Structural evidence on strike slip Kinematic inversion of the Kushk-e-Nosrat Fault zone, Central Iran

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Abstract

NW-tending faults in Central Iran are expected to represent dominant dextral components due to the northward motion of the Arabian Plate with respect to Eurasia. However, previously published works, as well as focal mechanism solution of the area's earthquakes, indicate evidence of sinistral kinematic along the major faults in Central Iran. Here we present detail structural kinematic data on the eastern part of WNW trending Kushk-e- Nosrat (KN) Fault zone to unravel the structural architecture and regional distribution of kinematic change at the northwestern margin of Central Iran zone. We classified fault data into two dextral and sinistral kinematic categories. Based on cross-cutting relationship and the superposition of kinematic indicators the sinistral related structures are yonger than the dextral one. The structural analysis of the KN Fault zone data suggests a kinematic inversion from dextral to young sinistral which is regionally attributed to the clockwise rotation of rigid South Caspian Basement Block (SCB) with respect to Eurasia.

Keywords: *Kinematic Inversion, Kushk-e-Nosrat Fault Zone, Central Iran Zone, South Caspian Block*

Introduction

Strike slip faults accommodate the transpressional deformation that transferred from continental collision zones to continental interiors (e.g. Molnar & Tapponnier, 1975; Jones & Tanner, 1995; Tikoff & Teyssier, 1994; Dewey *et al.,* 1998; Miller, 1998; Vernant *et al.,* 2004b; Allen *et al.,* 2011; Walpersdorf *et al.,* 2014). The strike slip faults include different groups such as: pre-existing reactivated faults, rigid body rotating bounded faults and strike-slip faults with large displacement in orogenic systems (Blick & Biddle, 1985; Sylvester, 1988; Woodcock & Schubert, 1994; Storti *et al.,* 2003; Cunningham, 2005; Spotila *et al.,* 2007; Cunningham & Mann, 2007). Kinematic inversion along strike slip faults is expected to happen when different displacement events occur along a pre-existing fault plane (e.g., Holdsworth *et al,* 1997). This inversion is recognizable through some indicators such as morphologic, structural, stratigraphical and geochronological records (White *et al.,* 1986; Holdsworth *et al.,* 1997; Lacassin *et al.,* 1998; Kim *et al.,* 2001; Maruyama & Lin, 2004; Javadi *et al.,* 2015). Examples of kinematic inversion along strike slip faults are the deflected river channels analysis, and fault rock structures along an active strike-slip fault zone in southwest Japan (Maruyama & Lin, 2004), residual of large right-lateral bends after the restoration of youngest, left-lateral river offsets in southeast Asia (Lacassin, 1998) and the reactivation evidence includes two different types of slickenlines on a single fault surface in north Cornwall, England and Doruneh Fault system in Central Iranian Microplate (Kim *et al.,* 2001; Javadi *et al.,* 2013).

The oblique continental collision of Arabian and Eurasian plates during late Eocene- early Oligocene (e.g., Hempton, 1985; McQuarrie, 2003, 2013; Allen *et al.,* 2004; Ballato *et al.,* 2011; Mouthereau *et al.,* 2012; Madanipour *et al.,* 2013, 2018) cause to large scale strike slip faulting in Central Iran zone such as Qom-Zefreh, Dehshir, and KN faults (e.g., Nogole-Sadat, 1985; Morley *et al.,* 2009; Babaahmadi *et al.,* 2010; Jamali *et al.,* 2011). Due to the northward motion of the Arabian plate relative to the central Iranian blocks and NW-SE trend of Central Iran structures, the strike slip faults is expected to have dextral component (e.g., Berberian & King, 1981; Nogole-Sadat, 1985; Safaei *et al.,* 2008; Safaei, 2009a; Morley *et al.,* 2009; Allen *et al.,* 2011; Babaahmadi *et al.,* 2010; Jamali *et al.,* 2011; Beigi *et al.,* 2016). However, several cases of left lateral movements along major earthquake faults have been reported inside the collision zone, especially at its northern margin in the Alborz Mountains (e.g., Allen *et al.,* 2003, Guest *et al.,* 2006, Ritz *et al.,* 2006). Deformation reorganization in Alborz Mountains in the northern margin of the Central Iran represents a Late Cenozoic slip sense inversion of major fault systems from right to left lateral strike slip motion (Trifonov *et al.,* 1996; Jackson *et al.,* 2002; Allen *et al.,* 2003; Guest *et al.,* 2006; Ritz *et al.,* 2006; Ehteshami & Yassaghi, 2007; Yassaghi & Madanipour, 2008; Hollingworth *et al.,* 2008; Abbassi & Farbod, 2009; Solaymani Azad *et al.,* 2011). There are also a number of earthquakes reported to ocurr along right lateral strike slip faults in the north and northwest areas of Central Iran that unexpectedly have left lateral focal mechanisms (Ambraseys, 1963; Berberian,1976; Berberian & Yeats, 2001; Bachmanov *et al.,* 2004; Elyaszadeh *et al.,* 2012; Orang *et al.,* 2014). Here we present detail structural kinematic data on the WNW trending Kushk-e- Nosrat (KN) Fault zone to unravel the regional distribution of kinematic change at the northwestern margin of the Central Iran that confirm a kinematic inversion from right to left lateral strike slip component.

Geologic setting

The Central Iran zone is considered as a part of Arabia- Eurasia collision zone resulted in the convergence of several basement blocks (e.g. Berberian & King, 1981; Jackson & Haines, 1995; Allen *et al.,* 2004). During Permian (Berberian & King, 1981) / Middle - late Triassic (Stampfli & Borel, 2003; Muttoni *et al,.* 2009) these basement blocks including Sanandaj-Sirjan Zone, Central Iran zone and Central-East-Iran Microplate has separated from Gondwana as a result of Neotethys rift and northward subduction of Paleotethys (Stöcklin, 1968; Takin, 1972; Davoudzadeh & Schmidt, 1984; Soffel *et al.,* 1996; Allen *et al.,* 2011). The late Triassic collision of Turan with Central Iran zone led to the initiation of northward Neotethys subduction and the appearance of several normal or transtensional fault sets in Central Iran (Berberian & King, 1981; Guest *et al.,* 2007a; Zanchi *et al.,* 2009a, b; Wilmsen *et al.,* 2009). The KN Fault zone (Fig.1) can be considered as an extensional preexisting structure at the northwestern margin of Central Iran (Guest *et al.,* 2007a; Morely *et al.,* 2009).

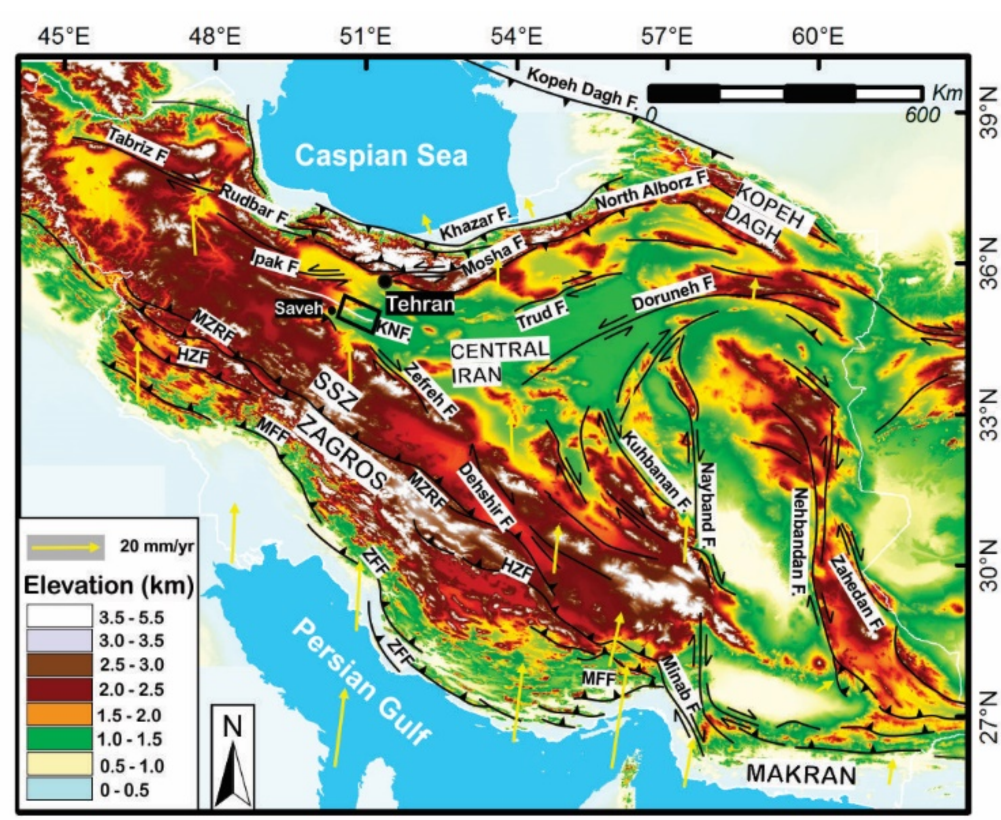

Figure 1. SRTM Topographic image of Iran along with major strike–slip faults. Main Faults are derived from (Berberian and King, 1981; Hessami et al., 2003) and the black square is related to the study area. KNF: Kushk -e- Nosrat Fault; MZRF: Main Zagros Reverse Fault; MFF: Mountain Frontal Fault; ZFF: Zagros Foredeep Fault; HZF: High Zagros Fault. GPS velocity vectors are from Vernant *et al*., 2004.

The Arabia- Eurasia collision started at early Oligocene (Soft collision, e.g., Hempton, 1985; Jolivet & Faccenna, 2000; Hessami *et al.,* 2001; McQuarrie *et al.,* 2003; Agard *et al.,* 2005; Horton *et al.,* 2008; Ballato *et al.,* 2011, Madanipour *et al.,* 2013, 2018) accelerated by the middle Miocene times due to subduction of Arabian lithosphere (hard collision, e.g., Sengör & Kidd, 1979; Axen *et al.,* 2001; McQuarrie *et al.,* 2003; Guest *et al.,* 2006a; Mouthereau *et al.,* 2012; Madanipour *et al.,* 2018). Then the extensional preexisting faults in Central Iran such as KN Fault have experienced inversion during that time (Guest *et al.,* 2007a). In Central, Iran this obliquity has been compensated mostly by oblique slip Faults with large strike slip components (e.g., Nogole-Sadat, 1985; Morley *et al.,* 2009; Babaahmadi *et al.,* 2010) and sometimes by strain partitioning into thrust /fold and strike-slip motion (e.g., Jamali *et al.,* 2011). Due to the northward motion of Arabia with respect to Eurasia since Tortonian the strike slip components of NW trending faults such as KN Fault in Central Iran are dominantly dextral (e.g., Berberian & King, 1981; Nogole-Sadat, 1985; Safaei *et al.,* 2008; Safaei, 2009b; Morley *et al.,* 2009; Allen *et al.,* 2010; Babaahmadi *et al.,* 2010; Jamali *et al.,* 2011; Mouthereau *et al.,* 2012; Beigi *et al.,* 2016).

Rock units

Eocene sedimentary, Volcanic and volcaniclastic rocks, early Oligocene marl (Lower Red Formation) and late Oligocene- early Miocene limestone and volcanic rocks (Qom Formation) have cropped out in the study area (Fig. 2 and 3). The Eocene rock units which are the oldest rock units exposed along the KN Fault zone consists of an alternation of andesitic- basaltic lava, tuff, and ignimbrite that are unconformably covered by the Oligocene-Miocene sedimentary units (Stocklin, 1968; Emami *et al.,* 1991). Continental lower Red Formation includes marls with gypsum, conglomerate, sandstone, shale, evaporates, and some interbedding of basaltic-andesitic lavas overlies the Eocene units in the eastern side of the study area (Furrer & Sonder, 1955; Emami *et al.,* 1991). Late Oligocene to early Miocene in age marine facies of the Qom Formation that includes 1200 m of carbonates, sandy limestones, marls, and shales in its type area (Furrer & Sonder, 1955; Emami *et al.,* 1991; Reuter *et al.,* 2007) are mostly exposed as narrow bands of allochthonous sediments within the Main KN Fault trace in the study area. Although the Qom Formation is mostly observed between the Lower Red and Upper Red Formations, but in the study area the Qom Formation directly lies on Eocene and Oligocene- Miocene volcanic rocks (Gansser, 1955; Emami, 1991) (fig. 2 and 4). There is no exposure of Upper Red Formation in the study area that often overlies the Qom Formation elsewhere (Furrer & Sonder, 1955; Abaie *et al*., 1964; Emami *et al.,* 1991; Morley *et al.,* 2009).

Data and results

We performed the structural fieldwork along the KN Fault to represent the structural analysis in this area. The fault kinematics was determined by the standard criteria for brittle shear zones (Doblas, 1998; Petit, 1987; Storti *et al.,* 2005). Fault population analysis was carried out using Daisy v.4.9 (Salvini, 2004).

Kushk-e Nosrat (KN) Fault zone is the most important NW-SE trending structure in the northwestern margin of Central Iran (Fig.1) cutting through the Eocene and Oligocene-Miocene volcanic and volcaniclastic rocks and Oligocene-Miocene Qom Formation (Fig. 2). The KN Fault activity causes a slight elevation difference (~280 m) between the fault zone and surrounding areas. To the east of the study area, the KN Fault trace abruptly disappears, while to the west it continues up to the NW of Saveh city (Fig.1). Totally we measured 227 Fault planes in Eocene and Oligocene-Miocene rock units along Eastern side of KN Fault zone in the south of Howz-e-Soltan lake (Fig.2, 5). The ~ 1.3 km wide KN Fault zone consists of steeply dipping principle fault plane (Fig.3) and associated subordinate fault segments. The stereographic plot and Gaussian distribution of total fault data provided in Fig. 5a and b indicate the dominant strike of ~ N115° along KN Fault zone. The low pitch angle of fault population data also show the dominant strike slip component of principle Fault activity (Fig. 5d).We have found different sets of kinematic indicators and slickenlines along KN Fault zone and classified them into two groups that are presented respectively:

The first group consists of right lateral strike slip fault associated with structures including: main dextral fault (~N110°-120°), synthetic (Riedel shear) dextral faults (~ N125°-135°) and antithetic (Anti Riedel shear) sinistral faults (~ N005°- 015°) (Fig. 5b, 6b, d).

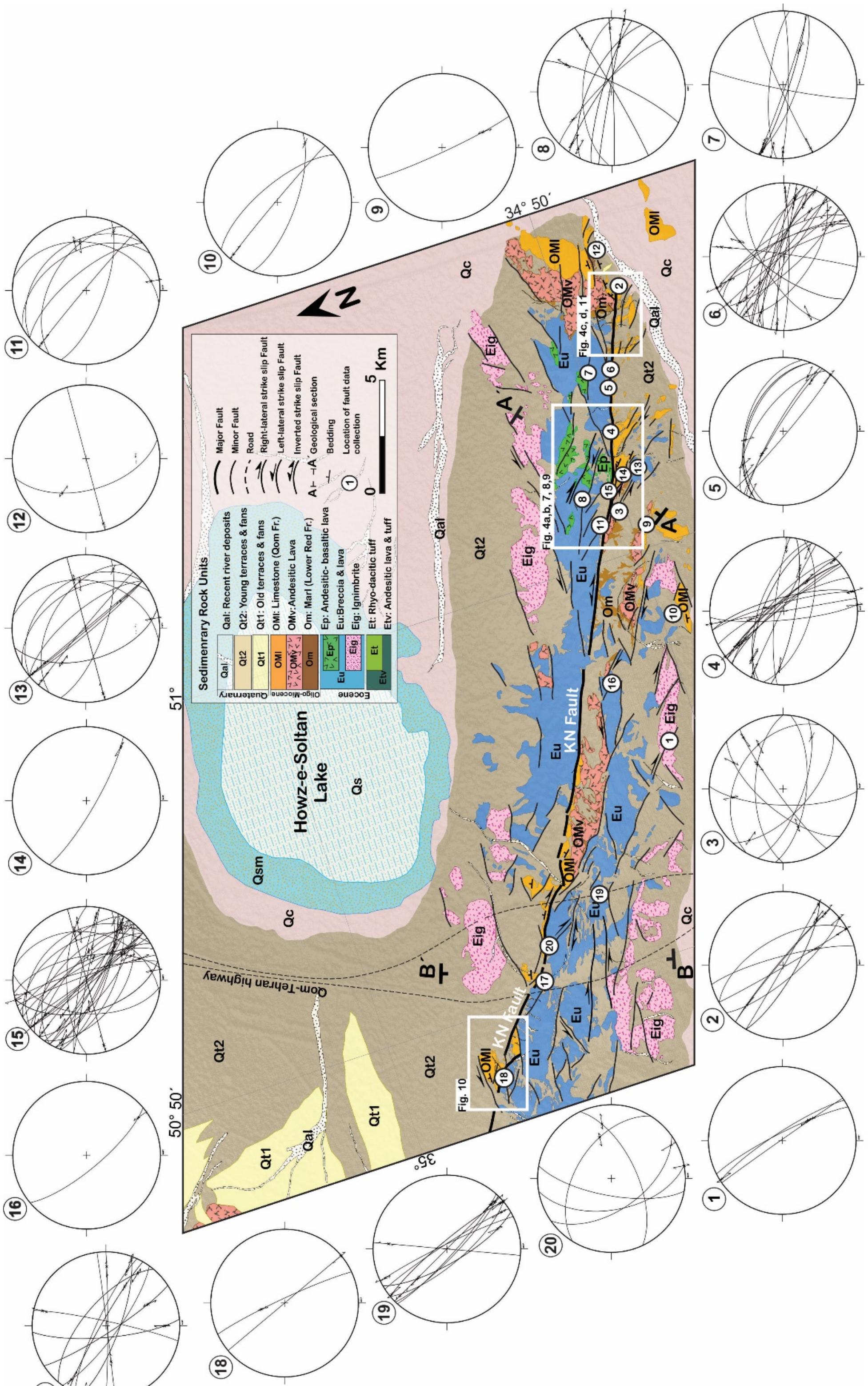

Figure 2. Structural and geological map of eastern termination of KN Fault on Satellite image in north of Qom and around Qom Tehran highway. The stereographic plots show field data collected from the fault zone.

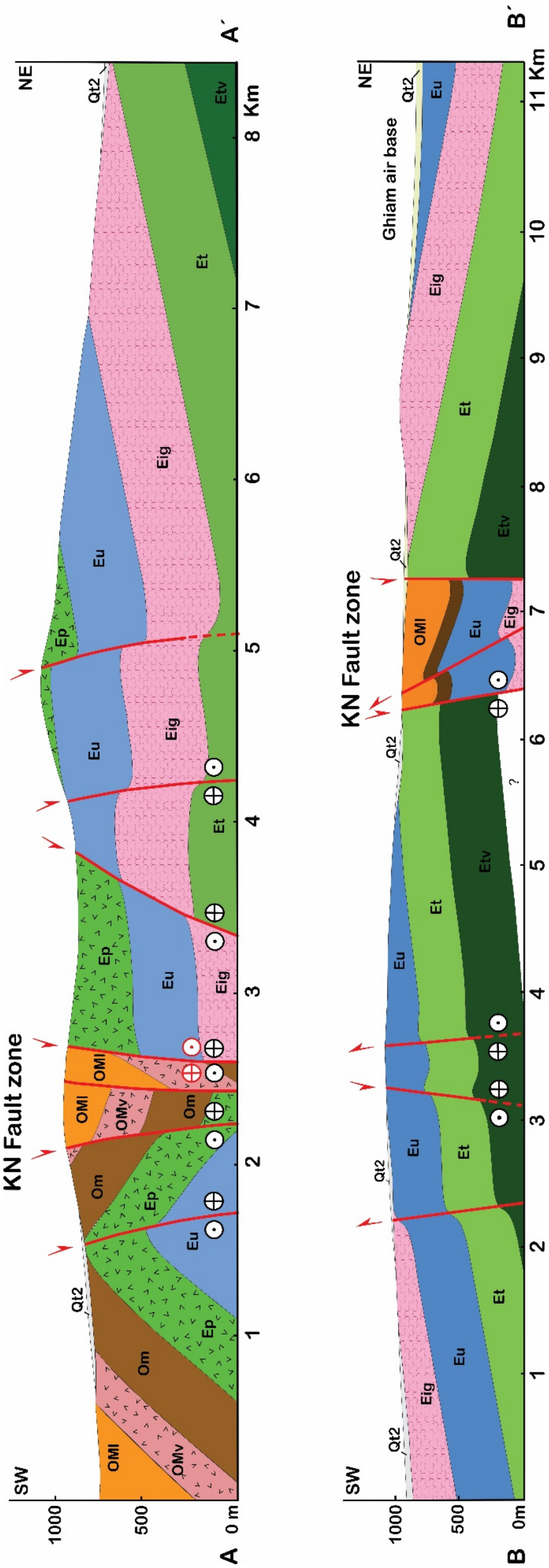

Figure 3. The NE-SW oriented geological cross sections across the KN Fault zone. For location of the cross sections See fig.3. Acronyms are the same as in Figure 2.

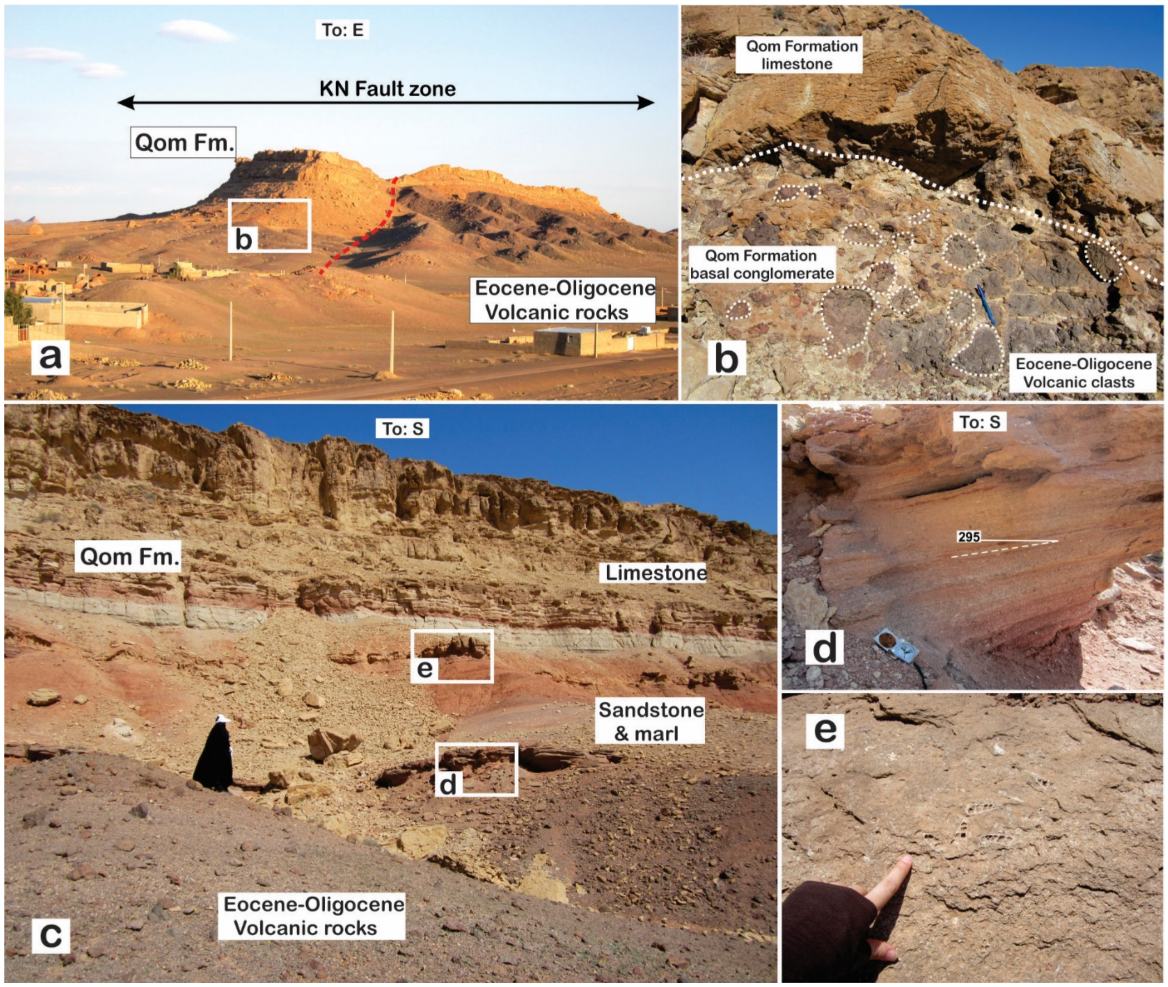

Figure 4. (a) Eastward view of the KN Fault zone representing the stratigraphic rock units exposed along the fault zone. (b). Basal conglomerate indicates the Eocene and Oligocene igneous rock clasts at the base of Qom Formation limestone. (c), (d) and (e). Qom Formation thick sedimentary units in the eastern margin of study area and KN Fault termination. See Fig. 2 for location.

A large group of field evidence indicate dextral dominant strike slip kinematic for hte KN Fault zone. For instance in the eastern part of the area that we have documented the KN Fault trace and its dextral kinematic using Riedel shears and S-C structures indicators (Fig. 7 and 8a, b). Several fault traces associated with the dextral movement of KN Fault are also presented in Fig. 8, including synthetic (R) dextral fault (Fig. 8e) and antithetic (R') sinistral fault evidence (Fig. 8f).

The second group of structures mapped along the KN fault zone consists of left lateral strike slip fault associated kinematic indicators. The main sinistral fault activity has occurred in a similar orientation to the dextral one, Synthetic (Riedel shear) sinistral faults along ~ N095°-105° and antithetic (Anti Riedel shear) dextral faults along ~ N035°- 045° (Fig. 5b, 6b, d). Several evidence of sinistral movements are traceable in the fault zone such as sinistral faulting along the KN fault zone go through the Oligocene – Miocene limestone (Fig. 9a-f) and also synthetic (R) sinistral fault movements (Fig. 9g) in the eastern area of KN fault zone.

There are several evidence indicating the overprinting of sinistral associated structures on previous dextral structures throughout the study area. In the western part of KN Fault trace and near the Qom-Tehran highway we have documented different arrays of fault kinematic indicators on a single fault plane striking ~N110° (Fig. 10a and b). According to cross-cutting relationships on the fault plane, the younger sinistral related structures along with a relative slickenline rake of 153° superimposed on older dextral related structures with slickenline rake of 025° (Fig. 10c-e).

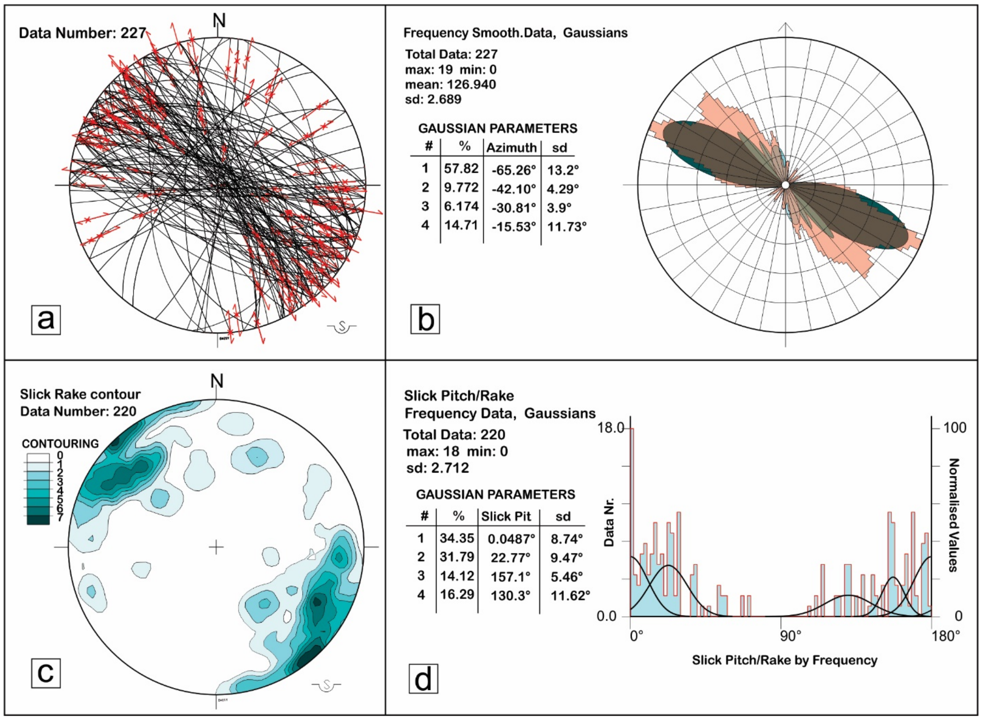

Figure 5. (a) The Stereographic plots (Schmidt net) of fault data along KN Fault zone in north Qom region. fault planes represent in great circles and red arrows show the slickenlines. (b) Frequency smoothed Gaussian distribution data of total fault strikes. (c) Contour plot of Slickenline rake values. (d) Polymodal Gaussian distribution of slickenline rake values by Daisy v.4.9.

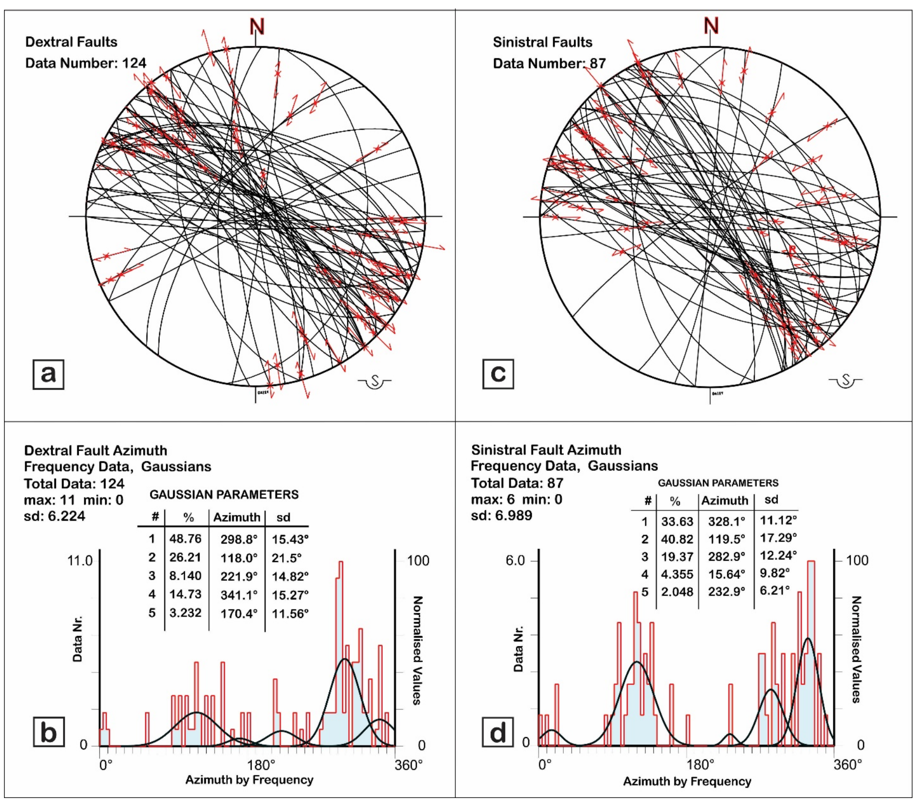

Figure 6. (a) and (b) The separated stereographic plots of cumulative fault data (lower hemisphere, Schmidt net) along KN fault zone at north of Qom related to dextral and sinistral fault kinematic groups, respectively. (c) and (d) Gaussian distribution of fault strike data related to dextral and sinistral fault kinematic groups, respectively.

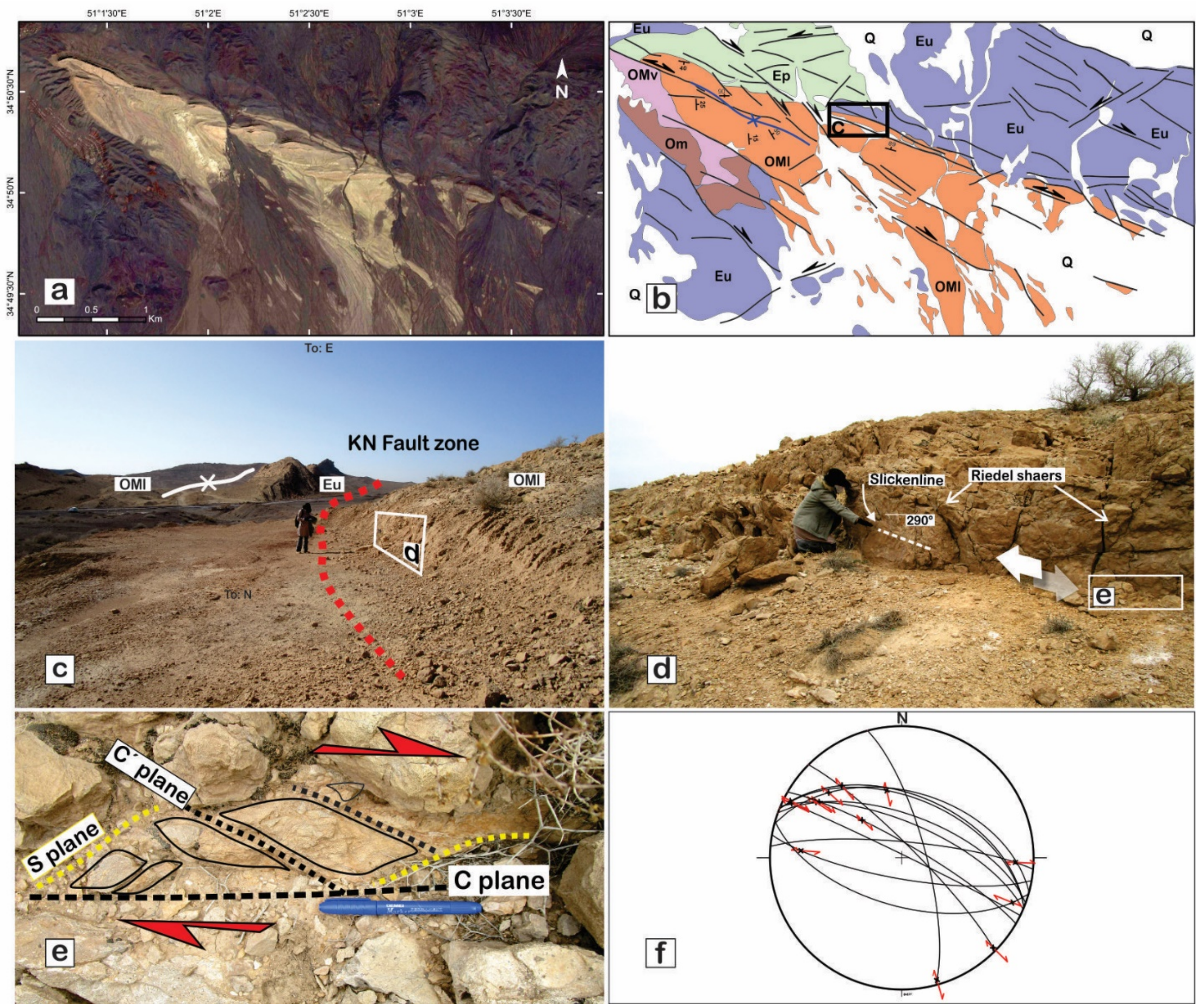

Figure 7. Dextral faulting evidence along KN fault zone in north Qom. (a) Satellite image of KN Fault zone SE of Hows-e-Soltan lake. (b) Simplified geological map of KN Fault zone SE of Hows-e-Soltan lake and related minor faults. (c) Field exposure of KN Fault damage zone involving Eocene and Oligocene volcanic and Oligo-Miocene Qom Formation. (d) evidence of dextral strike slip faulting along main KN Fault trace striking N290°. (e) Dextral mechanism along KN Fault in Fault breccias. (f). The Stereographic plot of fault plane data in this location. See Fig. 2 for location.

In the eastern part also the superimposition is traceable through the Eocene volcanic rock units. As for the previous case, different kinematic indicators are detectable on a single fault plane with the orientation of ~ N110° (Fig. 11a and b).

On these fault planes young sinistral kinematic indicators with slick rake of 016° has been overprinted on older dextral related kinematic indicators with slick rake of 020° (Fig. 11c-e). Such superimposition evidence indicates slip sense inversion from Dextral to sinistral strike slip dominant movement along the KN Fault zone.

Discussion

NE ward convergence between Arabia and Eurasia Plates might be expected to produce prominent structures in the collision zone with dextral component of fault activity or the combination of pure thrust and dextral strike slip motions through deformation partitioning (e.g., Berberian & King, 1981; Nogole-Sadat, 1985; Morley *et al.,* 2009; Allen *et al.,* 2011; Babaahmadi *et al.,* 2010; Jamali *et al.,* 2011). However, several cases of left lateral strike slip components observed along major earthquake faults (e.g., Allen *et al.,* 2003, Walker *et al.,* 2005; Guest *et al.,* 2006, Ritz *et al.,* 2006). Several earthquakes in the north and northwest areas of Central Iran and west of Alborz mountain represent left lateral component along the faults such as Rudbar, Avaj and Ipack faults (Ambraseys, 1963; Berberian, 1976; Berberian & Yeats, 2001; Bachmanov *et al.,* 2004; Walker *et al.,* 2005). This kinematic change from dextral to sinistral transpression in west and central parts of Alborz mountains has been attributed to the Intensifying of Convergence Between Iranian and Arabic plates due to the opening of Red Sea and SW ward motion of SCB in ~5 Ma (Axen *et al.,* 2001; Jackson *et al.,* 2002; Allen *et al.,* 2003; McQuarie *et al.,* 2003; Guest *et al.,* 2006a). On the other hand, a very young transtenssion in central and western Alborz with Pleistocene in age is attributed to the clockwise rotation of SCB (Ritz *et al.,* 2006).

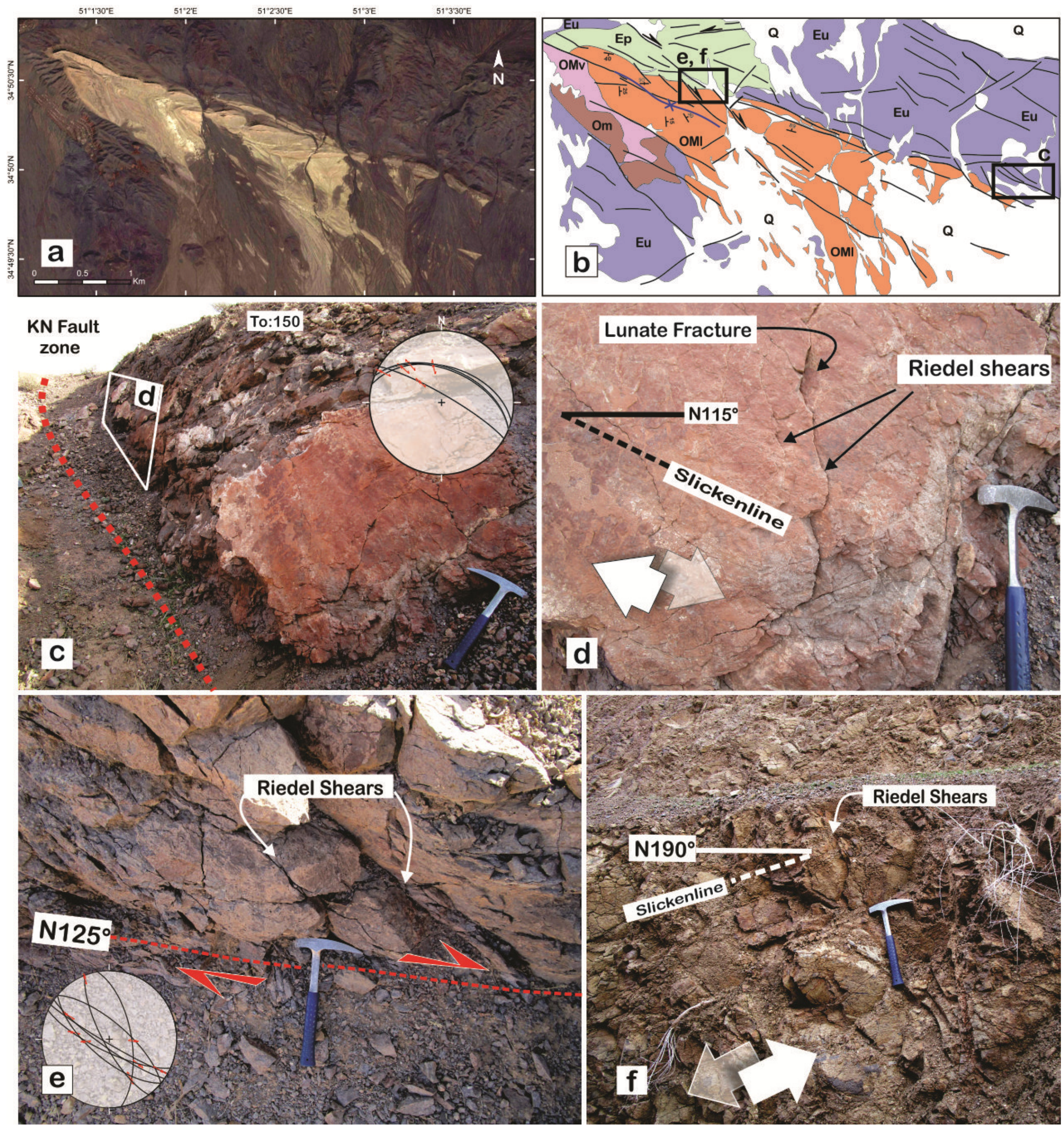

Figure 8. Dextral mechanism relative structures through the Eastern margin of the KN Fault zone. (a) Satellite image of KN Fault zone SE of Hows-e-Soltan lake. (b) Simplified geological map of KN Fault zone SE of Hows-e-Soltan lake and related minor faults. (c) The main N115° striking KN Fault trace affecting the Eocene volcanic rock units. (d) evidence of dextral strike slip faulting along main KN Fault trace striking N115°. (e) dextral strike slip fault as a synthetic fault in the dextral activity of KN Fault. (f) Sinistral strike slip fault as an antithetic fault in the dextral activity of KN Fault zone. See figure 2 for location.

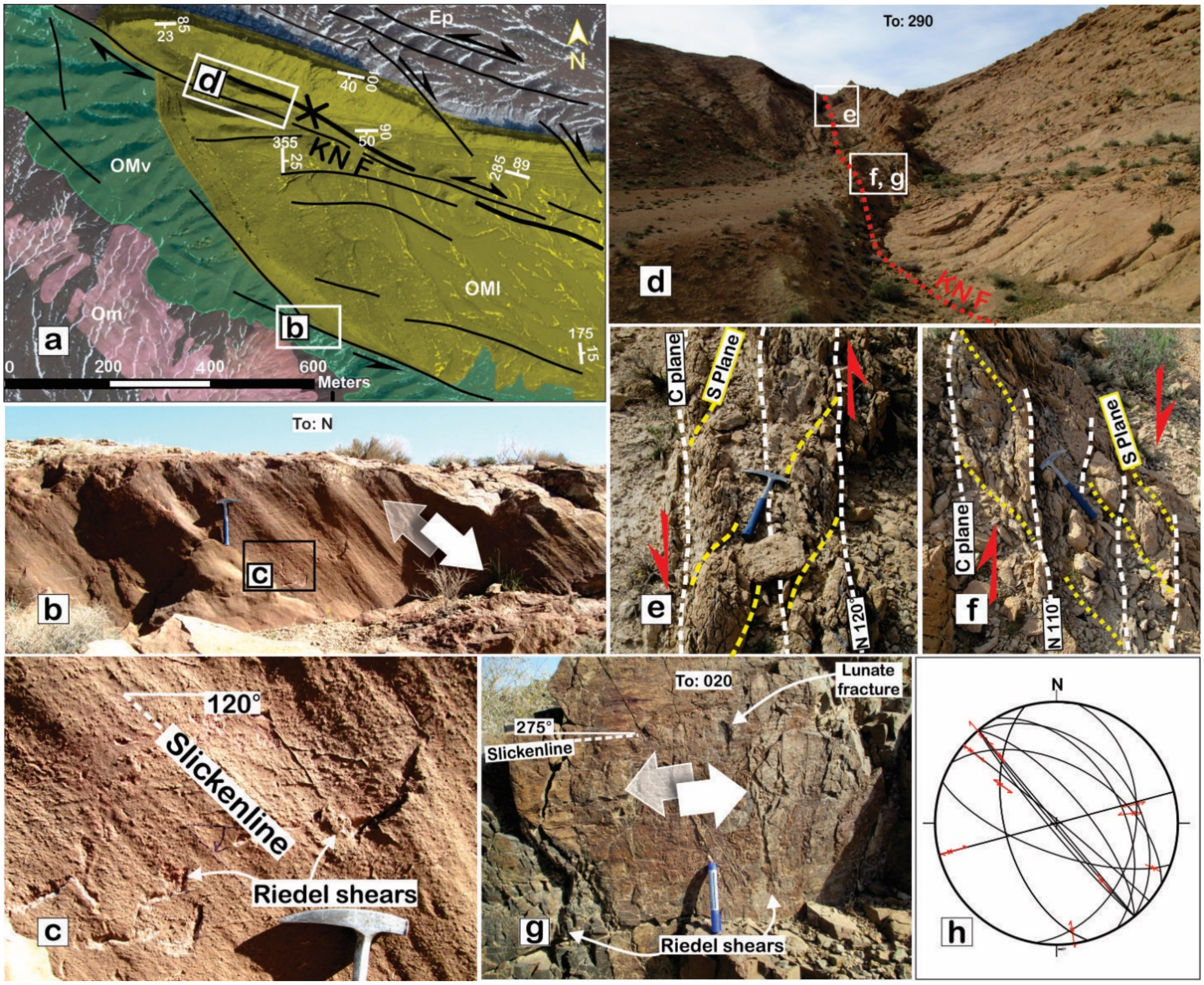

Figure 9. Sinistral mechanism relative structures through the Eastern margin of KN Fault zone. (a) Simplified satellite map of KN fault trace south of Hows-e-Soltan Lake. White squares represent the location of field surveys. (b) and (c) evidence of sinistral strike slip faulting along main KN Fault traces striking N120º. (d) The main N120° striking KN Fault trace affecting the Oligo-Miocene Qom Formation. (e) and (f) Sinistral and dextral movement evidence in Oligo-Miocene Qom Formation cohesive fault rock, respectively. (g) Sinistral strike slip fault as a synthetic fault in the sinistral activity of KN Fault. (g) The Stereographic plots of fault plane data in this location. See figure 2 for location.

The KN Fault activity has been mentioned in some previous studies. Babaahmadi *et al.,* 2010 and Allen *et al.,* 2010 have considered the KN Fault as a dextral strike slip fault whereas Guest *et al.,* 2007; Morley *et al.,* 2009 proposed to be a high angle fault with recent prominent reverse component that previously had prominent normal component. Some other evidence also suggests left lateral kinematic along the KN Fault zone (Ghalamghash *et al.,* 1998).

Our new detail structural analysis along the KN Fault zone provides evidence of kinematic inversion from an earlier stage of prominent dextral strike slip faulting to recent sinistral component based on overprinting of kinematic indicators and cross-cutting relationships. We have documented both dextral (fig. 7, 8) and sinistral (Fig. 9) strike slip movement-related structures. These evidence show that the sinistral activity related structures has generally affected all the primary structures and cut the previous dextral associated structures (Fig. 10, 11). In almost all over the study area the previous structures related to the dextral activity, have been cut and superimposed by NE-SW striking right lateral faults (R`) related to the sinistral activity of KN Fault zone (Fig. 12). All these evidence indicate that the kinematic change of SCB has influence sothward from Alborz to the Central Iran zone.

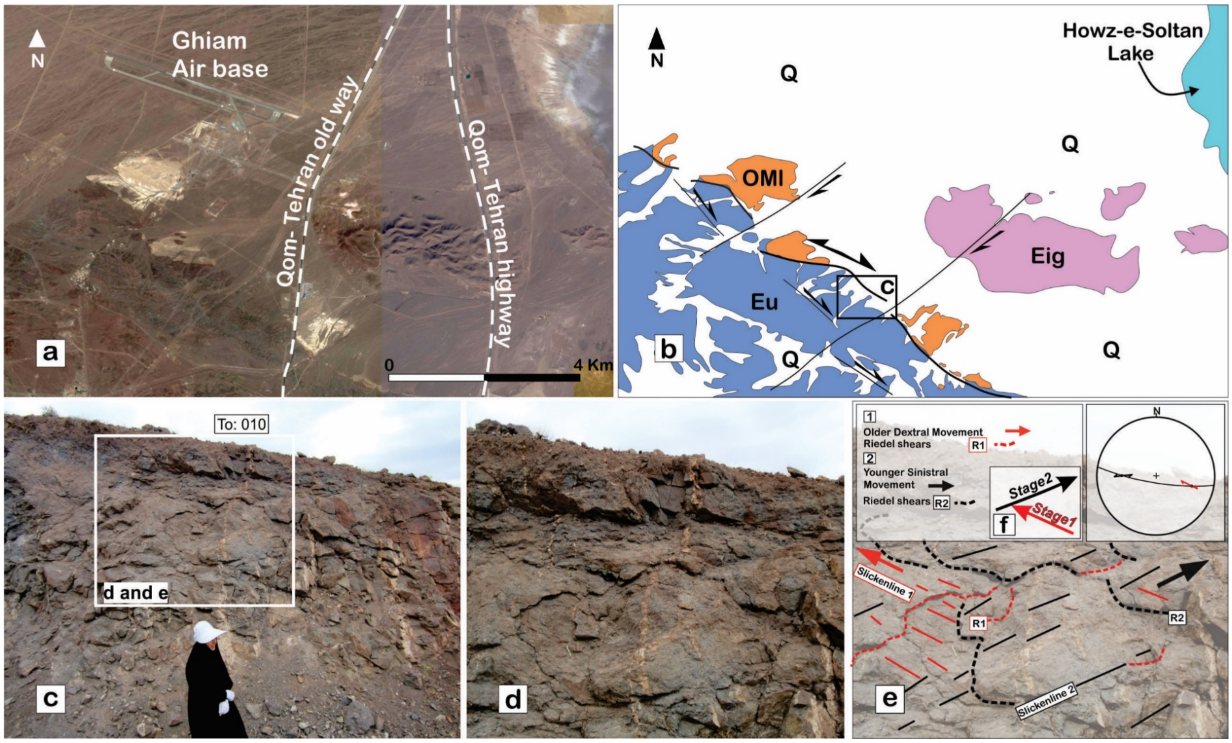

Figure 10. The overprinting of sinistral related structures on prior dextral related structures along the KN fault zone. (a) and (b) satellite image and simplified map of KN fault trace near the Qom-Tehran Highway. (c), (d) and (e) overprinting of younger sinistral movement kinematic indicators on prior dextral movement kinematic indicators on Eocene volcanic rocks along KN fault zone. (f) Relative ages of fault movements according to cross-cut relations and Superimposition of kinematic indicators. See figure 2 for location.

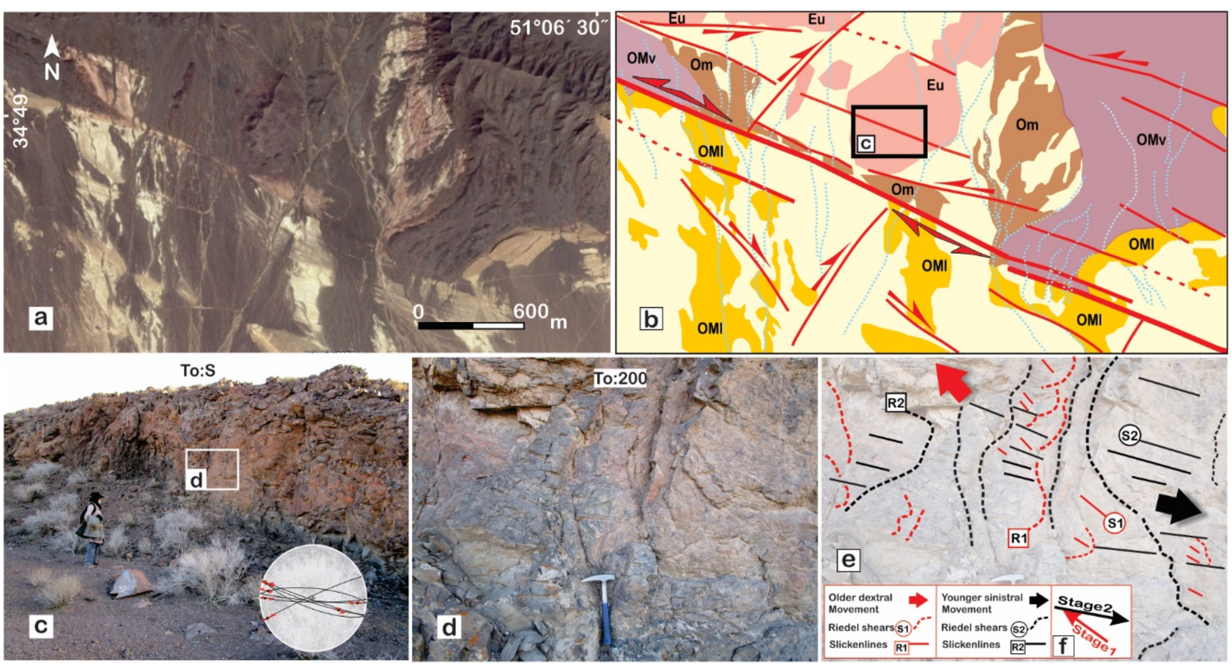

Figure 11. (a) and (b) satellite image and simplified map of KN fault eastern termination SE of Hows-e-Soltan lake. (c), (d) and (e) superimposition of younger sinistral movement kinematic indicators on prior dextral movement kinematic indicators on Eocene volcanic rocks along KN fault zone. (f) Relative ages of fault movements according to cross-cut relations and Superimposition of kinematic indicators. See figure 2 for location.

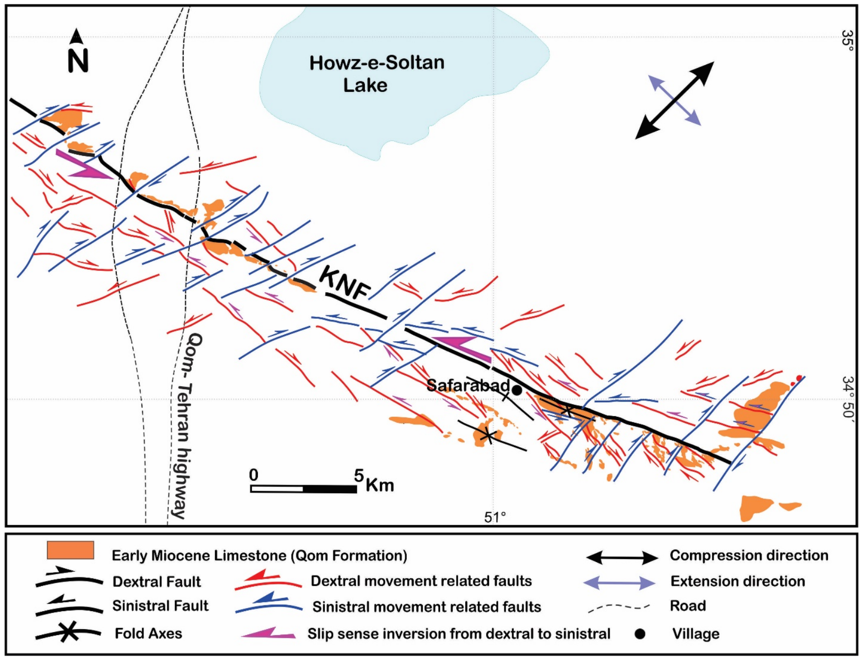

Figure 12. Simplified structural map of the study area that shows the order of structural events along the KN Fault zone based on field surveys and cross-cutting relationships. Dominant young sinistral kinematic related structures have generally affected all previous structures.

Conclusion

We used field observations and satellite images to investigate detail structural evidence of the KN Fault zone. Our findings indicate two different structural evidence in fault zone including dominant dextral and sinistral strike slip movement evidence. Based on cross-cutting relationship and overprinting of kinematic indicators we inferred that kinematic inversion from dominantly dextral to sinistral strike slip kinematic has occurred along the fault zone. As with similar observations of kinematic inversion in central and western regions of Alborz Mountains we suggest that the kinematic inversion along KN Fault zone has also occurred due to the clockwise rotation of SCB.

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