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Active Deformation Analysis in the Dehdasht Structural Basin Based on Geomorphic Features

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Abstract

The Dehdasht Structural Basin, at the boundary of the southern Dezful Embayment and the Izeh Zone, is bordered by large anticlines with Cretaceous to Oligo-Miocene outcrops above hidden basement faults. The drainage system within the Dehdasht Structural Basin and the surrounding is considerably influenced by growth of the Gachsaran diapiric anticlines and salt extrusions and of the boundary anticlines. The Bangestan anticline in the NW of the basin uplifted 655 m since the Maroon River was diverted. Comparing the uplifts recorded in the topography of the large anticlines which are related to the Mountain Front Fault, to their structural amplitudes shows that the Khaviz anticline on the southern Dehdasht Structural Basin has more recent activity than the Bangestan and the Kuh-e-Siah anticlines. Variations of the local base levels along these anticlines with regards to their recent uplift values suggest 30 to 45% contribution of the thrust faults on their forelimb in the active deformation of the structures bounding the Dehdasht Structural Basin.

Keywords: Dehdasht Structural Basin; Local base level variations; Active deformation; Maroon River; Central Zagros.

Introduction

Geomorphology and drainage system respond to deformation variation and provide indirect information of tectonic activity [1-4]. Therefore, analyzing the relation between active tectonics and surface processes or landforms could help detecting the variation in deformation styles and growth rate and direction of the active structures [5]. The drainage systems in mountain belts at least in Holocene time are the most sensitive indicators of surface horizontal and vertical deformation [6]. Interaction between growing folds and streams forms water and wind gaps when the uplift rate is, respectively, slower or higher than the stream incision rate [7, 8].

The Zagros belt is among of the active tectonic regions and its active deformation since 5 to 8 Ma [9, 10, 11], is concentrated in the Zagros Simply Folded Belt mostly as folding [4]. Historical and instrumental earthquakes along the Mountain Front Fault (MFF) in the Fars Arc and also in the Dezful Embayment to the south of the Khaviz anticline [12], local tilting of the Quaternary terraces near the MFF

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[13], Geodetic studies [14] and dating of the Holocene fluvial-marine terraces in the Fars Arc [15] show the recent Zagros deformation is mostly accommodated across the MFF [8]. Analyzing drainage system including their anomaly, deviation in their path or variation in the local base levels across the faults/folds has been used in different parts of the Zagros fold-and-thrust belt to study active deformation such as fold growth [8, 16-18].

The Dehdasht Structural Basin, which is the focus

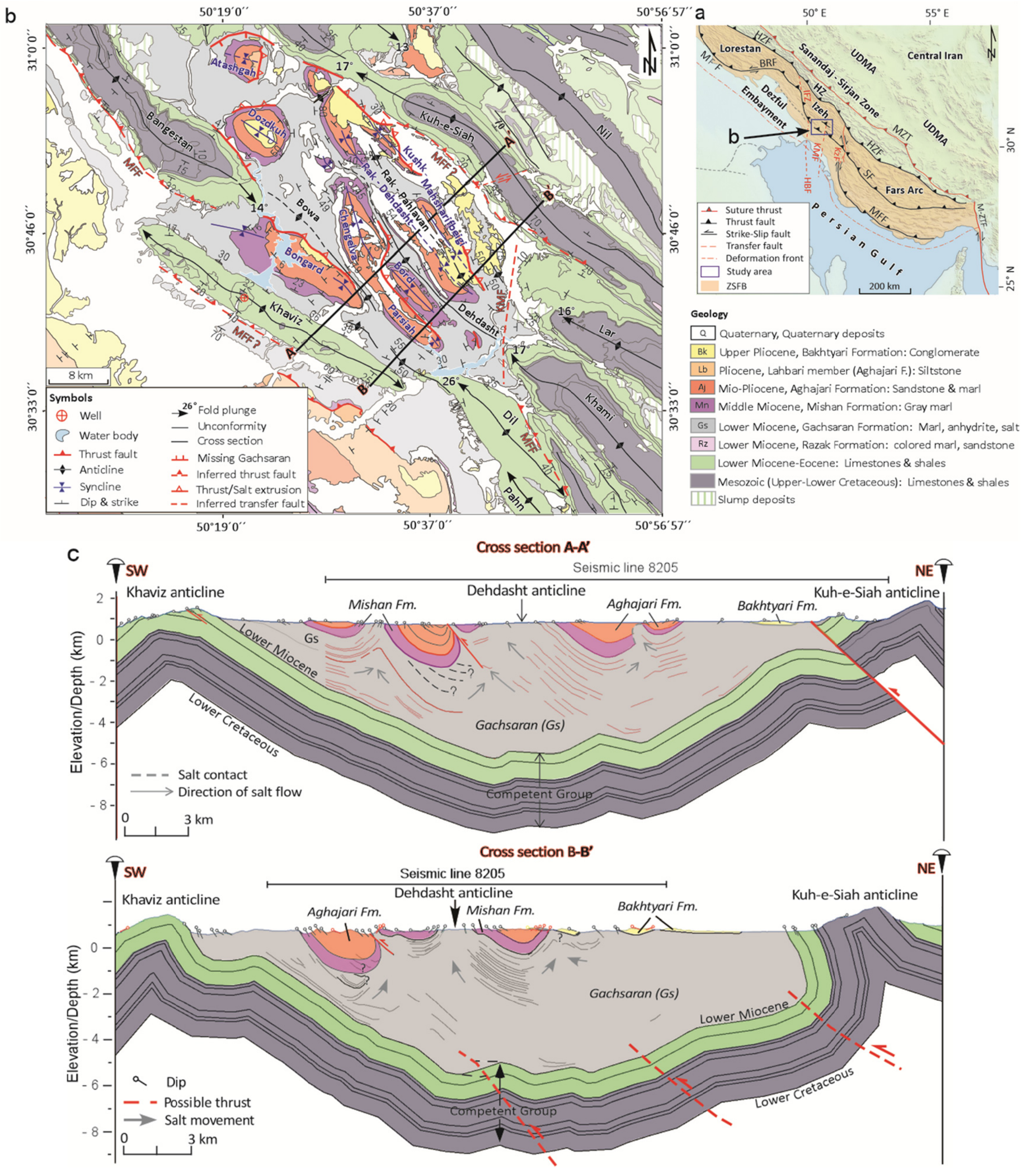

Figure 1. a) Location of the study area in the Zagros belt. UDMA: Urumieh-Dokhtar Magmatic Assemblage, MZT: Main Zagros Thrust, HZF: High Zagros Fault, Hz: High Zagros zone, BRF: Balarud Fault, IZF: Izeh Fault, HBF: Hendijan-Bahregansar Fault, KMF: Kharg-Mish Fault, KzF: Kazerun Fault, MFF: Mountain Front Fault. b) Geological map of the Dehdasht Structural Basin and its surroundings (after [26, 28]). c) Geological cross-sections across the SE and the center of the basin. See Fig. 1b for locations.

of this study, is located in the central part of the Zagros Simply Folded Belt (Fig. 1a). This lowland area, located between the Izeh Zone and the Dezful Embayment, is surrounded by the large anticlines of the Kuh-e-Siah, Bangestan, Lar, Khami, Dil and Khaviz (Figs. 1b, 3). The Dehdasht Structural Basin, characterized by surface anticlines resulted from diapiric activity of the Miocene Gachsaran Fm. in combination with contractional tectonics [19], is locally drained but it is also joined to the regional drainage systems to its NW and SE borders. In this study, the recent structural evolution of the basin is investigated using pattern of the drainage system and the surface morphology of the structures compared to their geometries at depth. In this regard, we use geomorphic features to study the effects of the geologic structures on drainage system of the basin and the amount by which the main limiting structures contribute in the active deformation of the basin. The results of this study could help to understand the recent deformation in the frontal part of the Zagros Simply Folded Belt.

Geological setting and structures of the Dehdasht Structural Basin

The Dehdasht Structural Basin is a part of the Dezful Embayment and defined at first by Sepehr and Cosgrove [20] as an embayment along the surface trace of the MFF. This embayed area is suggested to be formed by a segmentation of the MFF running beneath the Kuh-e-Siah anticline to the NE and the Mish anticline to the SE (Fig. 1b; [20]). The connection between the two segments is inferred by strike-slip faults moving the central block and the Khaviz anticline towards the SW [18] or by a lateral ramp to the east corresponding to the blind Kharg-Mish Fault [21] that caused changes in facies and thickness of the Cretaceous units [20, 22]. The Kharg-Mish Fault limits the NW terminations of the Lar, Khami and Dil closely-spaced anticlines (Figs. 1b, 3). The NW boundary of the Dehdasht Structural Basin is limited by the SE-dipping terminations of the Kuh-e Sefid, Tavechegah and Bangestan anticlines [Fig. 1b]. The less aligned position of the SE plunges of the anticlines along the NW border of the Dehdasht Structural Basin complicates its interpretation by means of a blind fault in depth as suggested by Sepehr and Cosgrove [20]. Furthermore, the Khaviz anticline forms the southern boundary of the basin where it is potentially affected by the MFF (e.g. [12]; Fig. 1b). The Main characteristics of the Dehdasht Structural Basin is the narrow and elongated growth synclines-minibasins containing the Neogene deposits with growth patterns that are resulted from synchronous shortening and diapiric evolutions [19]. These structures are decoupled from the structures of the underlying Competent Group at depth due to the thick Gachsaran evaporitic deposits between them (Fig. 1c).

The Competent Group of O'Brien [23], from Cretaceous to Early Miocene, is observed in the cores of the high-amplitude anticlines surrounding the Dehdasht Structural Basin (Fig. 1b). The Neogene deposits filling the basin are composed of evaporites of the Gachsaran Fm., a thin horizon of the Mishan marine and the Aghajari-Bakhtyari non-marine deposits (Fig. 1b, c) which have similar characteristics of those in Mesopotamian foreland basin and collectively termed the Fars Group (Fig. 2). The Gachsaran Fm. has covered the large part of the Dehdasht Structural Basin (Fig. 1c). The Mishan, Aghajari and Bakhtyari formations filling the growth synclines within the Dehdasht Structural Basin show mostly higher elevation with regards to the loose deposits of the Gachsaran Fm. in their adjacent diapiric anticlines (Fig. 3).

From structural geology point of view, the Dehdasht Structural Basin is completely different from the adjacent regions. To the SE there are 5 large closely spaced anticlines without accumulation of the Fars Group deposits (Fig. 1b). To the NW, number of the large anticlines decreases to three and the volume of the Fars Group deposits increases. Between these two regions (i.e. the Dehdasht Structural Basin) only two largely spaced anticlines of the Kuh-e-Siah and the Khaviz crop out and covered by a large volume of the Fars Group deposits (Fig. 1b, c). The dominant internal structures of the basin are the elongated synclines (minibasins) covered by the clastic deposits of the Fars Group and limited by the narrow ridges with outcrop of the Gachsaran evaporites (Fig. 1b). The anticlines and synclines within the basin could be categorized into three and four series, respectively (Fig. 1b). From NE to SW, the anticlinal series are the Rak-Pahlavan, the Dehdasht (along with the Khami anticline) and the Bowa (along with the Bangestan and Dil anticlines), and the synclinal series include the Kushk-Mahsharifbeigi, the Rak-Dehdasht, the Chengelva and the Bongard. In the central and SE Dehdasht Structural Basin the trend of synclines is NW-SW, parallel to the boundary large structures. However, to the NW by increasing the Gachsaran outcrop, the synclinal trends deviate and only two almost circular synclines (Dozdkuh and

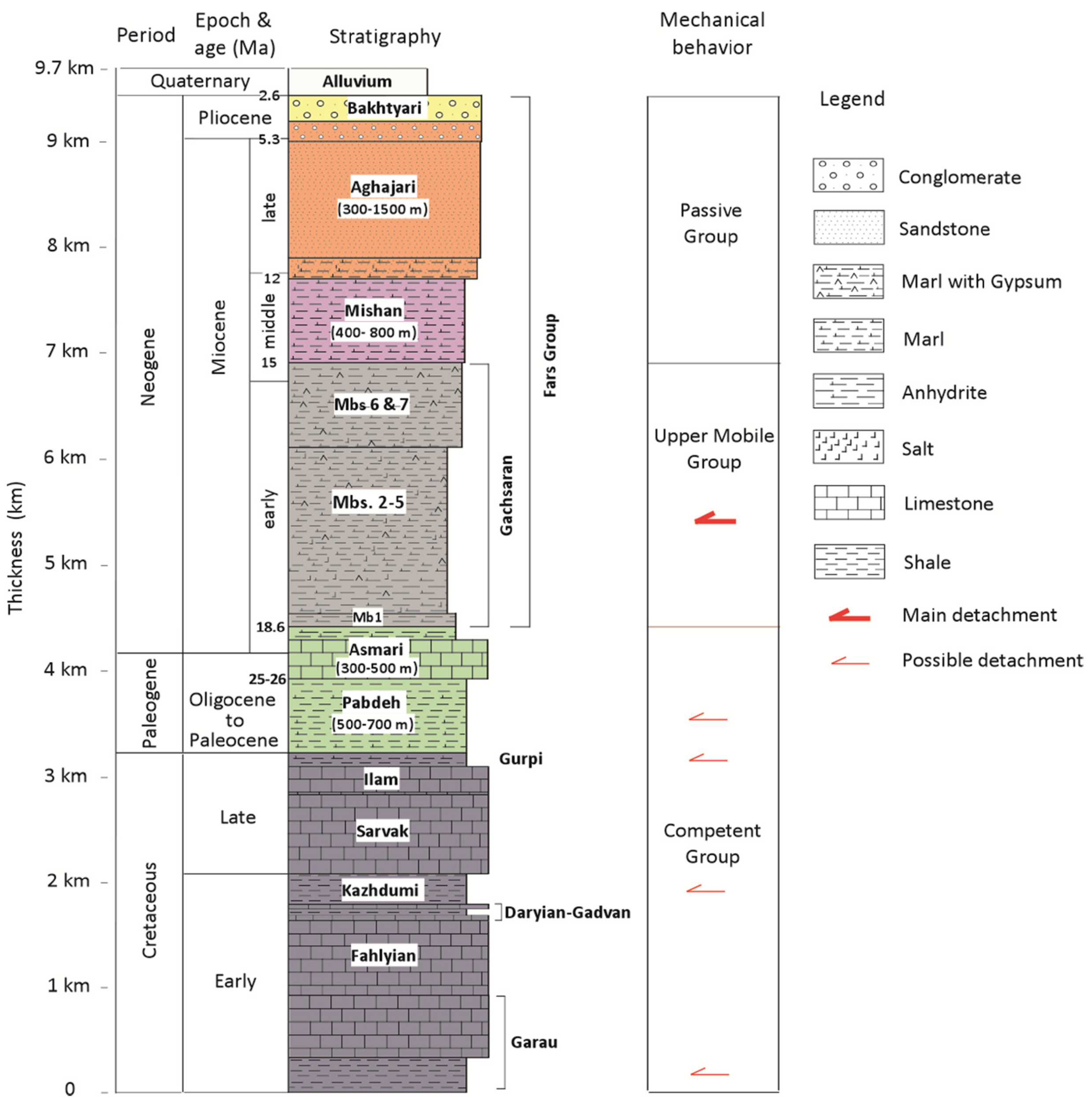

Figure 2. Stratigraphic column of the study area down to the Lower Cretaceous based on geological maps (after [26, 28]), well data from the Khaviz anticline (NIOC, unpublished report). Mechanical behavior is based on O'Brien [35]. Absolute ages are based on strontium isotope dating: Ages of base and top of the Asmari Fm. from the Khaviz anticline [16]; ages for the Mishan Fm. from the Aghajari anticline to the southwest [38]. Thickness of the Gachsaran Fm. is calculated by restoration of the regional cross-sections across the Dehdasht Structural Basin using area constant method.

Atashgah synclines) form at surface. There, the Rak-Kushk synclines are separated from the Dastwapas syncline by the N-S Torab diapiric anticline (Fig. 1b). The structures of the Competent Group within the basin are very low-amplitudes and low-wavelength anticlines forming the average- and large-amplitude anticlines exposed at the boundaries of the basin where they create the basin steep boundaries (Fig. 1c).

There are three important thrust faults in the study area including the MFF (on the southern limbs of the Bangestan, the Kuh-e-Siah and the Khaviz

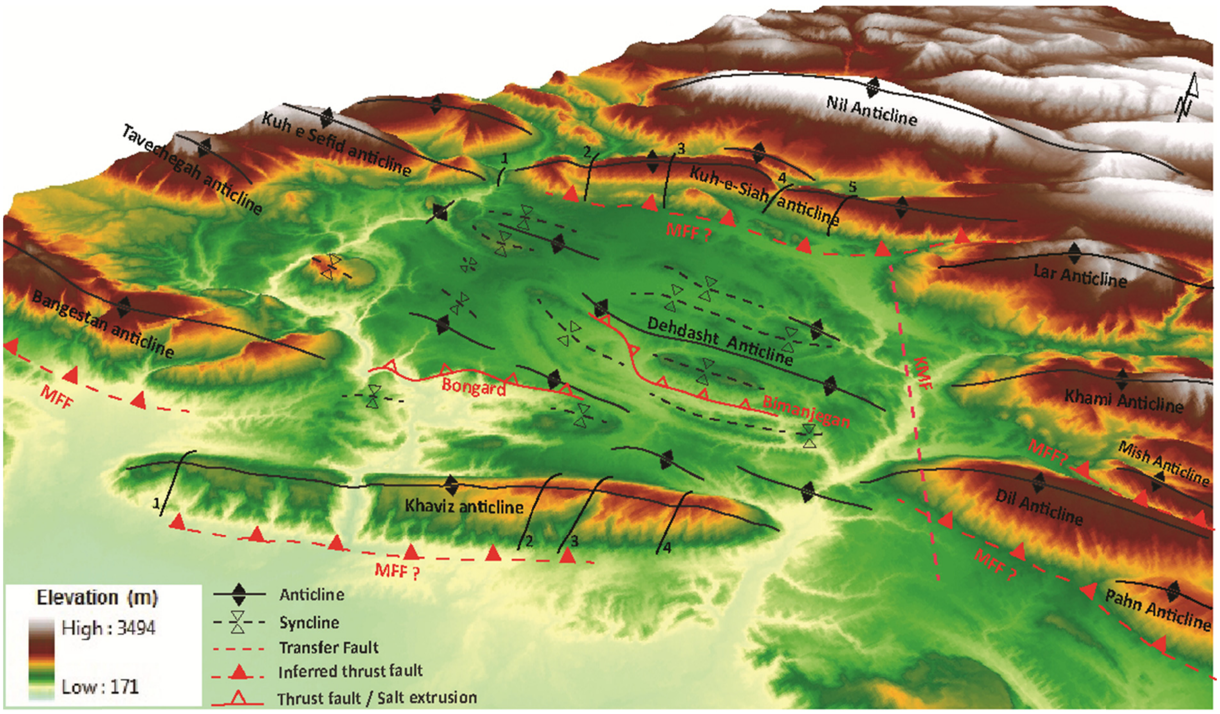

Figure 3. Digital Elevation Model (Dem 30m) of the Dehdasht Structural Basin and the surroundings. The numbers refer to the topographic profiles across the Khaviz and Kuh-e-Siah anticlines and are shown in Fig. 8. MFF: Mountain Front Fault.

anticlines), Bimanjegan and Bongard faults (Figs. 1b and 3). Bimanjegan and Bongard thrust faults are resulted from salt extrusion due to salt withdrawal within the Gachsaran Fm. under the synclines. The studies on the Kuh-e-Siah anticline show also several transverse and longitudinal strike-slip faults including one at the middle part of the anticline (Fig. 1b), which is suggested to be formed before the folding event [24].

Material and Methods

To define the pattern of drainage system in the Dehdasht Structural Basin, all of the permanent and temporary drainages are detected from the topographic maps [25] and the Digital Elevation Model (DEM 30m; [25]). The Dehdasht structures are presented through several balanced geological cross-sections prepared by using surface data (from field survey and remote sensing) and subsurface data (the interpreted seismic reflection profiles). Then, by comparing the structures at surface or depth to the drainage system the possible role of structures will be investigated.The locations showing diversion in the pattern of drainage system are specified for more detailed study using topographic profiles to find the controlling parameters. Surface morphology of the main anticlines of the region is studied by longitudinal and transverse topographic profiles. Their minimum uplift is calculated based on their maximum elevation from the local or regional base levels around them [11, 17], which is shown in Fig. 4a. To determine the recent uplift of the anticlines limited the Dehdasht Structural Basin their minimum uplift amounts are compared to their structural amplitudes in the geological cross-sections (Eq. 1).

$$U_{recent} = (U_{min}/A)*100 \qquad (1)$$

where U_{recent} depict the recent uplift percentage, U_{min} is the minimum uplift calculated from the topographic profiles along the anticlines (Fig. 4a), and A shows the anticline amplitude obtained from the geological cross-sections (Fig. 1c).

Using a comparision between the recent uplift of the large anticlines bounded the Dehdasht Structural Basin, we suggest the relative timing of their activity. The lower U_{recent} shows the older activity while the higher percentage reveals that the most activity of the anticline has been recorded in the topographic profile

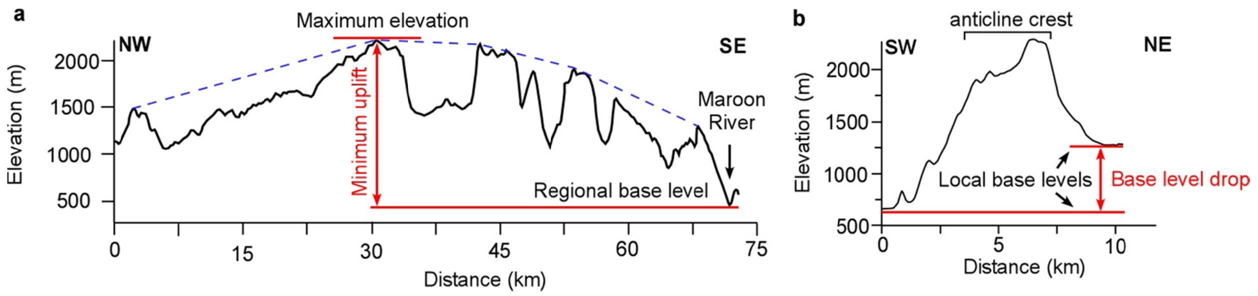

Figure 4. Calculation of a) the minimum uplift from the longitudinal topographic profile along the anticlines and b) the base level drop from the topographic profile across the anticlines in this study [based on 30, 31].

and the anticline is younger.

Additionally, variation in the local and regional base levels across the large anticlines which are related to the thrust faults are used for defining recent activity of the thrust faults (Fig. 4b) similar to the method used by Mouthereau et al. [11, 17]. By comparing the obtained base level drops (Fig. 4b), from the topographic profiles across the large thrust-related anticlines bounded the Dehdasht Structural Basin, to the minimun uplift of these anticlines, the possible thrust fault activity responsible for the recent uplift of the anticline will be calculated (Eq. 2).

$$Ta_{recent} = (D_p / U_{min\text{-}p})*100 \qquad (2)$$

where Ta_{recent} shows the recent activity of the thrust fault, D_p and $U_{min\text{-}p}$ are, respectively, the local base level drop and the U_{min} in each transverse topographic profile.

Finally, schematic models are proposed for evolution of the drainage system in some parts of the Dehdasht Structural Basin.

Results

Drainage system in the Dehdasht Structural Basin

The Dehdasht Structural Basin includes two drainage basins. The divide line of these drainage basins passes through the northwest of the Dehdasht anticline and its adjacent synclines (Fig. 5). Low order (minor) drainages and rivers within the Dehdasht Structural Basin drain away from this divide line to the Maroon River to the NW and to the Shah Bahram/Kheirabad River to the SE.

General pattern of the drainage system in the Dehdasht Structural Basin and its surroundings shows a parallel trend to the geological structures. The main rivers entering to this basin (including Maroon, Chorum and Shah Bahram rivers) pass parallel to the large anticlines through the synclines and mostly deviate around the nose of these anticlines or locally cut their noses (Fig. 5). These rivers after changing their courses around the nose of the anticlines continue as transverse rivers. The main drainages within the basin have also parallel courses with regards to the structures; however they mostly pass along the anticlines with outcrop of the Gachsaran incompetent evaporites and deviate occasionally (Fig. 5). These drainages originate from the local hills (ridges of the Gachsaran evaporites) within the basin. There is no important transverse river in the Dehdasht Structural Basin. In the following the drainage system in the Dehdasht Structural Basin is explained from the main rivers to the minor drainages.

The Maroon River which originates from the north of the Siah and Kuh-e-Siah anticlines (Fig. 5), to pass across the Kuh-e-Siah and Kuh-e-Sefid anticlines chose the low-elevated saddle between them. Then it flows to the SW through a path between NW nose of the Kushk-Rak and the Dastwapass synclines along the N-S Torab diapiric anticline (Fig. 5). After turning the Dozdkuh rounded syncline, it deviates around the SE nose of the Bangestan anticline. Then by passing through the Bongard syncline (containing the Mishan and Aghajari formations) and cutting the Khaviz large anticline, it drains to the Behbahan plain (Fig. 5). In the Bongard syncline, there are many low order parallel drainages joining the Maroon River from the both NW and SE noses of the syncline.

The main parallel rivers within the Dehdahst Basin drain to the SE to the transverse ShahBahram-Kheirabad rivers (Fig. 5). The Shah Bahram River flows parallel to the Lar anticline and cut its NW termination. Then it deviates toward the NW nose of

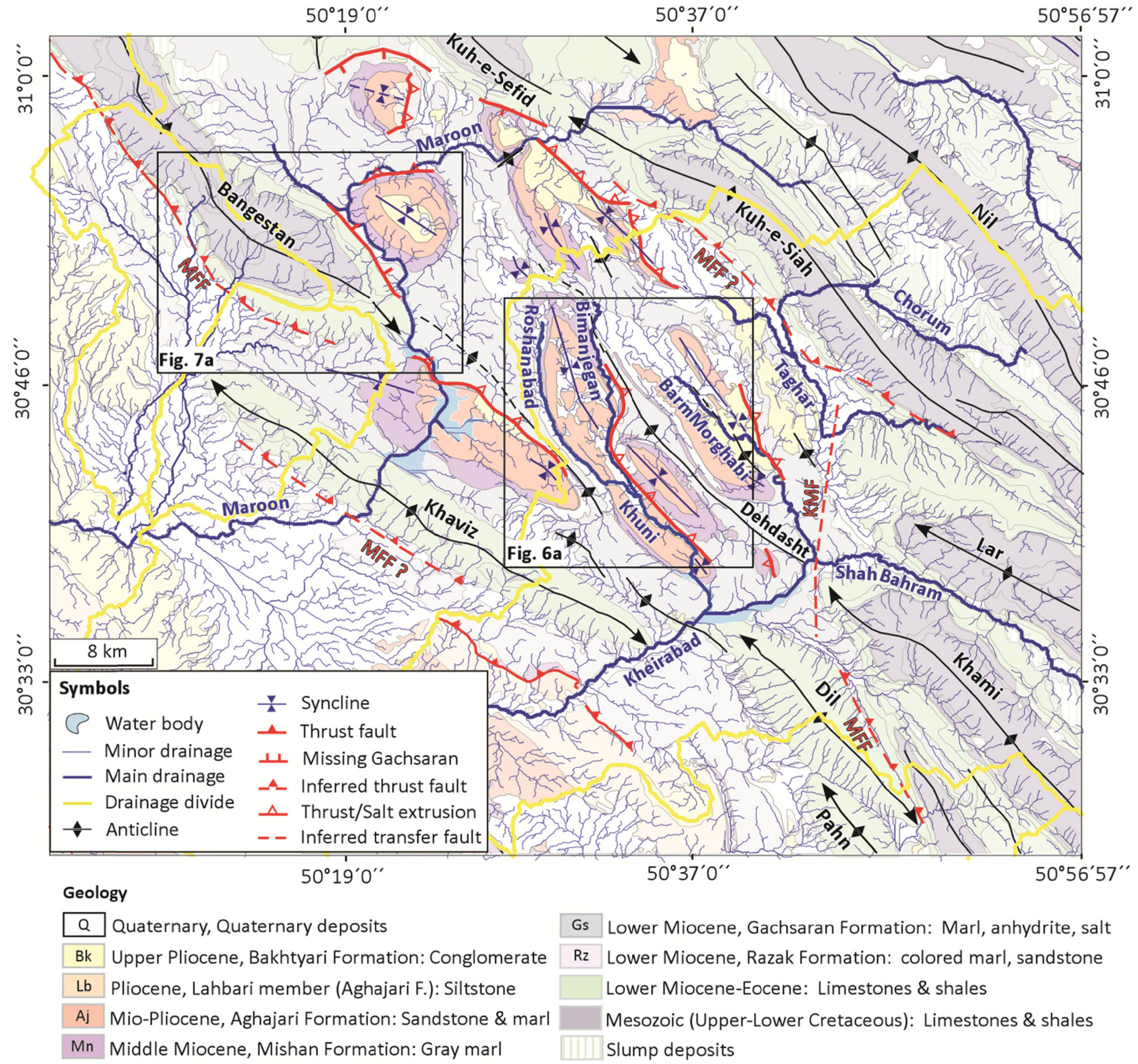

Figure 5. Drainage system of the Dehdasht Structural Basin projected over the transparent geological map.

the Khami anticline where it changes to the Kheirabad River after joining to the Barm-Morghabi parallel River coming from the central Dehdasht Structural Basin (Fig. 5).

The rivers which flows parallel to the folded structures within the Dehdasht Structural Basin are the Barm-Morghabi, Bimanjegan and Roshanabad rivers (Fig. 5). The Barm-Morghabi River flows along the Rak-Pahlavan anticlinal series between the two Dehdasht and Mahsharifbeigi synclines. While at the SE part of the anticline where the Bakhtyari deposits are significantly folded, the river deviates toward the SE Mahsharifbeigi syncline and finally drains to the Shah-Bahram River. The Roshanabad River flows along the elevated SW limb of the Chengelva syncline and follows its curvature. The Bimanjegan River which flows along the NW Dehdasht anticline, in the middle part deviates to the

SW and continues its course between the Bord and Parsiah synclines. Toward the SE it changes to the Khuni River which cuts the SE nose of the Parsiah syncline and drains to the Kheirabad River.

Minor and low-order drainages within the Dehdasht Structural Basin could be divided into two general groups. The first group contains the minor drainages originating from the large Kuh-e-Siah and Khaviz anticlines, respectively in the northern and southern boundaries of the basin, and drain into the basin (Fig. 5). They are mostly asymmetric and fork-like. The second group includes the minor drainages flowing from the local hills within the basin (either the diapiric anticlines or elevated noses of the growth

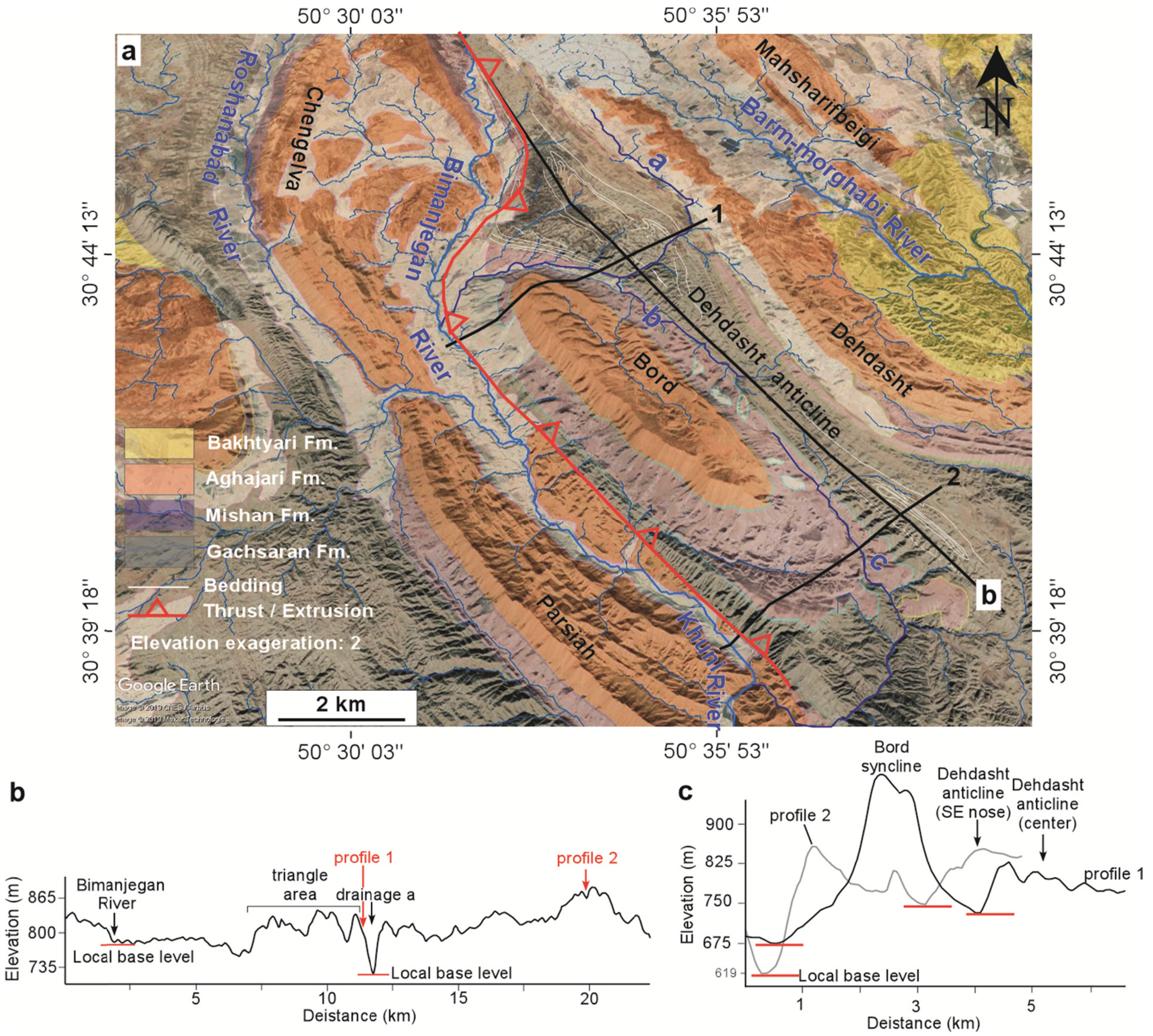

Figure 6. a) 3D picture of the Dehdasht anticline and the drainage system around it. The Gachsaran layers in the middle part and the SE nose (triangle-like areas) show subsidiary surface folding. See Fig. 5b for location. Numbers 1 and 2 indicate the location of transverse topographic profiles in part c. b) Longitudinal topographic profile along the Dehdasht anticline. c) Transverse topographic profiles (1 and 2) across the Bord syncline at the points of drainage diversions. See (a) and (b) for location. Elevation difference of the local base levels on the limbs of the syncline is 60-130 m which is related to the activity of the Bimanjegan Thrust due to the salt extrusion of the Gachsaran evaporites. "a", "b" and "c" refer to the minor transverse and parallel drainages.

synclines) and drains to the main parallel rivers of the basin and finally flow out the basin. The minor drainages in some parts of the Dehdasht Structural Basin especially to the NW (Between the Chengelva and Bongard synclines), where flow over the Gachsaran evaporites, show dendritic and symmetric patterns (Fig. 5). However, the pattern of the minor drainages is mostly asymmetric such as in the NE limb of the Rak- Pahlavan anticlinal series, around the Chengelva syncline or NW of the Kushk-Rak syncline over the Bakhtyari conglomerates (Fig. 5). Additionally, in some parts within the basin, diversion in the course of the drainages is detected including around the Bord syncline located on the SW limb of the Dehdasht anticline (Figs. 5 and 6).

Recent uplift of the main anticlines

In this section, the recent uplift of some large anticlines within and on the boundaries of the Dehdasht Structural Basin is investigated by using topographic longitudinal and transversal profiles and comparing the local base levels across them.

SW limb of the Dehdasht anticline

In the central Dehdasht anticline there is a triangle region of the Gachsaran evaporites showing surficial subsidiary folding (Fig. 6). There, on the southern limb of the Dehdasht anticline, the Chengelva syncline is divided into two smaller synclines (Figs. 1b and 6a). This triangle region makes a diversion in the courses of the transverse minor drainage "a" and the longitudinal Bimanjegan River (Fig. 6a). The transverse drainage "a" originating from the northern limb of the Dehdasht anticline flows firstly parallel to the northern extent of the triangle region then cuts the anticline at the SE limit of this region. The Bimanjegan River flowing along the crest of the Dehdasht anticline deviates to the SW at the NW limit of the triangle region. A longitudinal topography profile along the crest of the anticline shows a low uplift (60 m) of this triangle region with regards to the NW part of the anticline. It also indicates a 90 m incision of the drainage "a" (Fig. 6b). Minor drainages "b" and "c" originating from the bulged areas on the SW limb of the Dehdasht anticline firstly flow parallel to the Bord syncline and then deviate around the syncline noses (Fig. 6a). Transverse topographic profile across the Bord syncline at the location of the drainage diversions shows 60-130 m dropdown of the local base levels to the SW (Fig. 6c). The fall in the elevation of the local base levels could be related to the activity of the thrust/salt extrusion of the Gachsaran evaporites between the Bord and Parsiah synclines (Fig. 6a).

SE nose of the Bangestan anticline

The path of the Maroon transverse River after entering to the Dehdasht Structural Basin is diverted around the SE nose of the Bangestan anticline (Fig. 7). At the location of the river diversion there is an almost deep dry valley over the nose of the anticline where down to the Kazhdumi Fm. is outcropped. The convex-up profile (Fig. 7c; [26]), the location exactly at the point of the river diversion and the NE-SW trend comparable to the course of the former river shows the valley is a wind gap. Elevation difference between the previous (the wind gap) and the new (the current Maroon River) local base levels in the longitudinal topographic profile is 655 m which shows the uplift of the anticline since the river diversion (Fig. 7b). Additionally, based on the maximum elevation of the anticline (at the level of the Sarvak Fm.) with regards to the base level of the Maroon River at the SE nose of the anticline, the minimum uplift of the anticline is obtained 1710 m. The amplitude of the anticline at the location of the wind gap based on the available geological cross-section [27] is 2.8 km. Therefore, the U_{recent} of the anticline is obtained around 60%. The local base level on the southern limb compared to the northern limb of the anticline shows a dropdown of 500 to 700 m in the central part of the anticline while the drop decreases toward the noses especially to the SE nose (Fig. 7c, Table 1). The large dropdown of the local base level in the middle part of the anticline could be related to the Bangestan paleo-high reported by several studies (e.g. [28, 29]). The recent thrust activity (Ta_{recent}; Eq. 2) decreases from the NW nose (45%) to the SE nose (1%) (Table 1).

The Kuh-e-Siah anticline

A transverse topographic/structural profile across the central Dehdasht Structural Basin (based on the cross-section AA' in Fig. 1b) shows a 8 km relief between the syncline on the northern limb of the Kuh-e-Siah anticline and the base of the Dehdasht Structural Basin at the level of the Sarvak Fm. (Fig. 8). While, the topographic difference is 600 m. The large structural contrast could be resulted by the effect of the MFF as it is suggested by Sepehr and Cosgrove [20] for this place and by Emami et al. [30] using this method for the Lurestan Arc. The Geological cross-section (Fig. 1c) shows a thrust

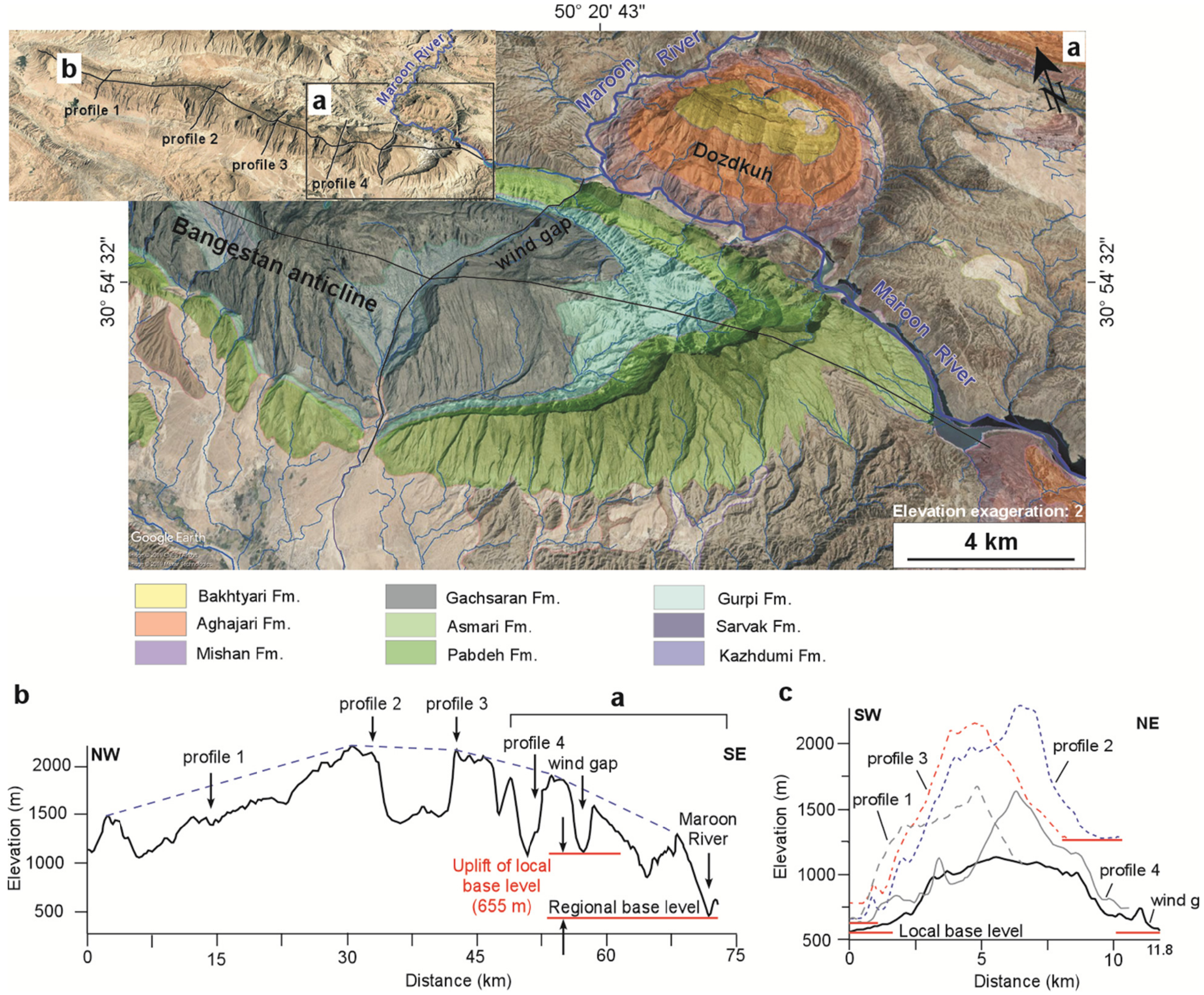

Figure 7. a) 3D picture of the SE nose of the Bangestan anticline shows diversion of the Maroon River around the nose of the anticline. b) Longitudinal topographic profile along the Bangestan anticline from the NW to the SE noses. c) Transverse topographic profiles across the anticline. Elevation contrast of the local base levels is higher in the middle part of the anticline (profiles 2 and 3). The wind gap profile is convex-up. See (b) and the inset for locations of the profiles.

fault at the surficial part in this location, too.

Longitudinal topographic profile along the crest of the Kuh-e-Siah anticline with only a deep valley (Chorum River) does not show a significant elevation variation at the level of the Sarvak Fm. (Fig. 9a). Elevation of the anticline's crest decreases generally toward the NW. The minimum uplift of the anticline considering the maximum elevation of the anticline (1942 m) with regards to the base level at its NW nose (Maroon River) is 1245 m (Fig. 9a).The amplitude of the anticline in the geological cross-sections AA' and BB' is 1.4 and 3.5 km, respectively (Fig. 1c). Using Eq. 1 gives the U_{recent} of 36% to 89% in, respectively, the middle and SE parts of the anticline. The transverse topographic profiles across the anticline show higher local base level on the southern limb (91 m at profile 1 and 179 m in profile 2; Fig. 9a) than the northern limb from the middle

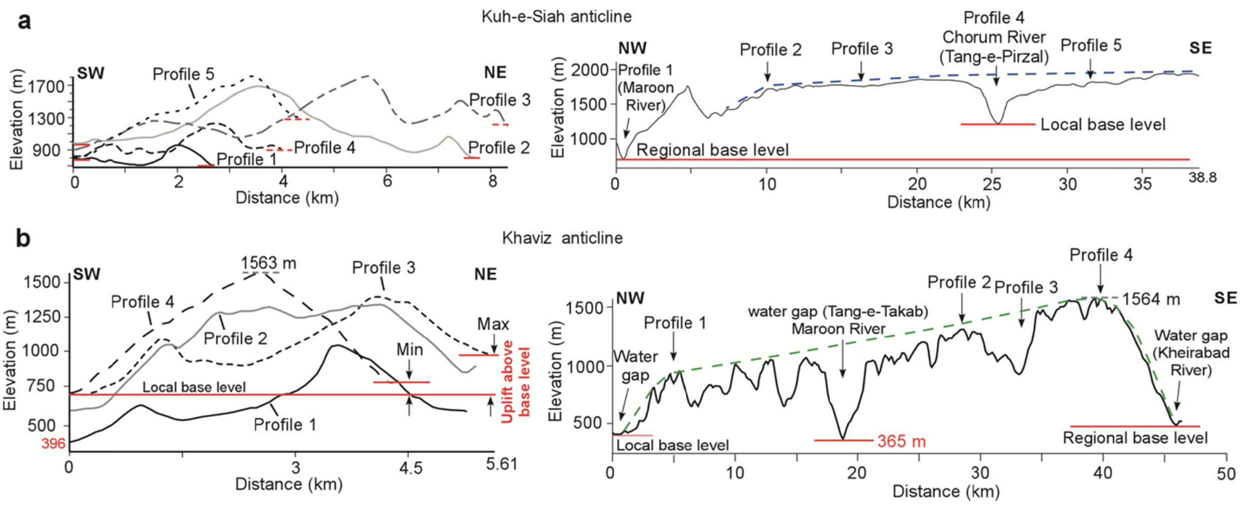

Figure 9. Longitudinal and transverse topographic profiles of (a) the Kuh-e-Siah and (b) the Khaviz anticlines. See Figs. 3 and the longitudinal profiles for location of the transverse profiles. Drop of the local base levels on the SW limb compared to the northern limb in the both anticlines are related to the thrust activity. On the NW nose of the Kuh-e-Siah anticline the drop direction of the local base level is reverse (profiles 1 and 2) compared to the other parts. Blue and green dashed lines on the longitudinal topographic profile show the possible surface of the anticlines, respectively, at the level of Sarvak and Asmari formations before erosion.

part to the NW nose (until the Kuh-e-Sefid anticline). However, from the middle part to the SE nose of the anticline the local base level in the northern limb has higher elevation than the southern one, which is higher to the SE nose (500 m in profile 5, Fig. 9a). Change in the direction of the base level drops fits exactly to the curvature of the anticline surface trace (at profile 3, Fig. 3). From this place to the SE, the folds of the Competent Group on the northern flank of the Kuh-e-Siah are very closely spaced in contrast to the southern limb with the Passive Group structures. While, toward the NW nose of the anticline the Fars Group has been deposited on the both northern and southern limbs (Fig. 1b). The salt extrusion within the Gachsaran evaporites over the Aghajari and Bakhtyari formations in the Kushk syncline could be the reason for higher base level on the southern limb of the anticline toward its NW nose. The drop of the base level toward the SW may relate to the recent activity of the MFF surface trace under the Kuh-e-Siah anticline.

Comparing the base level drops at the level of Sarvak Fm. from the transverse topographic profiles to the minimum uplift of the anticlines in those locations (U_{min-p}; Table 2) shows that the recent thrust activity affects the local base levels about 7% in the NW nose of the anticline (profile 2), 17% at the curvature of the anticline surface trace (profile 3) and 45% at the SE part (profile 5).

The Khaviz anticline

The Khaviz anticline affects the drainages on its northern limb (the Dehdasht Structural Basin) in a way that they flow parallel to the anticline trend toward the both noses where they are diverted (Fig. 5b). Longitudinal topographic profile along the crest of the anticline shows an increase in the elevation toward the SE (Fig. 9b). According to this profile, the minimum recent uplift of the anticline at the level of the Asmari Fm. is 1.2 km with regards to the base level of the Maroon River (Fig. 9b). The amplitude of the anticline in the geological cross-sections (Fig. 1c) is 1.2-1.7 km. The U_{recent} of the Khaviz anticline is calculated 70%-100% using Eq. 1. The transverse topographic profiles across the anticline show a dropdown in the elevation of the local base levels on

Table 2. Minimum uplift of the Kuh-e-Siah anticline in different parts (U_{min-p}) at the level of Sarvak and Asmari formations with regards to the Maroon River and the elevation difference of the local base levels across the anticline. See Fig. 9a for location of the profiles.

Profile	U_{min-p} (m)	Local base level elevation (Sarvak level) (m)		Base level dropdown to the SW (m), Sarvak level	Ta_{recent} (%)	Local base level elevation, Asmari level (m)		Base level dropdown to the SW (m), Asmari level	Ta_{recent} (%)
		NE limb	SW limb			NE limb	SW limb		
2	1022	1068	1050	68	7	880	979	-99	-10
3	1079	1226	1047	179	17	1188	894	294	27
4	1121	1300	800	500	45	1299	795	504	45

the southern limb. The maximum and the minimum drops, respectively, are in the middle part of the anticline (280-290 m, profiles 2 and 3) and near to the SE nose (90 m, profile 4; Fig. 9b). To the NW nose, the base level drop is about 215 m. The surface trace of the MFF is also suggested to the south of the Khaviz anticline based on the earthquake epicenters [12]. The seismic reflection profiles of the Mansourabad oil field to the Southern limb of the Khaviz anticline (unpublished report) show a thrust fault from the NW nose toward the SE, close to the location of topographic profile 3 [Fig. 3], which is shown in the geologic map, too (Fig. 1b). This base level drops could be related to the recent activity of the thsrust fault to the south of the Khaviz anticline.

Additionally, the effect of the recent thrust activity on the base levels (Ta_{recent}; Eq. 2) is 23% at the NW nose (profile 1), 30% in the middle part (profile 2) and 7% to the SE (profile 4) obtained by comparing the dropdowns in the elevation of the local base levels to the minimum uplift of the anticline (Table 3).

Discussion

In this section, first we describe how the geologic structures in the Dehdasht Structural Basin affect the drainage system. Then the recent deformation of the basin compares to its finite deformation.

Evolution of the drainage system in the Dehdasht Structural Basin

As mentioned earlier, diversions in the pattern of drainage system in the Dehdasht Structural Basin and the surroundings are directly related to the geological structures such as regional folds, diapiric anticlines and thrust/salt extrusion (e.g. Figs. 6 and 7). The effects of structures on the pattern of the drainage system are large enough to deviate even the boundary line of the two drainage basins covered the Dehdasht Structural Basin. The diapiric anticlines and the growth synclines – minibasins in the Dehdasht Structural Basin make the water divide deviates to the NW (Fig. 5a). The parallel course of the main drainages and rivers to the structures within the Dehdasht Structural Basin and the adjacent regions

Table 3. Minimum uplift of the Khaviz anticline in different parts (U_{min-p}) at the level of the Asmari Fm. with regards to the Maroon River and the elevation difference of the local base levels across the anticline. See Fig. 9b for location of the profiles.

Profile	U_{min-p} (m)	Local base level elevation		Base level dropdown to the SW (m)	Ta_{recent} (%)
		NE limb	SW limb		
1	570	547	412	135	24
2	940	848	567	281	30
4	1200	775	698	77	6

shows that the structural uplift was too rapid that the rivers could not cut them similar to those observed in the other places in the Zagros including the Fars Arc [11, 17].

Diversion of the main rivers around the noses of the large anticlines bounded the Dehdasht Structural Basin (the Shah Bahram River) and occasionally cutting them (the Maroon River cutting the SE Bangestan anticline) could imply on the lateral growth of the anticlines (e.g. [31, 18]) or progressive exposure of stiff lithology in the growing anticlines with different erodible strata (e.g. [32]). Chorum River to the north of the Dehdasht Structural Basin and the Maroon River at the NW, South and SW of the basin could cut the large anticlines transversely. It seems the Chorum River could cut the stiff Sarvak Fm. of the Kuh-e-Siah anticline by following a strike-slip fault suggested to be formed before folding during activity of the MFF ([24]; Fig. 1b). The Gachsaran evaporites have been deposited on the both sides of the saddle between the Kuh-e-Siah and the Kuh-e-Sefid anticlines. Therefore, cutting the Asmari limestone by the Maroon River could be addressed to the superimposition of the present river on the original river flowing over the loose thick Gachsaran deposits before lateral growth or the surficial exposure of the anticlines noses. This is suggested by Oberlander [36] for the transverse rivers cutting the large anticlines in the Dezful Embayment. Cut of the Khaviz anticline by the Maroon River could be explained by this way, too. At first the Gachsaran loose deposits were thick enough to provide the connection between the water basins on the both sides of the Khaviz anticline.

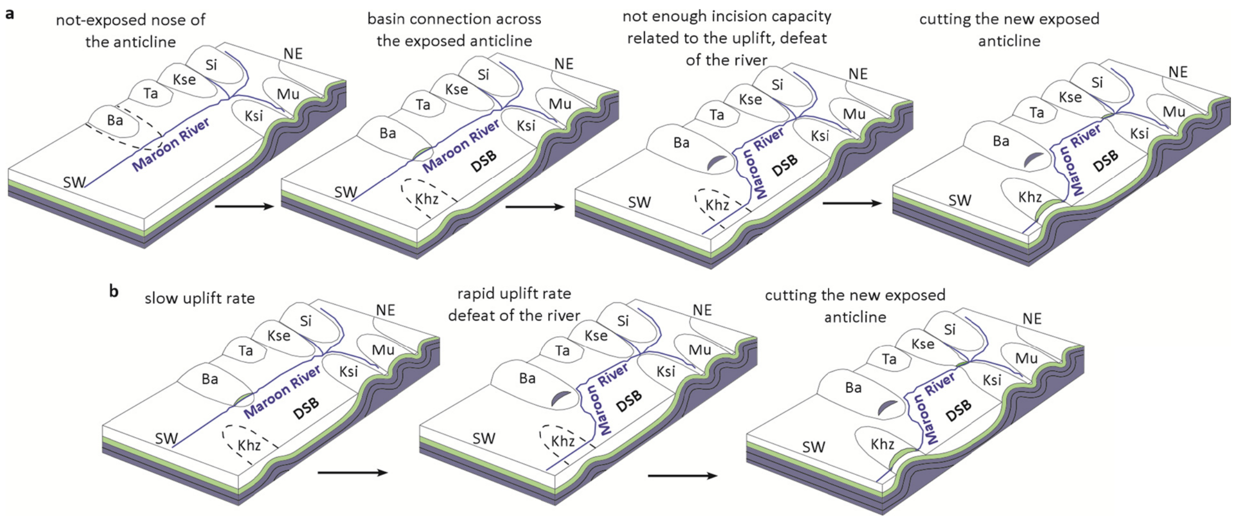

Figure 10. Schematic evolutionary model of the Maroon River moving across the SE Bangestan anticline. a) Model 1 (based on [36]). The basin on the both sides of the anticline is connected at first (due to not-exposed anticline or no lateral growth of the anticline) and then by exposing the anticline or its lateral growth the river deviates and leaves a wind gap over the nose of the anticline. b) Model 2. Slow and uniform uplift of the anticline at first let the river to cut the new growing anticline, while later rapid uplift makes it to defeat. Cutting the Khaviz anticline by the Maroon River is based on [36] in the both models. Ba: Bangestan anticline, Ta: Tavechegah anticline, KSe: Kuh-e-Sefid anticline, Si: Siah anticline, Mu: Mundun anticline, KSi: Kuh-e-Siah anticline, DSB: Dehdasht Structural Basin, Khz: Khaviz anticline. Dashed line shows the future location of the anticline exposure.

Therefore after exposure of the anticline to the surface the river continues to cut the stiff thin limestones of the Asmari Fm., too. Although, this is in contrast to the suggested model by Collignon et al. [33] for continuous incision of the Mand and Kul transverse rivers (in the Fars Arc) flowing over the stiff deposits underlain by the loose deposits.

Diversion of the Maroon River around the SE Bangestan anticline could be explained in two ways (Fig. 10). First, the river cut the deposits over the Bangestan anticline (down to the Kazhdumi Fm.) before exposure of the anticline at surface. Later, the surficial exposure of the anticline to the SE (due to the lateral growth or exposure of the stiff layers) causes the river to deviate (Fig. 10a). Another interpretation is related to the variation in the uplift rate. Since stability of transverse rivers relates to their quick respond ability to tectonic forces [33-36] therefore the first low and uniform uplift rate let the Maroon River to cut the SE Bangestan anticline. Then by increasing the uplift rate of the anticline, the river defeats and deviates (Fig. 10b).

Diversion pattern of the minor drainage "b" and the Bimanjegan River in the central Dehdasht Structural Basin is somehow similar to the pattern in the Central Otago in New Zealand showing diversion of drainages due to a new ridge growth [7]. Although in the Dehdasht Basin, diapiric activity of the Gachsaran deposits on the crest of the Dehdasht anticline and uplift of the Bord syncline due to thrust/salt extrusion of the Gachsaran evaporites cause the diversions (Fig. 11).

In addition to the structural effects, the lithological control and limited catchment area of the drainages could be effective on their diversions over the Dehdasht anticline as it is also suggested by Collignon et al. [33] in the Fars Arc.

Participation of the structural uplift in the present topography of the anticlines

The recent uplift (U_{recent}) of the anclines using Eq. (1), determines that how much of the present topography is formed by the structural uplift.On the SE nose of the Bangestan anticline about one third of the structural uplift (U_{recent} = 60%) is recorded in the topographic profile. For the Kuh-e-Siah anticline 36% to 89% (to its SE and central parts, respectively) of the anticline uplift is recorded to its recent topography while in the Khaviz anticline the values are 70% to 100%. Comparing the U_{recent} of theses anticlines could show the relative age of their activities if a uniform uplift rate is assumed. Accordingly, the SE Bangestan and the SE Kuh-e-Siah anticlines have older activities than the Khaviz anticline. Moreover, exposure of the Lower Cretaceous deposits on the Bangestan and the Kuh-e-Siah anticlines compared to the Khaviz anticline with outcrop maximum down to the Upper Cretaceous shows higher erosion and probably earlier exposure of the former anticlines at surface.

Uplift of the SE Bangestan anticline since diversion of the Maroon River (i.e. 655 m; Fig. 7b) is 23% of the total amplitude of the anticline. Since there is no available absolute age for the folding here, giving an exact time for diversion in the course of the Maroon rive is not possible. However, given an early reactivation of the MFF in the Central Zagros during Oligo-Miocene time (23-34 Ma; [37]) and assuming a uniform uplift rate, the age of the diversion is obtained 5.3-7.8 Ma (late Miocene, deposition of the Aghajari Fm.). Assuming middle Miocene (15-16 Ma) suggested by Sherkati and Letouzey [22] for timing of the folding in the Dezful Embayment, gives an age of 3.4-3.7 Ma (late Pliocene, Bakhtyari deposition). And considering the initiation age of deformation at the vicinity of the MFF in the Lurestan Arc (8 Ma; [10]), suggests 1.8 Ma (Pleistocene) for the age of deviation. Therefore, timing of the Maroon River diversion around the SE Bangestan anticline could not be older than late Miocene.

Diversion distance of a river due to the growth of an anticline is a function of the anticline growth distance [31]. Accordingly, by considering distance of the Maroon River from the point of its diversion to the exposed SE nose of the Bangestan anticline (about 13 km, Fig. 7a) and the suggested age of the Zagros folding mentioned above, the lateral growth of the SE Bangestan anticline is obtained between 1.7 mm/yr and 7.2 mm/yr. Keller et al. [38] suggests that lateral growth of an anticline could be 10 times faster than its vertical growth; the SE Bangestan anticline shows a vertical growth rate of 0.08-0.35 mm/yr (considering the suggested ages for the folding) which is 20 times less than its lateral growth.

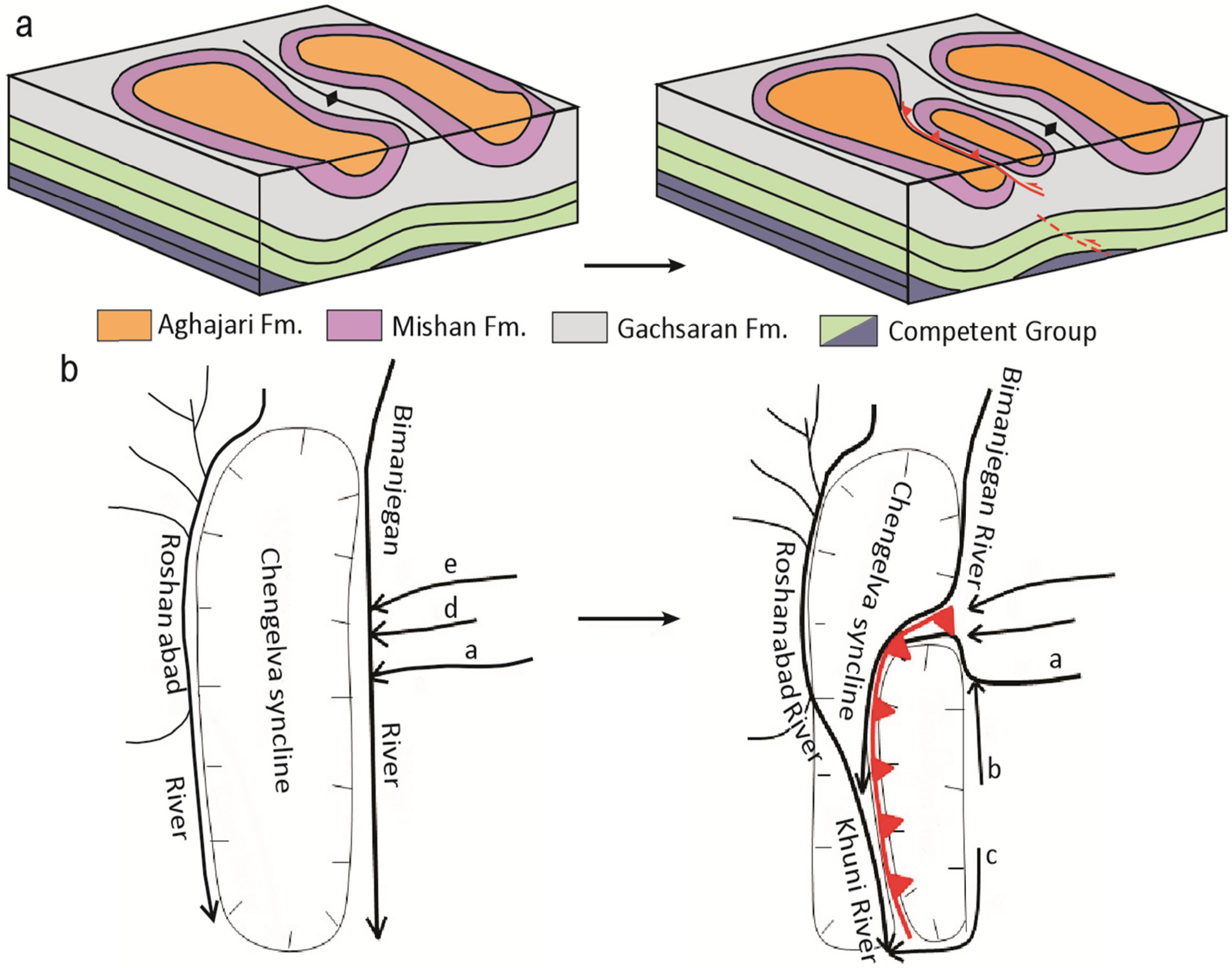

Figure 11. Schematic evolutionary model for the Dehdasht anticline and the adjacent synclines to the SW (a) and the drainage system around it (b). "a to e" show the minor drainages.

Conclusions

The pattern of drainage system and the trend of the main rivers in the Dehdasht Structural Basin and surroundings are affected by the tectonic structures. Within the basin the drainages are parallel to the diapiric anticlines of the Gachsaran evaporites and growth synclines-minibasins. Thrust/salt extrusion of the Gachsaran evaporites occasionally, such as in the Dehdasht anticline, makes a diversion in the course of the minor drainages or the rivers. The Maroon transverse River to the NW boundary of the basin is diverted around the SE Bangestan anticline due to the lateral growth and uplift of the anticline. However, the Maroon River cut the Khaviz anticline and the saddle between the Kuh-e-Siah and Kuh-e-Siah anticlines due to the basin connection on both sides of the anticlines and the later exposure of their noses to surface.

The SE Bangestan anticline since the diversion of the Maroon River shows 655 m uplift, which is 23% of the fold amplitude. Considering the suggested ages of folding for the Central Zagros (including the Dezful Embayment) and also close to the MFF (in the Lurestan Arc) and assuming a uniform uplift, the age of the Maroon River diversion around the Bangestan anticline is younger than late Miocene. Given the diversion distance of the Maroon River around the SE Bangestan anticline, the lateral SE growth rate of 1.7-7.2 mm/yr which is 20 times faster than the vertical growth of the anticline, is estimated.

Comparison between the amounts of minimum structural uplifts recorded in the topographic profiles of the large anticlines with regards to their amplitudes (i.e. structural uplift) shows that the SE Bangestan and SE Kuh-e-Siah anticlines with the outcrop of the Lower Cretaceous deposits have older activities than the Khaviz anticline with a dominant outcrop of the Oligo-Miocene Asmari limestones. Comparing the variation in the elevation of the local base levels across the Kuh-e-Siah, Khaviz and Bangestan anticlines to the minimum uplift of the anticlines suggests a maximum 30% to 45% contribution of the thrust faults activity in the recent uplift of these anticlines. The activity of the thrust faults is concentrated on the central, NW and SE parts of the Khaviz, Bangestan and Kuh-e-Siah anticlines, respectively.

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References

1. Alvarez W. Drainage on evolving fold thrust belts: a study of transverse canyons in the Apennines. Basin Research. 1999; 11: 267–284.
2. Bretis B, Bartl N, Grasemann B. Lateral fold growth and linkage in the Zagros fold and thrust belt (Kurdistan, NE Iraq). Basin Research. 2011; 23: 615–630.
3. Burbank DW, Meigs A, Brozovic N. Interactions of growing folds and coeval depositional systems. Basin Research. 1996; 8: 199–223.
4. Walker RT, Ramsey LA, Jackson J. Geomorphic evidence for ancestral drainage patterns in the Zagros Simple Folded Zone and growth of the Iranian plateau. Geological Magazine. 2011; 148 (5–6): 901–910.
5. Delcaillau B, Carozza JM, Laville E. Recent fold growth and drainage development: The Janauri and Chandigarh anticlines in the Siwalik foothills, northwest India. Geomorphology. 2006; 76: 241-256.
6. Burbank DW and Anderson RS. Tectonic Geomorphology. Blackwell Scientific, Oxford. 2001; 270 p.
7. Jackson J, Norris R, Youngson J. The structural evolution of active fault and fold systems in central Otago, New Zealand: Evidence revealed by drainage patterns. Journal of Structural Geology. 1996; 18: 217-234.
8. Burbank DW, McLean JK, Bullen M, Abdrakhmatov KY, Miller MM. Partitioning of intermontane basins by thrust-related folding, Tien Shan, Kyrgyzstan. Basin Research. 1999; 11: 75-92.
9. Allen M, Jackson JA, Walker R. Late Cenozoic reorganization of the Arabia–Eurasia collision and the comparison of short-term and long-term deformation rates. Tectonics. 2004; 23.
10. Homke S, Vergés J, Garcés M, Emami H, Karpuz R. Magnetostratigraphy of Miocene–Pliocene Zagros foreland deposits in the front of the Pusht-e Kush Arc (Lurestan Province, Iran). Earth and Planetary Science Letters. 2004; 225: 397–410.
11. Mouthereau F, Tensi J, Bellahsen N, Lacombe O, De Boisgrollier T, Kargar S. Tertiary sequence of deformation in a thin-skinned/thick-skinned collision belt: the Zagros Folded Belt (Fars, Iran). Tectonics. 2007; 26: TC5006.
12. Berberian M. Master “blind” thrust faults hidden under the Zagros folds: active basement tectonics and surface tectonics surface morphotectonics. Tectonophysics. 1995; 241:

193–224.
13. Mann CD and Vita-Finzi C. Holocene serial folding in the Zagros. In: Audley-Charles M.G., and Hallam A. (eds), Gondwana and Tethys. Geol. Soc. Spec. Publ. 1988; 37: 51-59.
14. Walpersdorf A, Hatzfeld D, Nankali H, Tavakoli F, Nilforoushan F, Tatar M, Vernant P, Chery J, Masson F. Difference in the GPS deformation pattern of North and Central Zagros (Iran). Geophysical Journal International. 2006; 167: 1077 – 1088.
15. Oveisi B, Lavé J, Van Der Beek PA. Rates and processes of active folding evidenced by Pleistocene terraces at the central Zagros front (Iran). In: Lacombe, O., Lavé J., Roure F. & Vergés J. (eds), Thrust Belts and Foreland Basins, Springer-Verlag "Frontiers in Earth Sciences" Series, New York. 2007; 265–285.
16. Bahrami S. Analyzing the drainage system anomaly of Zagros basins: Implications for active tectonics. Tectonophysics. 2013; 608: 914-928.
17. Mouthereau F, Lacombe O, Vergés J. Building the Zagros collisional orogen: Timing, strain distribution and the dynamics of Arabia/Eurasia plate convergence. Tectonophysics. 2012; 532-535: 27-60.
18. Ramsey LA, Walker RT, Jackson J. Fold evolution and drainage development in the Zagros mountains of Fars province, southeast Iran. Basin Research. 2008; 20: 23–48.
19. Heydarzadeh K, Ruh J, Vergés J, Hajialibeigi H, Gharabeigli Gh. Evolution of a structural basin: Numerical modelling applied to the Dehdasht Basin, Central Zagros, Iran. Journal of Asian Earth Sciences. 2020; 187: 104088.
20. Sepehr M and Cosgrove JW. The role of major fault zones in controlling the geometry and spatial organization of structures in the Zagros Fold-Thrust Belt. In: Ries A.C., Butler R.W.H. and Graham R.H. (eds), Deformation of the Continental Crust: The Legacy of Mike Coward. Geol. Soc. Spec. Publ. 2007; 272: 419436.
21. Najafi M, Vergés J, Etemad-Saeed N, Karimnejad HR. Folding, thrusting and diapirism: Competing mechanisms for shaping the structure of the north Dezful Embayment, Zagros, Iran. Basin Research. 2018; 30: 1200–1229.
22. Sherkati S and Letouzey J. Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment) Iran. Marine and Petroleum Geology. 2004; 21: 535–554.
23. O'Brien CAE. Tectonic problems of the oil field belt of southwest Iran. Proceedings of 18th International Geological Congress, London. 1950; Part 6: 45–58.
24. Khadivi V. Structural analysis of the Kuh-e-Siah anticline and the role of transverse faults on its geometries, NE of the Dehdasht area. Master thesis, Tarbiat Modares University, Tehran, Iran. 2015. Persian.
25. Aster Global Digital Elevation Model (DEM), V2. USGS, Global Data Explorer. http://gdex.cr.usgs.gov/gdex.
26. Burberry CM, Cosgrove JW, Liu JG. Spatial Arrangement of Fold Types in the Zagros Simply Folded Belt, Iran, Indicated by Landform Morphology and Drainage Pattern Characteristics. Journal of Maps. 2008; 4 (1): 417-430.
27. Favre G. SW Iran, Regional corss sections 10-17, Report No. 1233. National Iranian Oil Company. 1974.
28. Murris RJ. Middle East: Stratigraphic Evolution and Oil Habitat. Am. Assoc. Pet. Geol. Bull. 1980; 64: 597-618.
29. Ghabeishavi A, Vaziri-Moghaddam H, Taheri A. Facies distribution and sequence stratigraphy of the Coniacian–Santonian succession of the BangestanPalaeo-high in the Bangestan Anticline, SW Iran. Facies. 2009; 55: 243-257.
30. Emami H, Vergés J, Nalpas T, Gillespie P, Sharp I, Karpuz R, Blanc EP, Goodarzi MGH. Structure of the Mountain Front Flexure along the Anaran anticline in the Pusht-e Kuh Arc (NW Zagros, Iran): insights from sand box models. In: Leturmy P., and Robin C. (Eds.), Tectonic and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic. Geol. Soc., London. 2010; 155–178.
31. Melosh BL and Keller EA. Effects of active folding and reverse faulting on stream channel evolution, Santa Barbara Fold Belt, California. Geomorphology. 2013; 186: 119–135.
32. Oberlander TM. Origin of drainage transverse to structures in orogens. In: Morisawa M. and Hack JT (eds), Tectonic Geomorphology:

Proceedings of the 15th Annual Binghamton Geomorphology Symposium, Boston, Allen and Unwin. 1985; 155-182.

33. Collignon M, Yamato P, Castelltort S, Kaus BJP. Modeling of wind gap formation and development of sedimentary basins during fold growth: application to the Zagros Fold Belt, Iran. Earth Surface Processes and Landforms. 2016; 41 (11): 1521–1535.
34. Allen PA. Time scales of tectonic landscapes and their sediment routing systems. Geol. Soc. Spec. Publ. 2008; 296: 7-28.
35. Tucker GE and Slingerland R. Drainage basin responses to climate change. Water Resources Research. 1997; 33 (8): 2031-204.
36. Whipple KX and Tucker GE. Dynamics of the stream-power river incision model: Implications for height limits of mountain range, landscape response timescales, and research needs. Journal of Geophysical Research. 1999; 104: 661-674.
37. Ahmadhadi F, Lacombe O, Daniel JM. Early reactivation of basement faults in Central Zagros (SW Iran): evidence from pre-folding fracture populations in Asmari Formation and Lower Tertiary paleogeography. In: Lacombe O., Lavé J.,Vergés J., and Roure F. (Eds.), Thrust belts and Foreland Basins: From Fold Kinematics to Hydrocarbon Systems. Springer-Verlag. 2007; 205–228.
38. Keller EA, Gurrola LD, Tierney TE. Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. Geology. 1999; 27: 515–518.
39. Llewellyn PG. Deh Dasht geological compilation map, 1:100000. Iranian Oil Operating Companies, Geological and Exploration Division, Tehran. 1973.
40. Mcleod JH and Akbari Y. Behbahan geological compilation map, 1:100000. National Iranian Oil Company. 1970.
41. Ehrenberg SN, Pickard NAH, Laursen GV, Monibi S, Mossadegh ZK, Svånå TA, Aqrawi AAM, McArthur JM, Thirlwall MF. Strontium isotope stratigraphy of the asmari formation (Oligocene - Lower miocene), SW Iran. Journal of Petroleum Geology. 2007; 30:107–128.
42. Pirouz M, Simpson G, Chiaradia M. Constraint on foreland basin migration in the Zagros mountain belt using Sr isotope stratigraphy. Basin Research. 2015; 27: 714-728.