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Polyphase Inversion Tectonics in Western Alborz Mountains, Northern Iran

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Abstract

Fault kinematics in western Alborz mountains is complicated by range-parallel left lateral strike slip faults as well as a series of longitudinal zones of thrusts that are considered to be due to the inversion of pre-existing right lateral and normal faults, respectively. Previously proposed models suggested that the NW component of the motion resulted from the clockwise rotation of the South Caspian block is responsible for left lateral motion on the NW trending faults in western Alborz. However, a more recently proposed model suggests that only if several basement blocks rotate clockwise about vertical axes, the left lateral motion along range-parallel basement faults can occur. Recent GPS studies indicate that northern Iran including north central Iran, Alborz mountains as well as South Caspian block are rotating clockwise with respect to Eurasia. Here, I invoke the previously published evidence to suggest a new tectonic model to explain a sequence of inverse deformation episodes as well as the observed structural features and the active deformation in western Alborz mountains. According to this model the western Alborz mountains initiated as several east-west trending extensional (pull-apart) basins associated with left lateral motions on the large-scale strike slip basement faults and intervening normal faulting at least since the Late Triassic time. The inversion of left lateral strike slip faults in Late Cretaceous and Neogene times, however, could be due to a halt in block rotations. In other words, when the blocks stopped rotating, the NW trending faults bounding them may have been affected by the convergence between central Iran and the South Caspian block. This N-S compression would presumably cause dextral motion on the NW trending strike slip basement faults in western Alborz. The resulting dextral motion on the NW strike slip faults, in turn, caused pre-existing normal faults bounding the pull-apart basins to turn into reverse faults. As rotation of the central Iran-western Alborz-South Caspian blocks resumed first in Eocene and then in the Quaternary times, the NW trending basement faults regained their left lateral motions and the associated east-west basement reverse faults once again turned into the normal faults. However, geodetically observed shortening across the western Alborz mountains indicates that the east-west reverse faults within the cover unit have remained reverse. This contradiction may be explained by simultaneous shortening of the cover unit resulted from convergence between central Iran and South Caspian block, and extension of the basement due to clockwise rotation of the central Iran-western Alborz-South Caspian blocks.

Keywords: Inversion tectonics, Alborz, Block rotation, Seismicity, Iran

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1 Introduction

One of the fundamental issues that has been commonly addressed by the early workers is the active fault kinematics in the western Alborz mountains (Fig. 1). Both field observations and GPS velocity vectors demonstrate the present-day left lateral motion along the mountain-parallel faults in the western Alborz (e.g. Allen et al., 2003; Djamour et al., 2010). However, the left lateral faults are considered to be due to the inversion of pre-existing right-lateral faults, which are thought to have formed as a result of N-S convergence between central Iran and South Caspian block in Late Miocene time (Allen et al., 2003). Most of the previously suggested models use the present-day obliquity of the motion between the south Caspian block and central Iran to justify the left lateral motions on the NW trending faults (Allen et al., 2003; Ritz et al., 2006). The main difficulty that may arise by considering such kinematic models is that the present-day compression direction, deduced from GPS observations (Djamour et al., 2010; Mousavi et al., 2013) is not oblique enough to the NW rending faults in western Alborz mountains and thus cannot explain the observed left lateral offsets in geomorphology and in the focal mechanism solutions of the earthquakes occurred in the western Alborz. On the other hand, the occurrence of several extensional episodes, each followed by the inversion of the pre-existing extensional faults, (see e.g. Allen et al., 2003; Zanchi et al., 2006; Guest et al., 2006) have not been explained by a comprehensive tectonic model. Here, the clockwise rotations of the basement blocks in northern Iran are used to explain a sequence of inverse deformation episodes (i.e. polyphase inversion tectonics) as well as the inconsistencies observed in the structural features and active deformation in the western Alborz mountains.

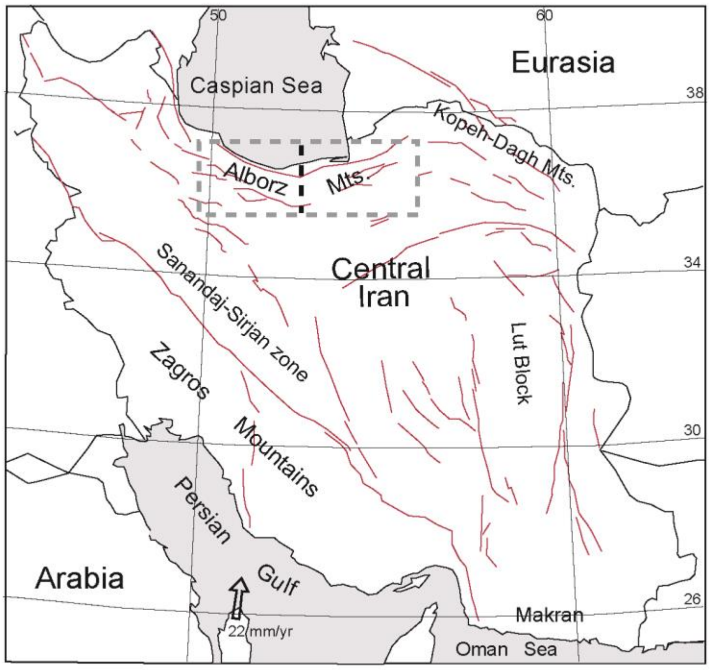

Figure 1. Regional map depicting tectonic units of Iran. Rectangle encloses the Alborz mountains and black dashed line separates western from eastern Alborz. Arrow at the bottom of the figure shows GPS derived velocity vector with respect to Eurasia (Vernant et al., 2004a).Red lines depict major faults of Iran.

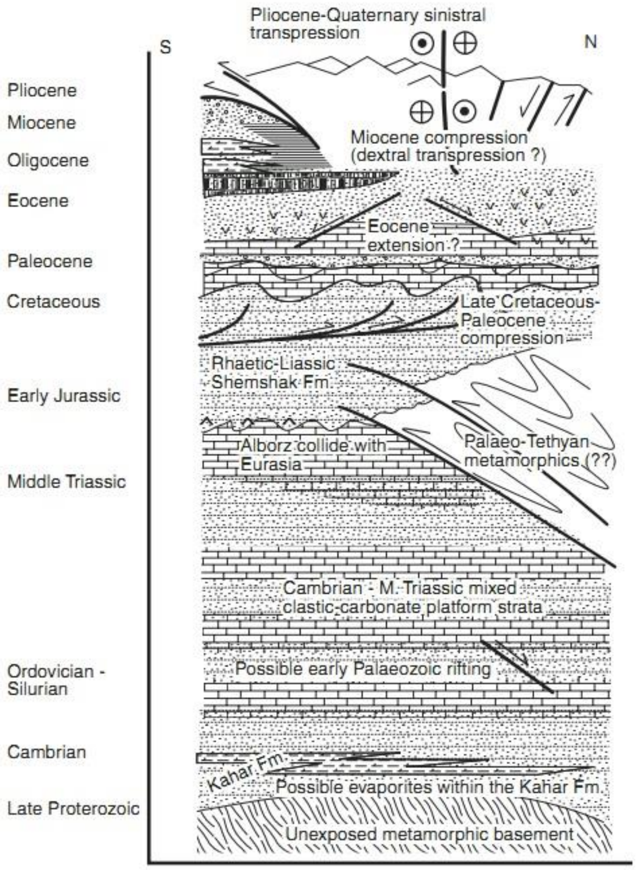

Figure 2. Schematic tectonostratigraphy of the Alborz mountains (after Guest et al., 2006).

2 Geological setting

The Iranian plateau extends over a number of continental fragments, welded together along the suture zones (Fig. 1). Alborz Mountains in northern Iran, as one of these fragments, is considered to be part of the early Paleozoic Gondwanan passive continental margin (Stocklin, 1974). Tectonostratigraphy column (Fig. 2) indicates that central Iranian block and the Alborz rifted away from Gondwana during Ordovician to Silurian time and collided with Eurasia during Triassic time (Allen et al., 2003; Guest et al., 2006).

Active deformation in the Alborz mountains is due to the convergence between central Iran and Eurasia which occurs at a rate of about 5 mm/yr (Vernant et al., 2004b). Deformation in the Alborz mountains is mainly due to the left lateral strike slip faults and a series of longitudinal zones of folding with thrusts that are primary dipping south on the northern side of the mountains while dipping north on the southern side (Allen et al., 2003). The thrust faults are considered to be due to the inversion of pre-existing normal faults, which were formed as a result of basement extension and thinning during the Eo-Cimmerian orogeny of the foreland basin in Late Triassic (Zanchi et al., 2006). Because of its sinuous form, the Alborz mountains have been traditionally divided into two segments, namely eastern and western segments (Fig. 1). Structural trend in the eastern segment is NE-SW while the western segment is trending NW-SE. Recent GPS measurements (Khorrami et al., 2019) indicate that in the eastern Alborz strike slip motion is predominant and occurs at a rate of about 8 mm/yr along the NE trending left lateral faults, while mountain-normal shortening occurs at a rate of about 2 mm/yr along thrusts. However, in western Alborz, left lateral motion occurs at a rate of about 4-6 mm/yr along the NW faults and mountain-normal shortening occurs at a rate of about 5-7 mm/yr along thrusts. Moreover, the total left lateral and dip slip movements along thrusts are estimated to be ~30–35 km and ~36 km, respectively, based on a restored structural cross section across the range (Guest et al., 2006).

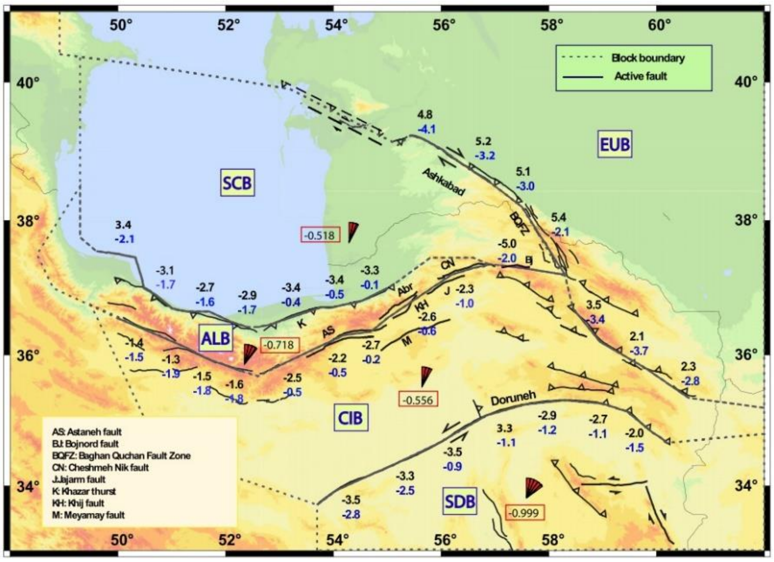

Figure 3. Map showing slip-rate variability (mm/yr) along the active faults from rigid block modeling. The upper values show the strike-slip component (positive indicates right-lateral slip). The lower values indicate the fault-perpendicular slip-rates (negative values indicate shortening). Dark gray lines represent active faults and dotted lines show block boundaries. The blocks are ALB: Alborz, CIB: Central Iran, EUB: Eurasian, SCB: South Caspian and SDB: South Doruneh blocks. Numbers inside the red rectangles are GPS block rotation rates in degree/Ma, in the center of each block, calculated from block modeling with locked faults. Counterclockwise rotation sense is positive (after Mousavi et al., 2013).

3 Observations and discussion

GPS measurements across northern Iran indicate that the western Alborz as well as central Iran and the South Caspian block involve clockwise rotations about vertical axes with respect to Eurasia (Fig. 3, Mousavi et al., 2013). However, Koyi et al. (2016) demonstrated that the left lateral movement along the NW trending faults in the western Alborz mountains is due to the clockwise rotation of the fault-bounded basement blocks about the vertical axes (Fig. 4). They also suggested that the rhombic blocks bounded along the NW trending left lateral strike slip faults as well as east-west trending thrust faults may have formed as a result of simultaneous north-south shortening of the cover unit and clockwise rotation of the basement blocks.

On the other hand, aside from the rifting period during Ordovician-Silurian time, several lines of evidence suggests that at least two more extensional episodes occurred during the development of the western Alborz mountains. Zanchi et al. (2006) showed that the graben structures in western Alborz formed in the foreland of the Late Triassic Eo-Cimmerian orogen, in early Late Triassic (Fig. 5). However, a second evidence of the extensional episode is marked by syn-extensional deposition of Karaj formation which is interpreted to record backarc extension in northern Iran during Eocene time (Allen et al., 2003). Therefore, the Late Cretaceous compressional phase illustrated in the tectonostratigraphy column (Fig. 2) and the Neogene inversion of the normal faults bounding the graben structures (Zanchi et al., 2006), have followed the two extensional episodes, respectively.

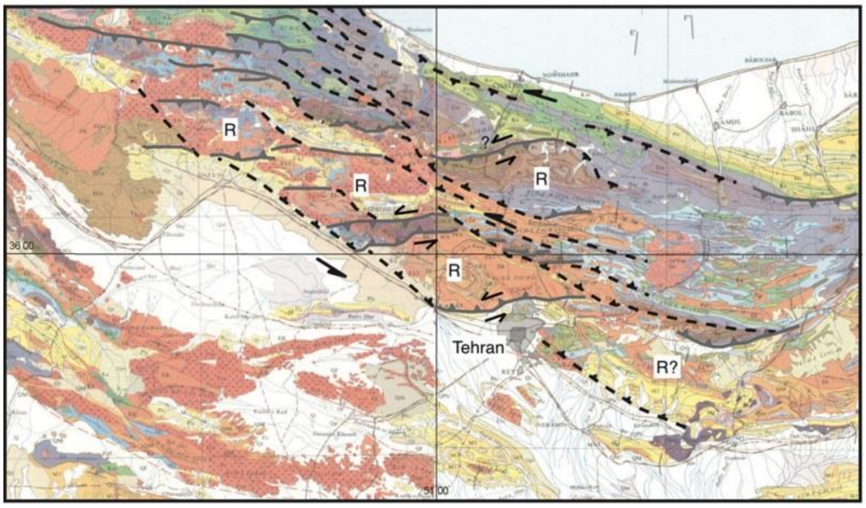

Figure 4. Geological map of the western Alborz Mountains (National Iranian Oil Company, 1977) showing rhombic structural features (after Koyi et al., 2016). These rhombic structures are considered to be positive flower structures due to inversion of pre-existing extentional (pull-apart) basins.

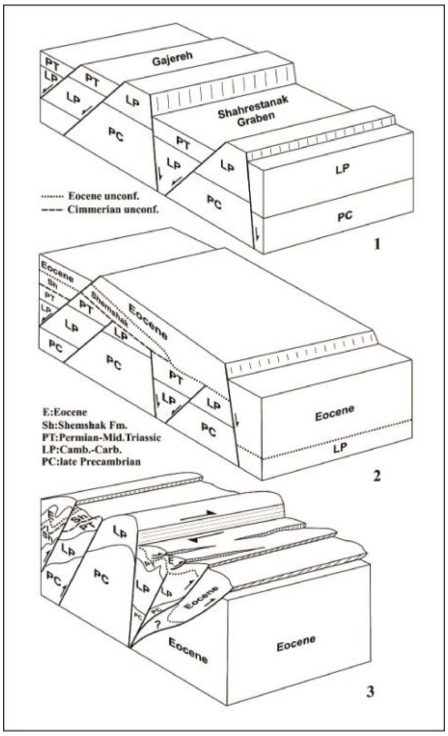

Figure 5. Evolution of part of the southern limb of the western Alborz mountains (Shahrestanak structure) during Mesozoic and Tertiary. (1) early Late Triassic, when grabens formed (2) sealing of the grabens (3) Neogene-Quaternary inversion of pre-existing normal faults (after Zanchi et al., 2006)

The model presented in this study invokes the previously published evidence to suggest that the clockwise rotations of the basement blocks in western Alborz caused several east-west trending extensional basins to develop as pull-apart basins along the NW trending left lateral basement faults. Hence, the evolution of the Alborz mountain belt should have involved an inversion of the pre-existing normal faults as east-west trending reverse faults. Here, the inversion of the pre-existing normal faults has been attributed to the inversion of the left lateral faults as the clockwise rotation of the basement blocks may have come to a halt in the Late Cretaceous and Neogene times. Present-day left lateral motion seen in geomorphology (Fig. 6) along the NW trending faults (Bachmanov et al., 2004, Ritz et al., 2006), though, suggest that the rotation of the central Iran-western Alborz-South Caspian blocks has resumed in the Quaternary time. Thus, the east-west trending reverse faults should again have turned into the normal faults. In fact, geomorphic and paleoseismic evidence (Fig. 6) (see Ritz et al., 2006) and the seismicity of western Alborz (Fig. 7) (see Ashtari et al., 2005; Soltani-Moghadam, 2020) show that some of the east-west trending faults in the western Alborz mountain have involved normal motions. Hence, the basement reverse faults seem to have inverted to form normal faults as clockwise rotation of the basement blocks resumed and left lateral faults reactivated in the Quaternary times.

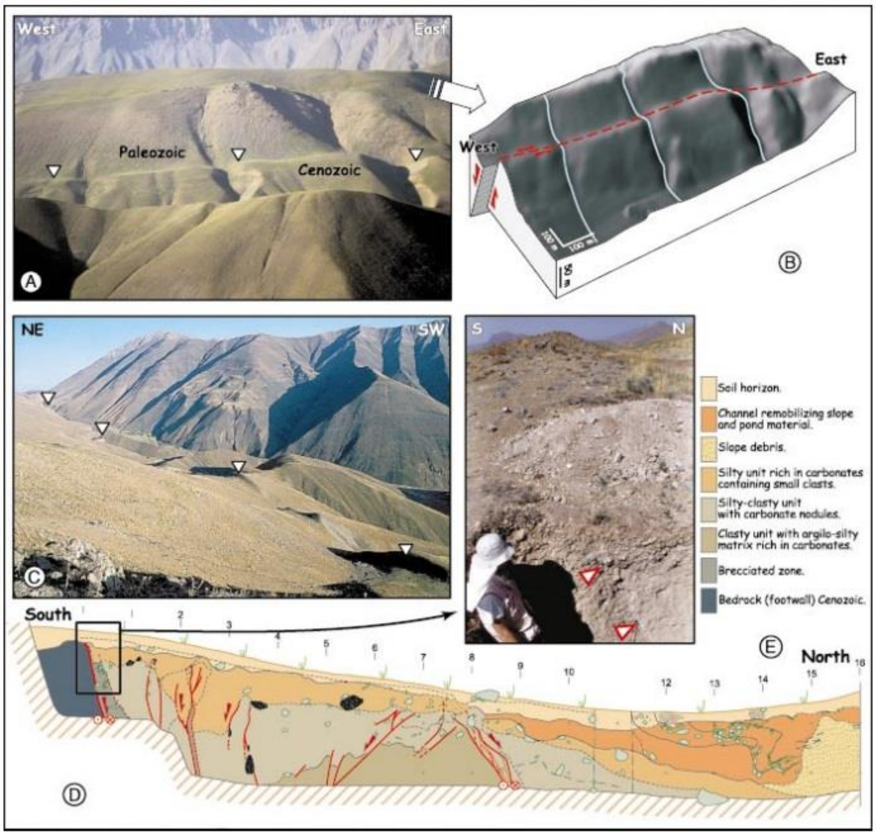

Figure 6. A: Eastern Mosha fault scarp in landscape. B: Corresponding digital elevation model (DEM) C: Picture of fault scarp. D: Log of one of trenches dug across fault scarp E: Picture of main rupture. (after Ritz et al., 2006).

Focal mechanism solutions of the earthquakes depicting present-day active faulting involve left lateral motions on nodal planes trending NW-SE. However, east-west trending faults indicate both the reverse and normal faults (Fig. 7). This contradiction can be explained by simultaneous shortening of the cover unit causing reverse faults within the cover and clockwise rotation of the basement blocks resulting in normal faults in the basement. On the absence of a precise estimation of thickness of the cover unit and uncertainty of the focal depths of the earthquakes it is hard to relate the reverse and normal earthquake faults to distinct horizons at depth.

4 Concluding remarks

In the following, the kinematic model (Fig. 8) proposed for the western Alborz region is summarized.

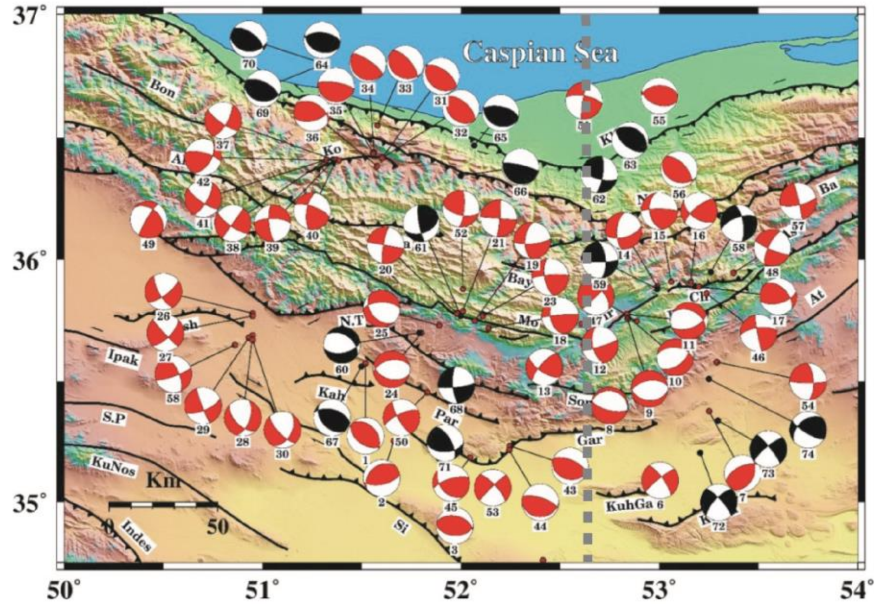

Figure 7. Focal mechanism solutions in Alborz mountains, north Iran, divided into two groups based on their quality A (Red, high) and B (Black, low) (after Soltani-Moghadam, 2020). Gray-dashed line marks the boundary between the eastern and western Alborz mountains.

1) According to the model presented in this study, the western Alborz mountains have developed as several east-west trending extensional (pull-apart) basins at least since the Late Triassic time (Fig. 8).

2) The east-west pull-apart basins were bounded by the large-scale NW-SE trending left lateral strike slip faults, rotating clockwise about the vertical axes, and by intervening east-west trending normal faults.

3) The inversion of the pre-existing east-west normal faults in the Late Cretaceous and Neogene times can be attributed to the inversion of the NW trending left lateral faults. The inversion of the NW trending left lateral strike slip faults to the right lateral strike slip faults, however, could be due to a halt in block rotations. In other words, when all the central Iran-Alborz and South Caspian blocks stopped rotating, the faults bounding them might be affected by the northward convergence of central Iran with respect to the South Caspian block (i.e. Eurasia). This N-S compression would presumably cause right lateral motion on the NW trending basement faults in western Alborz. The resulting right lateral motion on the NW strike slip faults, in turn, caused an inversion of the

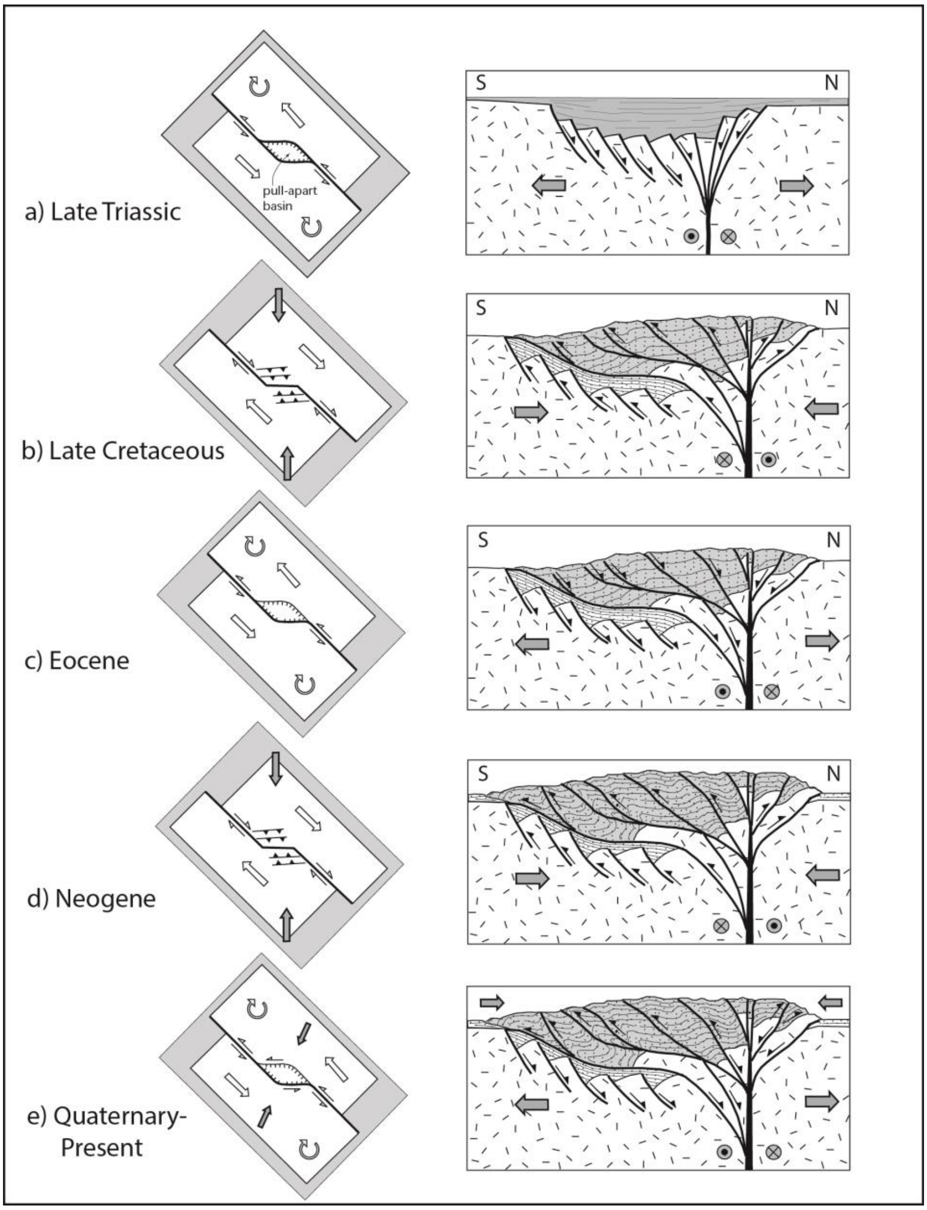

Figure 8. Cartoon showing polyphase inversion tectonics in western Alborz mountains. Left column is a generalized map view of two adjacent basement blocks separated by a bended fault. Right column shows cross sections across the two blocks. Crossed and dot-centered circles show sense of strike slip motions a) Late Triassic pull-apart basin formation associated with left lateral motion of the basement faults which are resulted from clockwise rotation of central Iran-Alborz mountains-South Caspian blocks b) Late Cretaceous positive inversion of normal faults caused contractional structures such as reverse faults and folds to develop as a result of right lateral movements along the basement faults c) Eocene negative inversion caused normal faults to reactivate. d) Neogene positive inversion and e) Quaternary negative inversion indicating present-day normal faults associated with left lateral motion along the basement faults. However, the reverse faults in the cover sediments have remained reverse as a result of simultaneous clockwise rotation of the basement blocks and compressional stress between central Iran and South Caspian block.

pre-existing normal faults bounding the pull-apart basins as reverse faults.

4) Resumption of the clockwise rotation of the central Iran-Alborz and South Caspian blocks, first in Eocene and then in the Quaternary time, caused the most recent inversion of the NW trending right lateral faults. These changes in the sense of motion along the NW trending faults in turn caused the east-west basement reverse faults turn into the normal faults. However, the reverse faults

in the cover unit being simultaneously affected by compressional stress between central Iran and the South Caspian block, remained reverse.

5) Unlike previous suggestions, the model presented in this study suggests that the western Alborz mountains may have not initiated as a passive continental margin but it is likely to have developed along several large-scale strike slip faults and intervening east-west trending dip-slip faults during Ordovician-Silurian time. An alternation of the clockwise rotation of the basement blocks and their cessation seems to have caused a sequence of inverse deformation episodes resulting in alternating the periods of negative (pull-apart basins) and positive (contractional structures) flower structures dominance.

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