Neotectonics of the Zanjan–Kazvin area, Central Iran: Left lateral strike-slip induced restraining stepovers

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Abstract: The neotectonics of the Zanjan–Kazvin area are dominated by the region-wide E-W trending left lateral strike-slip faults. These faults create restraining and releasing stepovers indicating strain partitioning. Instead of the NW-SE trending long range-parallel continuous thrust faulting suggested in previous studies, this paper demonstrates that there are E-W trending range-crossing left lateral strike-slip faults creating short range-parallel thrust faults in the restraining stepovers. Establishing this strike-slip–induced structural style might contribute to an understanding of the nature of the Elburz (Alborz) Mountains located between the Central Iran and Caspian blocks.

Key words: Neotectonics, Iran, Zanjan, earthquake, strike-slip fault

1. Introduction

Central Iran is located at the south of the Caspian Sea within the Alpine-Himalayan belt. The active tectonic belt between the Central Iran and Caspian blocks constitute the morphology of the E-W trending Elburz (Alborz) and N-S trending Talesh Mountains (Berberian et al., 1992; Priestley et al., 1994) (Figures 1a and 1b).

Different views have been published about the tectonic activity between the Central Iran and South Caspian blocks (Şengör, 1990; Berberian et al., 1992; Alavi, 1996; Allen et al., 2003; Guest et al., 2006). Şengör (1990) suggested that this zone is a right lateral palm tree structure using the first detailed studies of Stocklin (1968, 1974). After the 1990 Rudbar-Manjil earthquake, Berberian et al. (1992) reported left lateral strike-slip and reverse faults due to the oblique convergence. Alavi (1996) interpreted the Elburz Mountain as a thrust belt moving from the N-NE to the S-SW. Allen et al. (2003) supported the view of Berberian et al. (1992) and suggested that the oblique convergence caused strain partitioning and created range-parallel left lateral strike-slip and thrust faults in the Elburz Mountain. On the other hand, Guest et al. (2006) indicate that the convergence is compensated for by right and left lateral conjugate faults and thrusts.

There is no detailed geological study on the Talesh Mountains. The focal mechanism solutions of the earthquakes (i.e. 4 November 1978) indicate that the Talesh Mountain belt thrusts over the southern Caspian Sea (Berberian, 1983; Jackson et al., 2002) (Figure 1b). On the other hand, Berberian and Yeats (1999) suggested that in the west, N-S trending right lateral strike-slip faults exist in the area between the Sabalan volcano and the Talesh Mountains. However, the focal mechanism solution of the 28 February 1997 earthquake indicates N-S trending left lateral strike-slip faulting (Jackson et al., 2002). This controversy became apparent after the 11 August 2012 Varzaghan earthquake to the west of the Sabalan volcano (Figure 1b). According to the United States Geological Survey (USGS) and the Kandilli Observatory and Earthquake Research Institute (KOERI), this earthquake was a result of an E-W trending right lateral strike-slip fault. Moreover, GPS data previously confirmed the NW-SE trending right lateral shear (Masson et al., 2006) in the same area. The relationship between the N-S trending structures in the Talesh Mountains and the E-W and NW-SE trending right lateral system in the west and the E-W trending left lateral system in Elburz is not well explained.

Zanjan is located in this critical area. Although earthquakes of magnitudes of 5 to 7.4 have occurred in the Zanjan area since 1962, for example in 1962, 1990, 1998, (Jackson et al., 2002), 2002, and 2008 there have been limited studies published on this region's neotectonic features except for a recent article by Solaymani et al. (2011), which suggested that a thrust and right lateral strike-slip dominated the Zanjan fault network. However, our findings in this paper, based on field studies and
remote sensing data, present a quite different description of the neotectonic framework for the Zanjan–Kazvin area.

2. Regional geology

The study area is positioned at the Arabian-Eurasian convergence zone between the South Caspian block and Central Iran (Figure 1). The Sanandaj-Sirjan zone represents the metamorphic basement of Central Iran (Verdel et al., 2007) and is related to the subduction of the Neo-Tethyan oceanic lithosphere under Central Iran.

The simplified geological map shows an important angular unconformity after the Cretaceous period (Figures 2a and 2b). Palaeogene conglomerates and subsequently layered marine sedimentary units cover this unconformity (Stocklin, 1968). Eocene flysch sedimentation including volcanoclastic material reaches a thickness of 4 km. Following the Eocene volcanism, granitoid emplacement occurs during Miocene times. As can be seen all over Iran, the clastic and evaporitic units of the Red Formation accumulated during the Oligocene and Miocene periods. The upper part of the Red Formation contains a considerable amount of tuff and volcanic material with variable thicknesses. The uplifted Elburz and Sanandaj-Sirjan belts provide materials for the Red Formation (Tillman et al., 1981; Amini, 1997; Guest et al., 2007). In some studies (i.e. Ballato et al., 2008), the Upper Red Formation was interpreted as a product of a foreland basin under a contractional tectonic regime. However, Toori and Seyitoğlu (2011) determined that these sediments accumulated under an extensional regime.

In the study area, Quaternary alluvial deposits unconformably cover the earlier units and generally have a tectonic contact with the NW-SE trending ranges that are parallel to the Elburz belt. Morphotectonic studies indicate that the area is under the influence of a strike-slip system (Figure 2b).

3. Morphotectonics of the Zanjan–Kazvin area

The Elburz and Zagros deformational belts become close in the Zanjan area where the E-W trending Elburz Mountains

Figure 1. (a) Tectonic configuration of the study area. (b) Active faults of Zanjan and surrounding regions with the focal mechanism solutions of the earthquakes in the south-west margin of the Caspian block around the Tebriz–Zanjan–Tehran area (Jackson et al., 2002; CMT, 2012; KOERI, 2012; USGS-NEIC, 2012). Abbreviations: GC = Great Caucasus, KD = Küpe Dağ, SSZ = Sanandaj Sirjan Zone, and Z = Zagros. After Nowroozi (1972), Alavi (1991), Priestley et al. (1994), and Barka and Reilinger (1997).
suddenly turn to the N-S direction and are called the Talesh Mountains. The morphology of the Zanjan–Kazvin area is composed of NW-SE trending ranges (i.e. the Talesh, Tarom, Sultaniye, and Geydar mountains) and basins (i.e. the Kazvin, Tarom, Zanjan, and Sultaniye plains) (Figure 2b). In previous studies, the regional morphology was explained by NW-SE trending, range-parallel reverse and thrust faults (Berberian, 1976a, 1976b; Hessami et al., 2003; Solaymani et al., 2011). The existence of left lateral strike-slip faults in the region was recognised after the 1962 Buin-Zahra earthquake (Ambraseys, 1963) and the 20 June 1990 (Mw: 7.3) Rudbar-Tarom earthquake (Berberian et al., 1992). Later, one of the prominent structures of the region, the Mosha Fault, was determined to be a left lateral strike-slip fault from seismological and morphotectonic studies (Allen et al., 2003; Ashtari et al., 2005). This fault passes into the thrust faults in the north of Tehran (Allen et al., 2003; Landgraf et al., 2009) due to the restraining offset created by the Talegan Fault (Guest et al., 2006). On the other hand, Ritz et al. (2006) suggested that the Mosha Fault is a left lateral strike-slip fault with normal components and deduced that the Elburz belt is under the influence of a transtensional tectonic regime.

3.1. The Talegan Fault
The left lateral Talegan Fault has a length of 50 km and the height of the topography considerably decreases along the fault up to 1 km from east to west (Figures 3a–3d). The Talegan River has an E-W trending primary stream and its N-S tributaries contain morphological data indicating a left lateral displacement. Colour changing on satellite images is recognisable along the fault. The strike and dip of the fault have been estimated as N82E, 75SE using morphological features. The strike of the fault changes direction towards the east due to a restraining bend. In the middle of the Talegan Fault, the structural data were measured as N75W, 60SW, 40E (strike, dip, rake) (Nazari et al., 2009).

3.2. Kazvin releasing offset
The western end of the Talegan Fault creates a contractional step with NW-SE trending primary faults and passes to the North Kazvin Fault with a left lateral strike-slip fault.

Figure 2. (a) Simplified geological map of the study area after Bolourchi (1969), Stocklin and Eftekharneshad (1969), Davis et al. (1972), Annells et al. (1975), Clark et al. (1975), and Amidi (1978). (b) The important morphological and geological structures of the study area. Abbreviations: B = Basement, N = Neogene, Q = Quaternary, T = Tertiary, G = Geydar, ATF = Avaj Thrust Fault, CEF = Changuri-Erdehin Fault, GF = Güzeldere Fault, KTF = Kanavand Thrust Fault, LF = Legahi Fault, NKF = North Kazvin Fault, STF = Sarimsakl Thrust Fault, ZFZ = Zanjan Fault Zone, ZP = Zanjan Plain, and ZSTF = Zanjan-Sultaniye Thrust Fault.
with a thrust component (Berberian et al., 1983, 1993). The geological map of the area (Annells et al., 1975) and interpretations from satellite images show right stepping segments. The North Kazvin Fault separates the Eocene and older units in the north from Neogene conglomerates to the south. There is up to 500 m of topographical difference between these 2 units that is evaluated as a fault scarp (Annells et al., 1975; Berberian et al., 1983). Morphological evidence indicates that the central part of the scarp is relatively more active than the eastern and western ends (Toori, 2012).

Field studies demonstrate that the western margin of the Kazvin Plain is cascaded by NE-SW trending normal faults (Figures 4a–4f). These findings do not concur with the suggestion of Akbaba thrust faulting (Berberian et al., 1993) in the same area. The 2000-m-high Tarom Mountains descend to the 800-m-high Kazvin Plain within 30 km by NE-SW trending normal faults. Normal fault scarps are seen 2 km south-east of Marshun village (N70E, 40SE) and to the N-NW of Haft Sandik village (N65E, 52SE) (Figures 4a, 4b, and 4e). Some of the kinematic indicators are given in Figures 4c, 4d, and 4f. The normal faults to the west of the Kazvin Plain must be related to a releasing offset between the North Kazvin Fault and Geydar Fault or the Changuri-Erdehin Fault. At the same time, the Geydar Fault creates a restraining offset (ATF) with the Ipek Fault where the 22 June 2002 (M: 6.5) and 2 September 2002 (M: 5.2) earthquakes were located with the focal mechanism solutions of the NW-SE trending thrusts (Figures 1b and 2b).

3.3. Abhar–Sultaniye region

The NNW-SSE trending faults in the Sultaniye Mountains to the west and south of Abhar can be seen in the earlier geological maps (Bolourchi, 1969; Stocklin and Eftekharnezhad, 1969). These structures give an impression of right lateral displacement in the satellite images. In fact, they are originally pre-Neogene syn-sedimentary normal faults. The entire sedimentary sequence was deformed during post-Miocene times and these faults present a pseudo strike-slip image in the map view (Bolourchi, 1969; Stocklin and Eftekharnezhad, 1969; Toori, 2012). An example of the misinterpretation of these structures is seen in Figures 4a, 4b, and 4e. Some of the kinematic indicators are given in Figures 4c, 4d, and 4f. The normal faults to the west of the Kazvin Plain must be related to a releasing offset between the North Kazvin Fault and Geydar Fault or the Changuri-Erdehin Fault. At the same time, the Geydar Fault creates a restraining offset (ATF) with the Ipek Fault where the 22 June 2002 (M: 6.5) and 2 September 2002 (M: 5.2) earthquakes were located with the focal mechanism solutions of the NW-SE trending thrusts (Figures 1b and 2b).
in the work of Allen et al. (2011), where pre-Neogene tilted normal faults were interpreted as NNW-SSE trending right lateral strike-slip faults but no confirmed kinematic indicators were found in the field.

Instead, NW-SE trending thrusts were observed between Abhar and Geydar (Figures 5a–5d). To the south of Abhar in Kuhejin village, the old terraces along with north-east flowing streams have been uplifted 40 m due to this thrusting (Figure 5a). The point where the stream reaches the plain has been abandoned due to uplifting and a new alluvial fan has developed in the east further inside the plain. The thrust faults can be followed from Erdehin village to the south-east for at least 15 km. A set of north-east vergent thrust faults dipping 10°–30° south-west is observed between Bağdere and Erdehin (Figure 5b). To the west of Erdehin, the north-east margin of the Sultaniye Mountains thrust onto a Quaternary plain and a 1-km-wide cataclastic zone has developed. In contrast, 1 km north-east of Karaağaç village, the south-west vergent thrusts have a north-east dip. Jurassic units have moved along these faults onto Tertiary conglomerates. When the opposite vergent thrusts to the south-west of Abhar are taken into account, a double vergent thrust structure can be proposed for the region. These structures can be followed to the north-west to the prominent WNW-ESE and E-W trending left lateral strike-slip faults at the north of Erdehin (Figures 5c and 5d). The stream where the village Turkande is located is on the left lateral strike-slip fault, which shows a 7-km-long displacement of the coal layers. The branches of the left lateral faults slice Kuze Mountain and constitute a 10-km-wide and 40-km-long fault zone called the Changuri-Erdehin Fault (Figure 5). The E-W trending Changuri-Erdehin Fault and northern Güzeldere Fault create a restraining stepover with thrust surfaces (N45W, 50SW) outcropped south of Chapdere. Along the thrust fault, deeply incised valleys indicate vertical rapid erosion in the region. It is speculated that the restraining stepover between the Changuri-Erdehin and Güzeldere faults affect the regional drainage system to the south-east of Sultaniye and cause the opposite flow direction of the Abhar and Zanjan rivers to the south-east and north-west, respectively (Figures 6a and 6b).

3.4. Sultaniye–Zanjan area

Previously recognised by Stocklin and Eftekharnezhad (1969), the E-W trending Güzeldere Fault has a morphological expression on the topography and passes through Tertiary and older units. The Güzeldere and Günay streams are perpendicular to the fault and show right lateral displacement but the kinematic indicators in the field provide evidence of a left lateral movement (Figures 7a–7f). The Güzeldere Fault and northern Zanjan Fault create a restraining stepover and the area between
these faults is uplifted, which results in the Güzeldere and Günay streams being diverted to the right to a lower topography. The old beds of these streams shifted left towards the higher topography and were consequently abandoned. These morphological features demonstrate a left lateral displacement of 2.5 km. In addition, along the Güzeldere Fault, the Eocene tuff unit is displaced left laterally by 4 km (Figure 7).

The restraining stepover between the Güzeldere Fault and Zanjan Fault creates the NW-SE trending Zanjan-Sultaniye Thrust Fault (ZSTF), which has a S-SW dipping low-angle (10°) fault surface (Figures 8a–8f). It can be followed from the south of Zanjan to Yusufabad in the centre of the Sultaniye plain (Figure 7). Along the ZSTF, Palaeocene conglomerates (Fajan Fm.) and Eocene volcanoclastic units thrust onto the Pliocene sedimentary unit with a high angle and overturned beds (Figures 7d, 7e, and 8). A few tear faults are observed on the ZSTF, including one located in Noktabandi village. The tear fault has a geological displacement of 300 m and the same amount of morphological dislocation on the stream route (Figure 8c). The north-west sector of the ZSTF can be

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Figure 5. Uplifting structures of the Sultaniye Plain. B = Bağdere, Ch = Chapdere, E = Erhan, Ka = Karaağaç, T = Turkande, CEF: Changuri-Erdehin Fault, GF: Güzeldere Fault. (a) Old and new alluvial fans of the stream flowing from Kuhejin village to the north-east. (b) South-west dipping thrust faults between Bağdere and Erdehin villages. (c) and (d) Morphological and structural evidence of left lateral shear to the west of Erdehin village.
followed in the field but its south-eastern sector is traceable only by morphological indicators, which gradually disappear from the plain, probably due to blind thrusting. On the hanging wall of the ZSTF, the Pliocene sedimentary unit has a syncline with 15°–25° dipping limbs; however, the same unit in the footwall is nearly vertical. This observation demonstrates that the age of thrusting is post-Pliocene (Figure 8).

3.5. The Zanjan Fault
The geologically and morphologically most prominent strike-slip structure slicing the Sultaniye Mountains is the E-W trending left lateral Zanjan Fault. This fault begins to the south of Zanjan city from the ZSTF and continues west for 50 km, according to the morphological evidence (Figures 9a–9c). The main shear zone of the fault is 1 km wide. Several segments and displacements can be observed within the 10 km width (Figures 10a–10d). The Zanjan River has a left lateral displacement along the fault (Figure 10). To the south of Zanjan city, dislocations on the river channels of 2 m, 120 m, and 140 m are observed. In the same direction, on the road to Bijar, an alluvial fan and neighbouring streambed show displacement of 290 m. At a distance of 1 km south of Zanjan, at the road cut of the Bijar road, red claystones and siltstones of the Red Formation are exhumed along the fault and show a tectonic contact with the Quaternary units.

The regional geological map (Stocklin and Eftekharnezhad, 1969) indicates that the Palaeogene conglomerate unit has a displacement of 10 km in the shear zone of the Zanjan Fault (Figure 10a). At the same time, this fault displaced the morphology from east to west as seen in the fault parallel topographic sections (Figure 10b).

One of the segments of the Zanjan Fault is located to the north of Mehtar. This segment is observed in the Quaternary units and there is at least a 60-m-long left lateral displacement with a normal component defined by a fault scarp and related sediment accumulation (Figure 10c). The Dandi road has been built on the mountain pass that was
created naturally by the western continuation of this fault on the Sultaniye Mountain. Along this road, fault surfaces and cataclastic zones are common features (Figure 10d).

The typical characteristics of the Zanjan Fault are seen around Chavarzag village (Figures 11a–11e). The displacement of granitoids and the course of the Mehtar stream together with the slickenlines on the fault surfaces indicate a left lateral strike-slip movement (Figure 11b). Small left lateral segments of the Zanjan Fault around Chavarzag village create restraining stepovers and a consequent uplift of the area (Figure 11d). This rapid uplift caused the erosional demolition of a 120-year-old graveyard (Figure 11e).

The restraining stepover of the Zanjan Fault created a NW-SE trending uplifted morphology to the west of Yusufabad. The typical characteristics of the Zanjan Fault are seen around Chavarzag village (Figures 11a–11e). The displacement of granitoids and the course of the Mehtar stream together with the slickenlines on the fault surfaces indicate a left lateral strike-slip movement (Figure 11b). Small left lateral segments of the Zanjan Fault around Chavarzag village create restraining stepovers and a consequent uplift of the area (Figure 11d). This rapid uplift caused the erosional demolition of a 120-year-old graveyard (Figure 11e).
Zanjan. This morphology can be followed for 25 km from 5 km south-east of Mollalar village to Andabad village (Figures 12a–12d). There are terraces in the abandoned dry valley 5 km south-east of Mollalar. If the left lateral shift of the Zanjan Fault were reconstructed, this dry valley would correspond to the Mehtar stream. The amount of displacement in this reconstruction concurs with the 10-km-long left lateral dislocation of the Palaeogene conglomerates (Figure 12). The main segment of the Zanjan Fault has E-W strike to the east and south of Mollalar village and the overstepped segments create left lateral deflection in the Arpaçay River (Figures 13a–13h).

The western end of the E-W trending Zanjan Fault sliced Güzay Mountain, where the Mesozoic limestones are dislocated left laterally by 1.5 km (Figure 13f).

3.6. The north of the Zanjan Fault

To the north of the Zanjan Fault, the NW-SE trending Andabad Thrust Fault can be followed from Arpaçay to Andabad, where Oligo-Miocene limestones thrust onto Neogene and younger units along north-east dipping fault surfaces (Figure 13g). It is interesting to see the other NW-SE trending Kanavand, Sarımsaklı (Sarimsaglu), and Legahi thrust faults towards the east, parallel to the Andabad Thrust Fault.

The most prominent linear structure recognised from satellite images on the Zanjan plain is the Kanavand Thrust Fault, which is located to the south of Kanavand village 25 km north-west of Zanjan. The rapid uplift created by this fault causes considerable erosion of the sediments of the Armagan and Sohrein streams and changes the local topography.

The Sarımsaklı Thrust Fault is located north-west of Zanjan between the Tarom Mountains and the Zanjan plain (Figures 14a–14d). Along with the north-east dipping fault surface, Eocene units thrust onto Quaternary sediments. Thrusting is also observed within the Quaternary units (Figure 14a). As shown via satellite image and map, the Sarımsaklı Thrust Fault is located on the distal part of an alluvial fan that has developed due to the uplift of a hanging wall. The topographical difference between the hanging wall and footwall occurs at approximately 40 m and can be recognised on both sides of the road passing through the fault scarp. Based on the remote sensing study of Allen et al. (2011), the Sarımsaklı Thrust Fault is interpreted as a
right lateral oblique-slip thrust fault. However, slickenlines on the fault surface indicate thrust faulting (Figures 14b and 14c). The reason for the right lateral strike-slip morphological indicators is the topography dipping in 2 different directions. As explained in the block diagram in Figure 14d, the topography in the west of Zanjan is dipping to the south-west and the streams flow in the same direction. The region is also tilted to the west due to thrust faulting; consequently, streams flow towards the lowest topography and create an artificial right lateral diversion (Figure 14d).

In the N-NW of Zanjan, north of Legahi village, a small hot spring is located on the NW-SE trending linear structures as seen on aerial photos at a scale of 1:20,000. These structures correspond to the Legahi Thrust Faults.

At the north of the Zanjan Fault, the existence of the Andabad, Kanavand, Sarimsaklı, and Legahi thrust faults indicate that there is another E-W trending left lateral strike-slip fault further north. Its location is most probably at the north-west end of the Tarom Mountains, but the morphology of the area is so flat that it is difficult to identify the trace of the fault.

4. Discussion

There are 2 different views of the tectonic evolution of Central Iran. In the first view, the Eocene–Oligocene magmatic activity (Alavi, 1996; Verdel, 2009) is attributed to the subduction of the Neotethys. The central Iran basins developed under the Oligocene contraction due to the collision of the Arabian and Eurasian plates (Allen et al., 2003). Moreover, the Upper Red Formation (Middle-Late Miocene) is also interpreted as the product of a contractional basin (Alavi, 1996; Ballato et al., 2008).

The second view suggests core complex formation under an extensional regime and related basin formation during the Oligocene-Miocene (Tillman et al., 1981; Hassanzadeh et al., 2004; Stockli et al., 2004; Gilg et al.,
Toori and Seyitoğlu (2011) proposed that the Oligocene-Miocene Lower Red, Qom, and Upper Red formations accumulated in the extensional basins that are related to the core complex formation.

The post-Miocene convergence between the Arabian and Eurasian plates created a neotectonic contractional regime. This contraction is partly accommodated by a strike-slip system (Allen et al., 2006).

The southern Caspian block is moving to the north-west and Central Iran is moving to the east due to the convergence between the Arabian and Eurasian plates (Nowroozi, 1972; Priestley et al., 1994; Hollingsworth et al., 2008). These movements create left lateral shear in the Elburz Mountains. This left lateral shear was also recognised by GPS studies (Vernant et al., 2004). Although GPS data are very limited in the study area, left and right lateral movements have been reported for the east and west, respectively (Masson et al., 2006; Reilinger et al., 2006) and it is suggested that left lateral movement is restricted on the east of the study area (Jackson et al., 2002).

In the Zanjan area, the basin and ranges lie on the NW-SE direction and previous studies such as that of Hessami et al. (2003) suggested that the NE edge of the Sultanîye Mountains is limited by the range parallel thrusts. This study, however, demonstrates that thrusts are developed in the restraining stepovers between the E-W trending left lateral strike-slip faults. This creates rapid uplift and
Figure 11. Digital elevation model (DEM) of Chavarzag village. Note that the granite at the east of the village drags to the left and shows brittle deformation. (a) Google Earth image of the details of small segments in Chavarzag village, with E-W trending left lateral fault trace to the east of Chavarzag village. (b) E-W trending fault surface and nearly horizontal slickenlines of the Zanjan Fault to the north of Chavarzag village. (c) E-W trending left lateral fault trace to the NW of Chavarzag village. (d) A consequence of the rapid uplift of the area to the south-east of the village. (e) Erosional demolition of the graveyard due to rapid uplift of the area.

Figure 12. Left lateral 10 km displacement of the Mehtar riverbed along the Zanjan Fault. (a) Google Earth image of the abandoned Mehtar riverbed. (b) A segment of the E-W trending left Lateral Zanjan Fault on a Google Earth image. (c) and (d) Relics of river terraces in the abandoned river bed.
erosion on the restraining areas relative to other places. Erdehin, Chapdere, Chavarzag, and Andabad villages on Sultaniye Mountain can be given as examples. Post-Neogene sediments containing metamorphic rock fragments indicate that this rapid uplift and erosion play an important role for the exhumation of the basement rocks. In the restraining areas, reverse channel diversions are common features; therefore, remote sensing studies without field observations can create erroneous tectonic interpretations.

The seismic activity of the region is well explained by the left lateral strike-slip system and related restraining and releasing stepovers. The 1 September 1962 earthquake was related to left lateral movement on the Ipek Fault. The focal mechanism solution of the 22 June 2002 earthquake indicates a thrust fault with a right lateral component and must be related to the Avaj Thrust Fault. This fault is developed in the restraining stepover between the Ipek and Geydar faults. In the Tarom region, the epicentres of the main shocks and aftershocks of the 22 July 1983, 20 June 1990, and 28 November 1991 earthquakes indicate similar restraining stepover locations in the left lateral strike-slip system. The 27 May 2008 earthquake was related to normal faulting and can be given as example of a seismic activity in the releasing stepover.

The neotectonics of the Zanjan–Kazvin area are controlled by the E-W trending left lateral strike-slip faulting and the related restraining and releasing stepovers. Morphologically, the most prominent structure is the Zanjan Fault crossing the Sultaniye Mountains. The most noticeable example of the morphological effect of a restraining stepover is the opposite flow directions of the Zanjan and Abhar rivers. The example of a releasing offset in the region is the position of the Kazvin Plain.

The structural data from fault surfaces and slickenlines demonstrate that the principle stress axes ($\sigma_1 = 199/2; \sigma_3 = 289/2; \sigma_2 = 64/87$) are compatible with the axes obtained from the focal mechanism solutions of the earthquakes (Figure 15).
The data presented in this paper indicate that the convergence between the Central Iran and Caspian blocks as documented by GPS studies is not compensated for by the long, continuous NW-SE trending thrust faults drawn along the border of the basins and ranges as described in previous studies. Instead, this convergence is taken up by range-crossing left lateral strike-slip faulting with thrust faults on the restraining stepovers indicating strain partitioning (Figures 16a and 16b).

Figure 14. Google Earth image of the Sarımsaklı Thrust Fault (STF) in north-western Zanjan. (a) Cross-sectional view of NE dipping thrusting in the Quaternary fluvial deposits. (b) Eocene units thrust onto Quaternary fluvial deposits along a segment of the STF. (c) Inset shows the fault surface and the position of slickenlines. (d) A block diagram explains the artificial right lateral diversion of the Sarımsaklı River along the STF.
Figure 15. Main neotectonic features and the focal mechanism solutions of the earthquakes (grey) in the south-west of the Caspian basin and around the study area (CMT, 2012; KOERI, 2012; USGS-NEIC, 2012). Structural data (black) obtained from field studies provide regional stress directions after Angelier (1990) and Žalohar (2009), in agreement with the seismological data.

Figure 16. (a) The regional faults from the previous studies (Berberian, 1976a, 1976b; Berberian et al., 1992; Allen et al., 2003; Solaymani et al., 2011). (b) The simplified neotectonic framework of the study area based on the new observations presented in this paper.
Acknowledgements
This paper is a part of a PhD study of the first author, who thanks his family for financial support and thanks Korhan Esat and Rasoul Esmaeili for their help during his PhD studies.

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