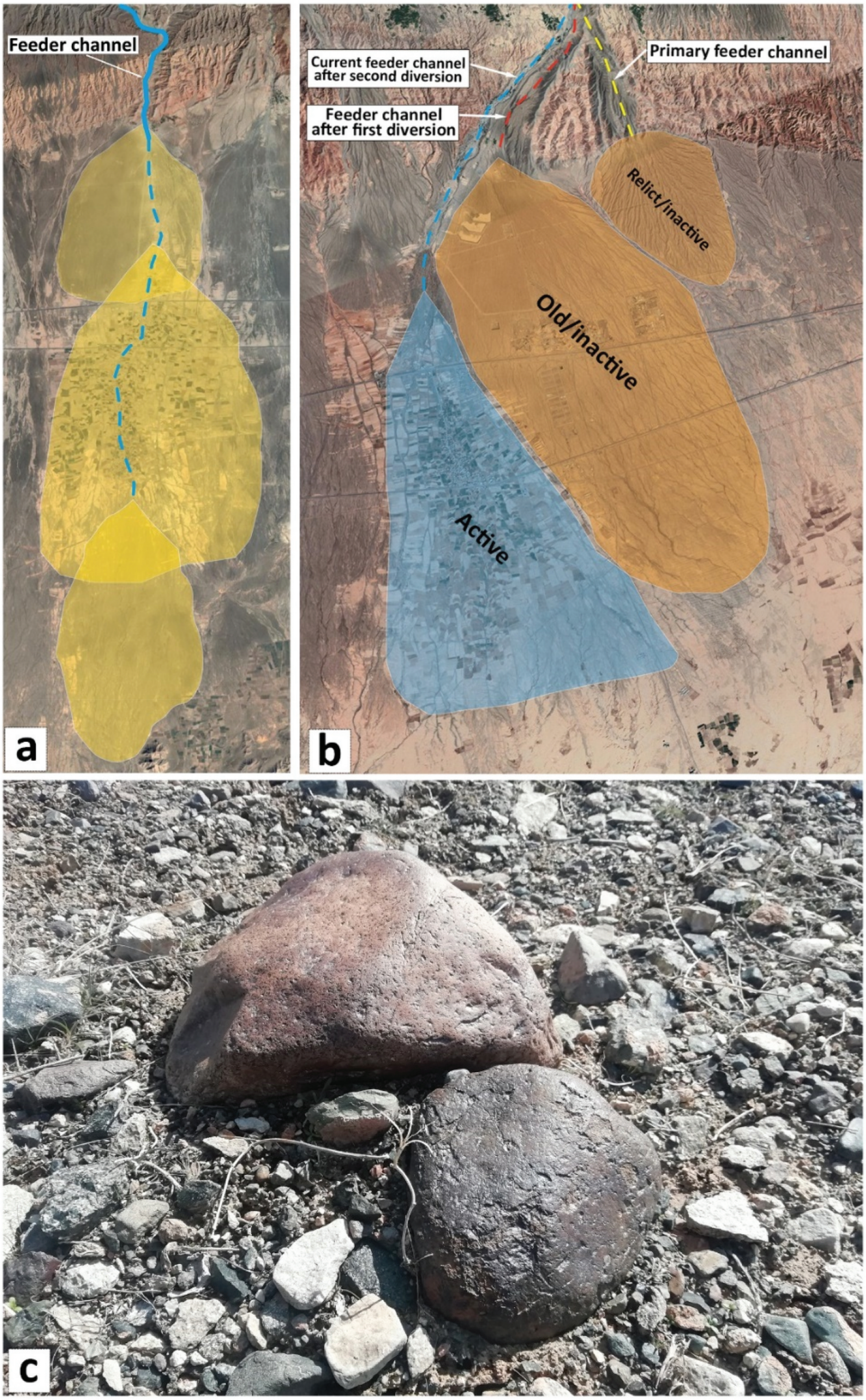

Figure 4. Telescopic (a) and multistage (b) alluvial fans in the study area. Tectonic activities and thrust faults are responsible for such a complex fan system in the studied area. On the telescopic fans, the upper sections receive water and sediment only while flooding, whereas when there are no floods, the lower section is the only part of the fan that receives water and sediment. Rock varnish (c) shows that the fan surface has not been affected by the flooding for a prolonged time.

Table 2. Morphometric characteristics of alluvial fans and their corresponding basins.

Fan No.	FA (km^2)	BA (km^2)	FS (%)	BS (%)	FT (km)	R (km)	AF	Bs	SA (degree)	W/L
1	21.78	48.15	2.89	40.33	4.63	8.07	41.08	3.58	84.77	0.34
2	20.29	14.51	4.02	36.92	1.84	9.13	64.08	4.16	72.27	0.23
3	15.25	11.74	3.58	36.30	2.83	8.78	62.99	4.42	55.98	0.21
4	17.74	33.58	3.88	48.72	3.38	8.91	45.98	2.50	49.25	0.24
5	35.15	5.65	4.28	27.41	4.82	10.67	83.60	3.03	81.15	0.31
6	26.32	40.60	4.17	54.56	2.8	10.69	56.67	1.71	53.31	0.25
7	33.33	48.10	3.88	46.65	5.06	9.24	66.43	1.58	93.81	0.41
8	16.97	51.40	3.77	47.94	2.65	6.50	81.16	1.80	76.02	0.4
9	34.39	38.27	3.63	33.79	7.37	7.75	26.48	2.42	80.22	0.63
10	16.50	34.23	4.42	42.14	2.44	6.86	54.07	3.38	64.53	0.37
11	82.39	20.37	6.37	23.90	7.33	14.76	20.36	1.88	51.14	0.41
12	22.22	47.20	3.80	49.53	4.47	14.16	33.70	1.39	43.54	0.16
13	17.40	23.77	4.95	34.01	1.97	8.13	70.44	4.30	69.50	0.25
Mean	27.67	32.12	4.12	40.18	3.97	9.51	54.39	2.71	67.35	0.32

a mean value of 0.32 (Table 2). Smaller values of the width-to-length ratio imply elongation of alluvial fans, whereas higher values of W/L indicate confinement at the distal parts of the fans.

Correlations between indices

Based on the Pearson correlation matrix analysis, correlations between morphometric parameters of alluvial fans and the drainage basins have emerged. Notably, the basin area (BA) exhibits the strongest positive correlation with the width-to-length ratio (W/L) at 0.253, and a comparatively weaker positive correlation with the sweep angle (SA) at 0.134. Conversely, a negative correlation is observed between the basin area and alluvial fan slope (FS) (−0.408), fan area (FA) (−0.203), and fan radius (R) (−0.175). Interestingly, there is almost no discernible correlation between the basin area and alluvial fan toe length in the study area (0.095).

Furthermore, the basin slope (BS) demonstrates negative correlations with several fan morphometric indices, including fan area (−0.569), fan slope (−0.507), fan toe length (−0.425), radius (R) (−0.188), width-to-length ratio (W/L) (−0.294), and sweep angle (SA) (−0.186).

Similarly, the asymmetry factor exhibits negative correlations with various fan morphometric indices, including fan area (−0.495), fan slope (−0.178), fan toe length (−0.646), radius (R) (−0.468), and width-to-length ratio (W/L) (−0.277), while displaying a positive correlation with the sweep angle (SA) (0.403).

Lastly, with the exception of the sweep angle (SA) (0.146), the basin shape index (Bs) demonstrates negative correlations with all fans morphometric indices, with the strongest correlations observed with fan radius (R) (−0.435) and fan toe length (FT) (−0.431), followed by fan area (FA) (−0.377), width-to-length ratio (W/L) (−0.238), and fan slope (FS) (−0.197).

Discussion

Tectonics is considered as one the primary factors of conceptual models of alluvial fan evolution (Harvey et al., 2005; Iacobucci et al., 2024; Ritter et al., 1995; Sarp, 2015). For instance, alluvial fans accommodation space – which controls the fan morphology – is primarily influenced by tectonics (Bahrami, 2013; Muñoz-Salinas et al., 2024; Singh & Tandon, 2007; Viseras et al., 2003). By analyzing the morphometric characteristics of both the alluvial fans and their corresponding drainage basins, which can be indicators of tectonic activities, valuable insights can be gained regarding the influence of tectonic activities on fan development (Calvache et al., 1997; Peng et al., 2024; Yamani et al., 2012), particularly in regions where research in this domain is limited. Previous studies in Iran have primarily concentrated on the prominent mountain ranges such as the Zagros and Alborz, as well as the southern and central regions of the country (Alaei et al., 2017; Alipoor et al., 2011; Alizadeh et al., 2022; Bagha et al., 2014; Bahrami, 2013; Dehbozorgi et al., 2010; Ebrahimi et al., 2023; Ehsani & Arian, 2015; Taesiri et al., 2020). However, the Joghatay mountain range in the northeast has received limited attention in this regard. Therefore, this study aims to fill this research gap by investigating the impacts of tectonics on alluvial fans, specifically focusing on the previously understudied Joghatay mountain range.

Our findings indicate a moderate level of tectonic activity within the Joghatay mountain range. Notably, the tectonic activity within this region has manifested in asymmetry factor values exceeding 50 in 8 out of 13 basins. An asymmetry factor value greater than 50 signifies uplift on the right side of the river, while values below 50 denote uplift on the left side (Knighton, 1981; Shi et al., 2021; C.-P. Zhang et al., 2015). However, the mean asymmetry factor value in our study area is calculated at 54.39, suggesting moderate levels of tectonic activity in the basin areas. It is noteworthy that the asymmetry factor values for basins No. 2, 3, 5, 8, and 13 surpass the mean AF value, indicative of heightened tectonic activity. This observation suggests that faults such as the Sabzevar thrust fault, Kamiz thrust fault, and Sarough thrust fault (in the case of basins 2, 3, 5, and 8) have exhibited increased activity in the eastern regions of the Joghatay range (Figure 2(a)). Conversely, for fan No. 13, located furthest to the west, the Abroud thrust fault emerges as the primary active fault. Furthermore, a comparison of the asymmetry factor values between basin 13 and basins 9, 11, and 12 implies complex movements along the Abroud thrust fault, potentially occurring at different times. This assertion is supported by the fact that the asymmetry factor value for fan 13 exceeds 50 (measuring at 70.44), indicating uplift on the right side of the main channel, while the other four fans have experienced uplift on the left side, with values below 50.

High basin shape values are associated with elongated basins and relatively high tectonic activity (Dehbozorgi et al., 2010; Ramírez-Herrera, 1998). In contrast, low values of basin shape index represent a more circular-shaped basin associated with low tectonic activity (Abou'ou Ango et al., 2023; Chang et al., 2015; El Hamdouni et al., 2008). The basin shape (Bs) values can be categorized into three classes: class one ($Bs > 2.9$), class two ($1.9 \le Bs \le 2.9$), and class three ($Bs < 1.9$) (Buczek & Górnik, 2020; Chang et al., 2015). This classification allows for the assessment of tectonic activity levels within an area, with high, moderate, and low activity corresponding to classes 1, 2, or 3, respectively. In our study area, the mean value of the Bs index indicates moderated tectonic activity, with a value of 2.71.

Drainage basin and alluvial fan relationships

Results show a relatively strong negative relationship between basin area and alluvial fan slope, indicating that smaller basins lead to steeper fans which is in accordance with the results of other studies (Blissenbach, 1952; Kostaschuk et al., 1986; Le Hooke & Rohrer, 1979; Saqqa & Atallah, 2013). For instance, the area of the basin corresponding to alluvial fan 11 is 20.37 km^2, while the alluvial fan's slope is 6.37%, which is the steepest among all fans examined. Conversely, alluvial fan 1 has a catchment basin with an area of 48.15 km^2 and a slope of 2.89%. This reverse relationship can be due to the fact that larger basins contribute more sediment to the fan, resulting in a gentler slope due to the deposition of sediments (El Asmi et al., 2023). This pattern is consistent with previous research conducted in Iran (Bahrami, 2013; Beaumont, 1972), as well as in Ganga plain in India, the great basin, Eastern California in the United States, and Spain (Goswami et al., 2009; Harvey, 2005; Hawley & Wilson, 1965; Viseras et al., 2003).

Furthermore, our findings indicate a weak negative correlation between basin area and fan area (Figure 6(d,j)). While previous studies have reported positive relationships between basin area and fan area (Bahrami, 2013; Beaumont, 1972; Bull, 1962; Goswami & Tyrrell, 2018; Hooke, 1968; Ventra & Clarke Lucy, 2018), the reversed relationship observed in our study area may be attributed to the lithological and tectonic characteristics of the basin area. In alluvial fans where the drainage basins primarily consist of erodible materials, an increase in basin area typically results in a corresponding increase in fan area (Mokarram et al., 2023; Özpolat et al., 2022). The complex lithological composition and tectonic activity, coupled with the convoluted system of alluvial fans on the pediment, could also contribute to the weak relationship between basin area and fan area in our study area.

As illustrated in Figure 5, despite the small drainage basin, fan 11 covers an extensive area of 82.39 km^2. Field surveys and satellite imagery analysis revealed that fan 11 was initially formed by a much larger basin. However, due to thrust fault activity, the feeder channel shifted, resulting in the formation of a smaller basin that now supports fan 11 (Figure 5). This disconnection from the original basin and subsequent sediment accumulation from the new smaller basin, developed over time, serve as indicators of tectonic activity in the study area, impacting the development of alluvial fans.

In our study area, the basin slope correlates with both the area and slope of alluvial fans (Figure 6(d,e)). However, this relationship exhibits a moderate reverse correlation. Contrary to conventional expectations, where a positive relationship between basin slope and fan area and slope is typically observed – indicating that steeper basins result in larger and steeper fans (Bahrami, 2013; Salehipour Milani & Beshkani, 2020; Viseras et al., 2003) – our study area demonstrates a reverse relationship. This reversal in the relationship between basin slope and fan area and fan slope may be attributed to various factors, including climatic conditions and sediment transport dynamics (Chen et al., 2022; Guerit et al., 2014; Stock et al., 2008; Ventra & Clarke Lucy, 2018). These factors can significantly influence the amount of sediment

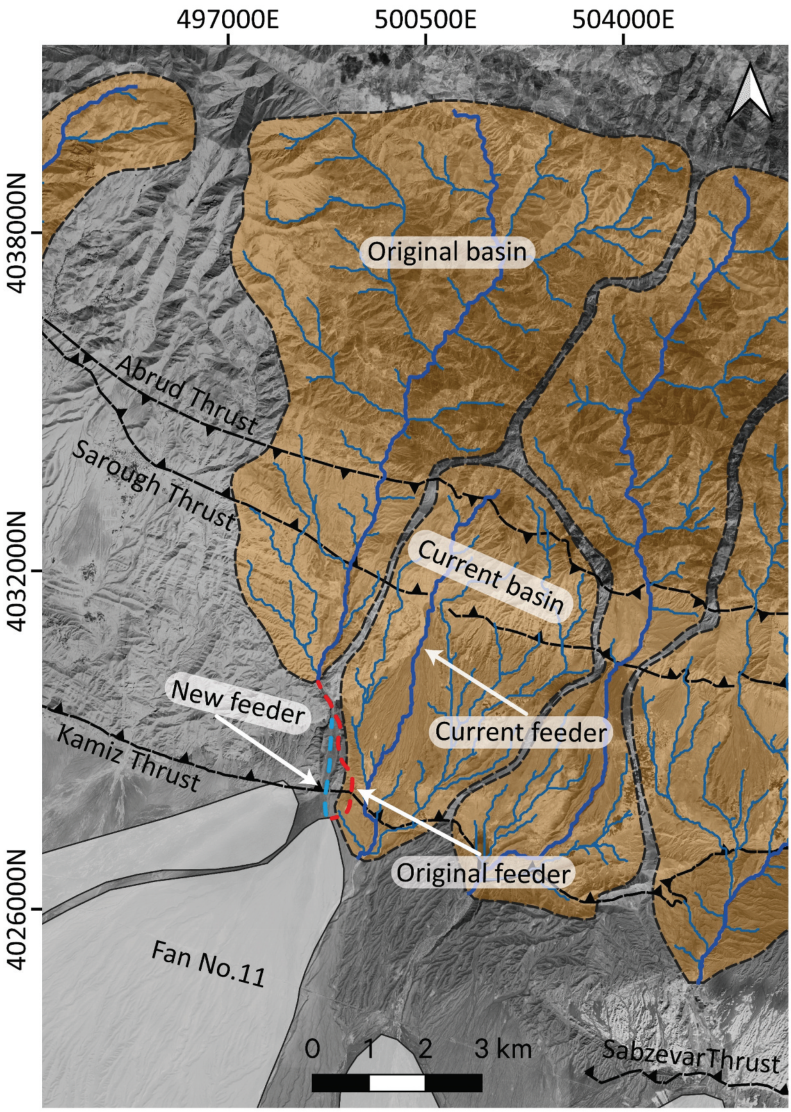

Figure 5. The impact of thrust faults in the study area on the development of alluvial fans.

deposition on the alluvial fan, thereby altering the expected relationship between basin slope and fan characteristics.

Previous literature has consistently reported positive correlations between drainage basin slope and sweep angle, as well as the width-to-length ratio (W/L) of alluvial fans (Bahrami, 2013; Mokarram et al., 2023; Viseras et al., 2003). However, our study reveals a reverse relationship for these parameters in our area, although this relationship is not particularly strong. Several factors may contribute to this observation, including variations in lithology, tectonic activity, and sediment transport dynamics within our study area.

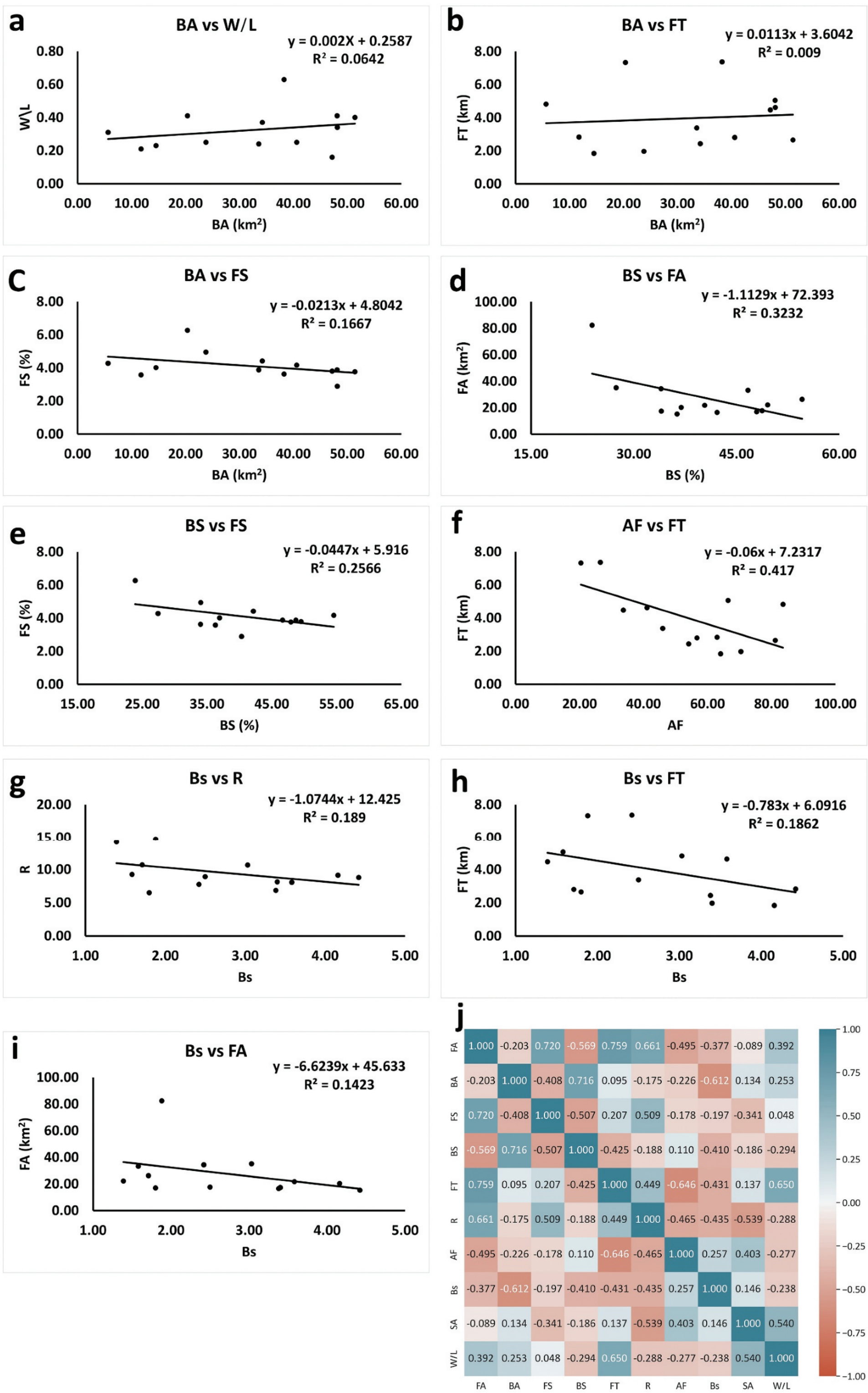

Figure 6. Linear relationship and R^2 values between BA vs W/L (a), BA vs FT (b), BA vs FS (c), BS vs FA (d), BS vs FS (e), AF vs FT (f), Bs vs R (g), Bs vs FT (h), and Bs vs FA (i), and Pearson's correlation coefficient between the investigated parameters (j).

According to Lecce (1991) and Shoshta and Marh (2021), the transportation of sediments to the fan area is not effectively facilitated by larger and gentler catchment basins, as they function as sediment storage areas instead. Conversely, smaller basins have the capability to transport sediments to the fan surface more efficiently, given their inability to store sediments. Therefore, larger and steeper basins create smaller and gentler fans. This is also confirmed by our results showing the negative correlation between BA-FS\BA-FA and BS-FS\BS-FA.

Pearson correlation analysis shows that asymmetry factor has the strongest relationship with sweep angle, among other morphometric characteristics. The relationship between AF-SA in the studied area reveals that tectonic uplifting in the drainage basin resulted in smaller sweep angle values and lateral confinement of the alluvial fans. The lateral movement of our studied fans could also be related to the activity of the faults and propagation of an uplifting anticline (Figure 7). Active faults in the mountain front may shift the alluvial fans laterally, away from their feeder channel (Bowman, 2019; R. Figueroa et al., 2021; Özpolat et al., 2022).

Results of our study also show that basins characterized by higher AF values (e.g., fans 2, 3, 8, and 13) have created alluvial fans with smaller FT values. Conversely, alluvial fans with greater FT values (e.g., fans 11, and 9) are associated with basins with smaller AF values.

Analysis of sweep angle values (Table 2) shows that all studied fans have a sweep angle value of less than 95°. SA values smaller than 180° indicate the lateral confinement of the alluvial fan. Alluvial fans developed in an unconfined condition become semi-circular, and their SA values approach 180° (Mukerji, 1990; Shoshta & Marh, 2021). In tectonically active regions, exemplified by the Danehkhoshk anticline in the Zagros Mountains, distinctive features including highly entrenched fans with sweep angles predominantly smaller than 50 degrees and extended bases represent a clear manifestation of significant tectonic activity (Bahrami, 2013). These geomorphic elements are intricately influenced by both tectonic uplift and the development of V-shaped valleys, playing pivotal roles in determining the fan's morphology and morphometry. Conversely, in regions characterized by lower tectonic activity, the sweep angle becomes subject to the interplay of various factors, including climatic conditions, base level variations, and the characteristics of the drainage basin (Menier et al., 2017; Robl et al., 2017). Notably, our study reveals larger sweep angle values when compared to highly active areas (Lin et al., 2009; Moreno & Romero-Segura, 1997; Stokes & Gomes, 2020). This observation implies that tectonic forces, in conjunction with climatic influences, collaborate in shaping the morphological characteristics of the studied alluvial fans.

The analysis of the correlation coefficient between basin shape (Bs) and morphometric parameters did not yield significant outcomes, suggesting that the morphometric characteristics of the studied alluvial fans are not substantially influenced by the drainage basin shape. However, the basin shape index exhibited a moderate reverse relationship with alluvial fan radius. This phenomenon can be attributed to the tendency of elongated basins to deliver sediment in a more focused manner, potentially resulting in a larger radius on the side where the stream exits the basin (Mokarram et al., 2022; Shoshta & Marh, 2021). Additionally, basin shape demonstrated a reverse relationship with fan toe length in our study area. However, we believe that this relationship may be more closely related to other factors such as sediment transport dynamics or tectonic activity. Further

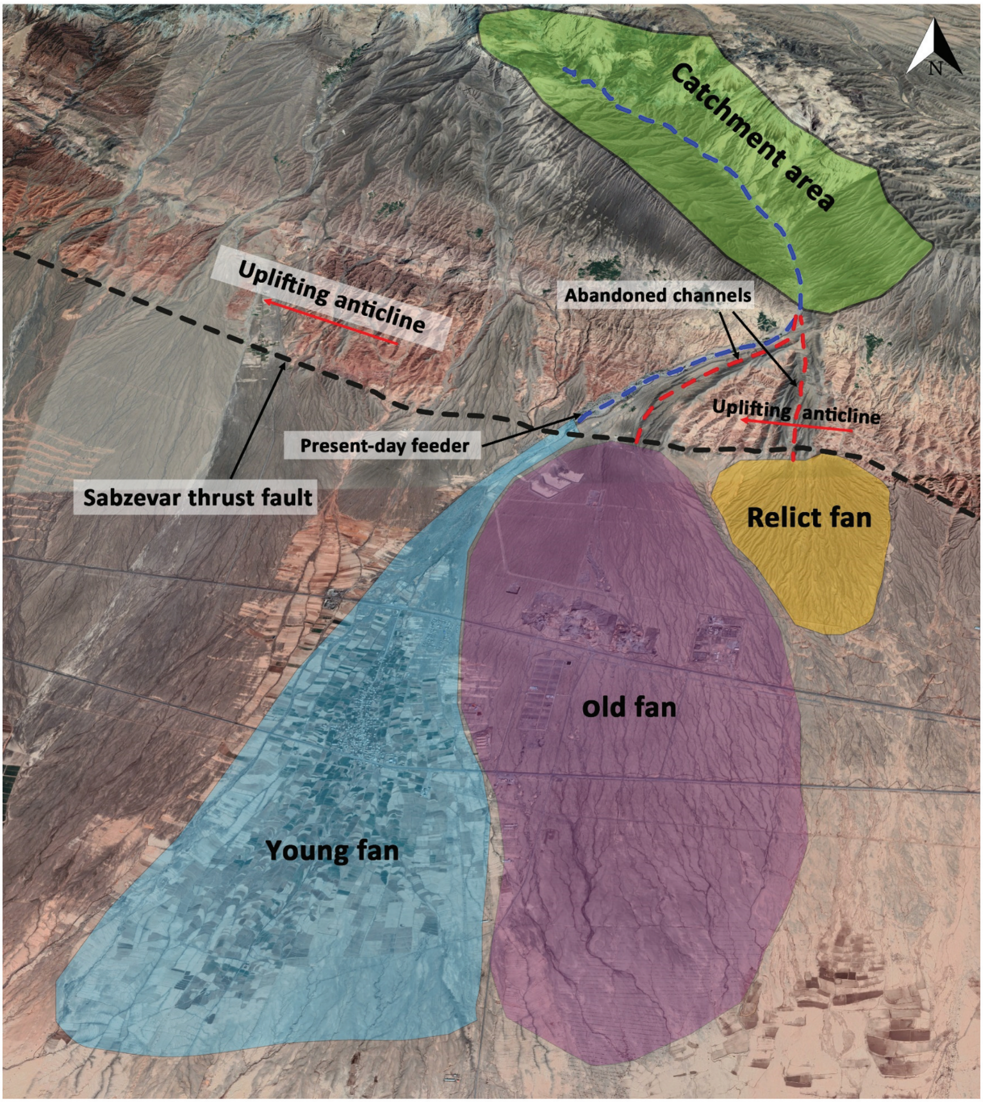

Figure 7. Satellite imagery showing the impact of tectonics and fault activity on (1) forming different alluvial fan surfaces (e.g., relict, old, and young), (2) impact of tectonics and fault activity on lateral confinement of alluvial fans.

investigation is needed to fully elucidate the underlying mechanisms driving these observed relationships.

An increase in the sweep angle usually results in an increase in the fan toe length (Bahrami, 2013); however, in our studied fans, there is a weak relationship between the sweep angle and fan toe length (Table 2), which can be attributed to the lateral confinement of the alluvial fans. In fan 9, where the alluvial fan is not laterally confined, the fan toe length is proportional to the sweep angle, whereas in fan 5, despite the high sweep angle value, the fan toe length is short.

In addition to the drainage basin characteristics that signify tectonic activity, fault activities can profoundly impact alluvial fans. Fault activities have the potential to alter the drainage pattern within the basin area, change the course of feeder channels, influence sediment dynamic characteristics, and induce uplift on one side of the fault while causing subsidence on the other (Hernandez-Marin & Burbey, 2009; Hodgson David & Haughton Peter, 2004; Leeder & Jackson, 1993). In our study area, the presence of thrust faults serves as a clear indication of ongoing tectonic activities. The effects of fault activity on the alluvial fans studied are notable, including the incision and truncation of alluvial fan apices, repeated displacement and relocation of depositional space, and the presence of fault scarps (Figure 5). Among the significant faults in the study area, the Sabzevar thrust fault stands out. The Sabzevar thrust fault along with Kamiz and Sarough thrust faults has played a crucial role in altering the course of feeder channels within the alluvial fans and promoting the development of an anticline composed of Neogene sediment at the apexes of these fans (Figure 7). Research conducted by Azor et al. (2002) suggests a direct correlation between fault activity and the propagation of this anticline. Consequently, this process has resulted in the deepening of the apexes of alluvial fans and the uplift of older surfaces within them. Based on field evidence and the remnants of alluvial fans found atop the anticline, it can be inferred that the propagation of the anticline occurred during the Quaternary period. Furthermore, observations suggest that the Sabzevar thrust fault was active during the Quaternary period, further supporting the notion of ongoing tectonic activity in the region during this time frame.

Conclusion

Based on our findings, asymmetry factor and basin shape values suggest the activity of tectonics in the Joghatay mountain range. Our study further demonstrates a negative correlation between alluvial fan slope and basin area, which aligns with similar research conducted on alluvial fans in arid (e.g., Iran, and United states). In these regions, it has been observed that an increase in the basin area is associated with a decrease in alluvial fan slope. Additionally, our results indicate a weak correlation between the basin area and the alluvial fan area, which can be attributed to the intricate lithology and tectonic activity present in the Joghatay mountain range.

All alluvial fans examined in this study exhibit sweep angles that are smaller than 95°, which suggests that they are laterally confined. Lateral confinement has led to the formation of elongated alluvial fans within the study area. The literature suggests that alluvial fans with sweep angles greater than 180° tend to be semi-circular, which indicates that they have formed under unconfined conditions. The results of this study suggest that the lateral confinement of the alluvial fans investigated may be attributed to the fault activity and the propagation of an uplifting anticline. Moreover, the confinement has also led to smaller fan toes, as evidenced by the weak correlation between sweep angles and fan toes.

According to our results, the morphometric characteristics of alluvial fans exhibit a negative correlation with the slope of their corresponding basin, particularly with the parameters of FA, FS, and FT. This relationship is primarily influenced by the sediment properties of the catchment. Our results suggest that smaller and steeper fans are typically formed by larger and gentler basins, while larger fans tend to form by smaller and more rugged basins due to their sediment transport efficiency.

While morphometric indices serve as valuable tools for assessing relative tectonic activity in a region, their utility in understanding the impacts of tectonic activities on alluvial fans is limited due to several factors. One significant limitation is that the morphometry and development of alluvial fans are influenced not only by tectonics but also by other factors such as climate and anthropogenic activities. Therefore, future studies should consider incorporating the effects of climatic and anthropogenic factors to provide a more comprehensive understanding of the dynamics shaping alluvial fans.

In terms of studying the tectonic impacts on alluvial fans in northeast Iran, we recommend conducting a study that encompasses alluvial fans in neighboring mountain ranges, including Kopet Dag and Binalood. This broader scope would allow for a more detailed inventory of tectonic impacts on alluvial fans in this less-studied area of Iran. By encompassing multiple mountain ranges, researchers can gain insights into regional variations in tectonic activity and its effects on alluvial fan morphology and development. Such comprehensive studies are essential for advancing our understanding of landscape evolution and natural hazard assessment in tectonically active regions.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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