Active transtension inside central Alborz: A new insight into northern Iran–southern Caspian geodynamics

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ABSTRACT

The tectonic activity in the Alborz mountain range, northern Iran, is due both to the northward convergence of central Iran toward Eurasia, and to the northwestward motion of the South Caspian Basin with respect to Eurasia inducing a left-lateral wrenching along this range. These two mechanisms give rise to a NNE-SSW transpressional regime, which is believed to have affected the entire range for the last 5 ± 2 m.y. In this paper, we show that the internal domain of central Alborz is not affected by a transpressional regime but by an active transtension with a WNW-ESE extensional axis. We show that this transtension is young (middle Pleistocene). It postdates an earlier N-S compression and may have been initiated when the South Caspian Basin started moving. Consequently, our results suggest that the South Caspian Basin motion may have taken place more recently than previously proposed.

Keywords: Iran, central Alborz, South Caspian Basin, active tectonics, transtension.

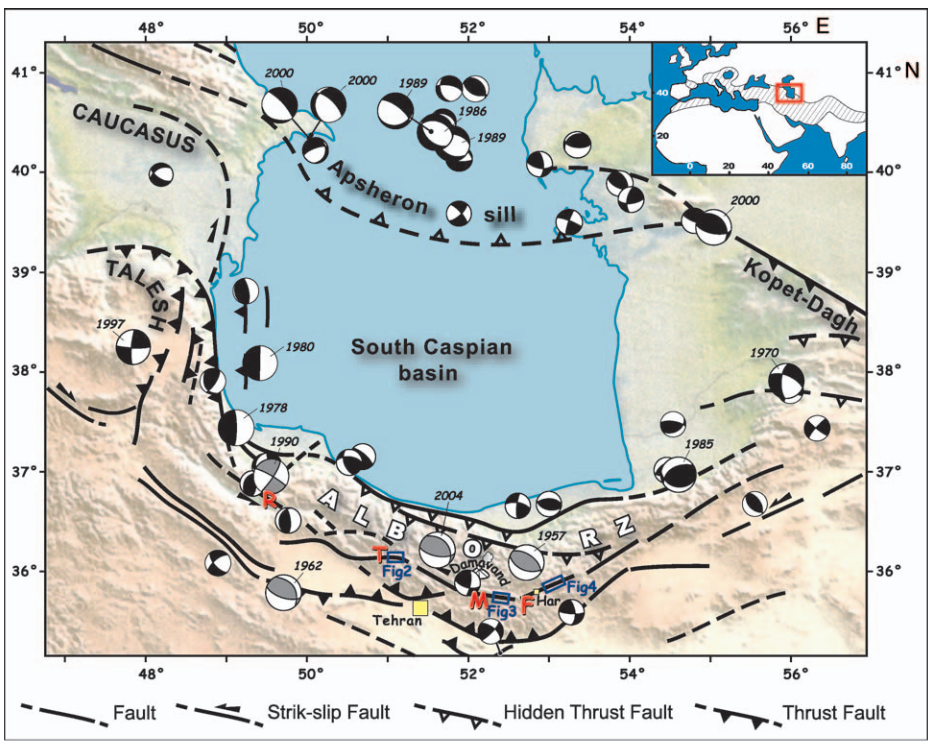

Figure 1. Map of the South Caspian region with active faults and focal mechanisms (larger spheres with dates correspond to earthquakes having magnitude ≥6). Focal mechanisms are from Jackson et al. (2002) for Apsheron sill and Kopet Dagh area, and from Ashtari et al. (2005) for Alborz. Gray spheres are from McKenzie (1972) for 1957 earthquake, from Jackson et al. (2002) for 1962 and 1990 earthquakes, and from U.S. Geological Survey for 2004 earthquake. Abbreviations: T—Taleghan fault, M—Mosha fault, F—Firuzkuh fault, R—Rudbar fault, Har—Harandeh village.

INTRODUCTION

Surrounding the South Caspian Basin, the Alborz mountain range shows strong tectonic activity with several destructive earthquakes in the past (Berberian and Yeats, 2001). A V-shaped structure characterizes its central part (longitudes 50°E to 54°E) with folds and faults trending NW-SE in the western Alborz and trending NE-SW in the eastern Alborz (Fig. 1). Structural and seismological data for the Alborz show that the deformation is partitioned along range-parallel thrusts and left-lateral strike-slip faults (Jackson et al., 2002; Allen et al., 2003). A recent global positioning system (GPS) study showed that N-S shortening across the Alborz occurs at 5 ± 2 mm/yr and that the left-lateral shear across the overall belt has a rate of 4 ± 2 mm/yr (Vernant et al., 2004). Seismological data recorded in Alborz and other areas surrounding the South Caspian Basin allowed Jackson et al. (2002) to conclude that the South Caspian Basin is moving NW with respect to Eurasia; using the global GPS data set, the maximum northern component of the South Caspian plate movement is 5–6 mm/yr. This model accounts for the seismic activity along the Apsheron ridge, the eastward overthrusting of the Talesh, and the left-lateral movement along the WNW-ESE Rudbar fault, to the north, west, and southwest of the South Caspian Basin, respectively (Fig. 1). Coupled with the N-S convergence of central Iran, the southwestward motion of the South Caspian Basin with respect to central Iran leads to a NNE-SSW transpressional regime in Alborz. This transpression would have started between 3 and 7 m.y. ago. Before this date, right-lateral movements observed along range-parallel strike-slip faults in western Alborz suggest that the range was deforming against the rigid and stable South Caspian domain under a N-S compressional regime (Axen et al., 2001; Jackson et al., 2002; Allen et al., 2003).

However, in the internal domain of central Alborz, morphotectonic features do not fit with the above kinematical and chronological model. These features concern the Taleghan, the eastern Mosha, and the Firuzkuh faults, which are three main active faults, each around 70–80 km long that trend E-W, WNW-ESE, and NE-SW, respectively (Fig. 1). These three faults are more or less connected and belong to a range-parallel shear zone inside the central Alborz. The area covered by these faults is 250 × 50 km², between 50°30′ and 53°00′E longitude, and includes the Damavand, a dormant volcano corresponding to the highest peak in the Middle East (5670 m).

During historical seismicity, these three faults have been the sites of large earthquakes (Berberian and Yeats, 2001), but so far, the absence of strong instrumental events along them has not allowed us to determine their focal mechanisms. On the geological maps, these faults are indicated as thrust faults along which Mesozoic, Paleozoic, or Proterozoic deposits overthrust Cenozoic deposits. These thrusting movements are considered still active (e.g., Berberian et al., 1996) and associated with left-lateral strike-slip faulting along the eastern Mosha fault (e.g., Allen et al., 2003) and the Firuzkuh fault (e.g., Berberian et al., 1996; Jackson et al., 2002). Study of recent morphological features and associated structures affecting the Quaternary deposits along these faults allows us to propose a different interpretation of their present kinematics. This has implications in terms of understanding the recent geodynamical evolution of the central Alborz–South Caspian region.

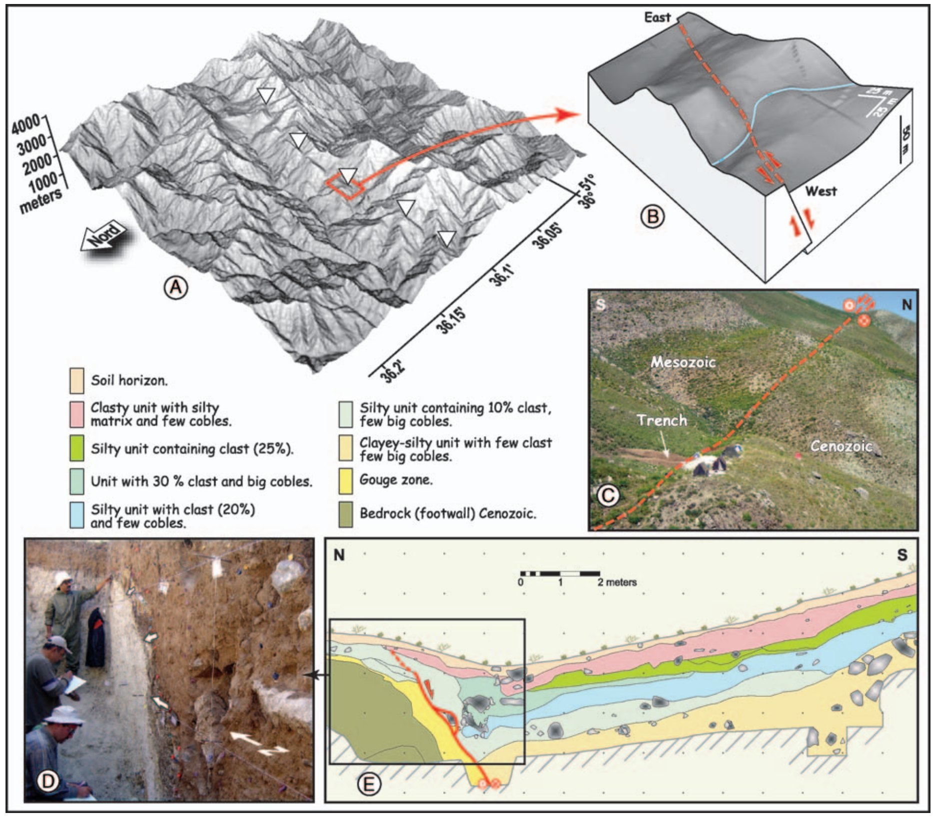

Figure 2. A: Digital elevation model (DEM) obtained from "Asara" 1:50,000 topographical map showing Taleghan fault scarp. B: DEM obtained from global positioning system (GPS) kinematics survey. C: Picture of the fault scarp. D: View of the Taleghan fault in trench and (E) corresponding log.

MORPHOTECTONICS AND STRUCTURAL ANALYSES

Along the three mentioned faults, we analyzed satellite pictures, air photographs, and the large-scale digital elevation models (DEM; generated from digitizing 1:50,000 scale topographic maps). Then we did extensive field work within selected sites, analyzing the morphology, using small-scale DEMs generated from GPS kinematics surveys, and the structures affecting the recent deposits within paleoseismological trenches dug across fault scarps.

Figure 2 shows a synthesis of our observations along the Taleghan fault. At all scales, we observe a clear fault scarp attesting to the recent (Pleistocene-Holocene) surface rupture along the fault. The morphology of the scarp indicates that the dip of the Taleghan fault is toward the south. Therefore, the counterslope observed all along the scarp clearly indicates that the recent movements have a normal component (Figs. 2A and 2B) associated with left-lateral displacement as shown by the shifting of the talwegs and the ridges. According to the DEM in Figure 2B, the ratio *H*/*V* between the horizontal (H = 13 m) and the vertical (V = 17 m) components is 0.76. In trenches, the geometry and kinematics of the fault affecting the recent deposits are consistent with what is observed at a larger scale in the morphology (Figs. 2D and 2E). From the compilation of our observations, the mean strike, dip, and pitch for the Taleghan fault in its eastern part are N105°E, 60°S, and 50°E, respectively. This makes it a normal left-lateral strike-slip fault.

Along the eastern Mosha fault, the shifting of the talwegs and ridges (Figs. 3A and 3B) attests to the predominant left-lateral wrenching, as mentioned by Allen et al. (2003) and Bachmanov et al. (2004), along a north-dipping fault plane. However, the shutter ridges cannot explain the counterslope morphology of the scarp observed all along the fault (Figs. 3B and 3C). There is a clear slight normal component associated with the left-lateral horizontal movement. The ratio *H*/*V* between horizontal (H = 100 m) and vertical (V = 20 m) components is 5, according to the digital elevation model (Fig. 3B). The mean strike, dip, and pitch of the fault are N100°E, 70°S, and 20°W, respectively. This makes it a left-lateral normal fault. These geometry and kinematics are also observed in trenches at smaller scale, where a main north-dipping surface rupture associated with conjugated horst and graben structures is affecting Holocene deposits (Fig. 3D). Along the main fault plane (Fig. 3E), we measured fault-slip data of N098°E, 70°N, and 20°W, indicating a left-lateral normal movement. More to the west, at the junction between eastern and central parts of the Mosha fault, where the fault bends to the NW (see Fig. 1), our preliminary observations suggest that the fault has a pure left-lateral movement.

The morphology along the Firuzkuh fault clearly shows a counterslope scarp as observed along the Taleghan and the eastern Mosha faults. Between Firuzkuh city and Harandeh village, along the southern part of the Firuzkuh fault, the geometry of the fault scarp indicates that the dip of the fault is toward the SE (Figs. 4A and 4B), which is consistent with the observation in Harandeh village of a main (pluri-decametric) fault plane affecting the Mesozoic deposits trending N060°E and dipping 55°SE. Figure 4A shows that the talwegs have shifted with apparent and opposed strike-slip movements along a counterslope scarp, suggesting that the fault has a normal movement associated with a slight left-lateral component. North of Firuzkuh city, we surveyed a site showing a dried valley perched on the northern side of the fault, whereas on the southern side, the corresponding present stream appears downthrown and shifted left-laterally (Figs. 4C and 4D). Against the scarp, we found lacustrine deposits that have been incised by regressive erosion. These features are consistent with those observed to the south of Firuzkuh and suggest that the fault is dipping south and has a main normal component associated with a slight left-lateral movement. From the digital elevation model (Fig. 4D),

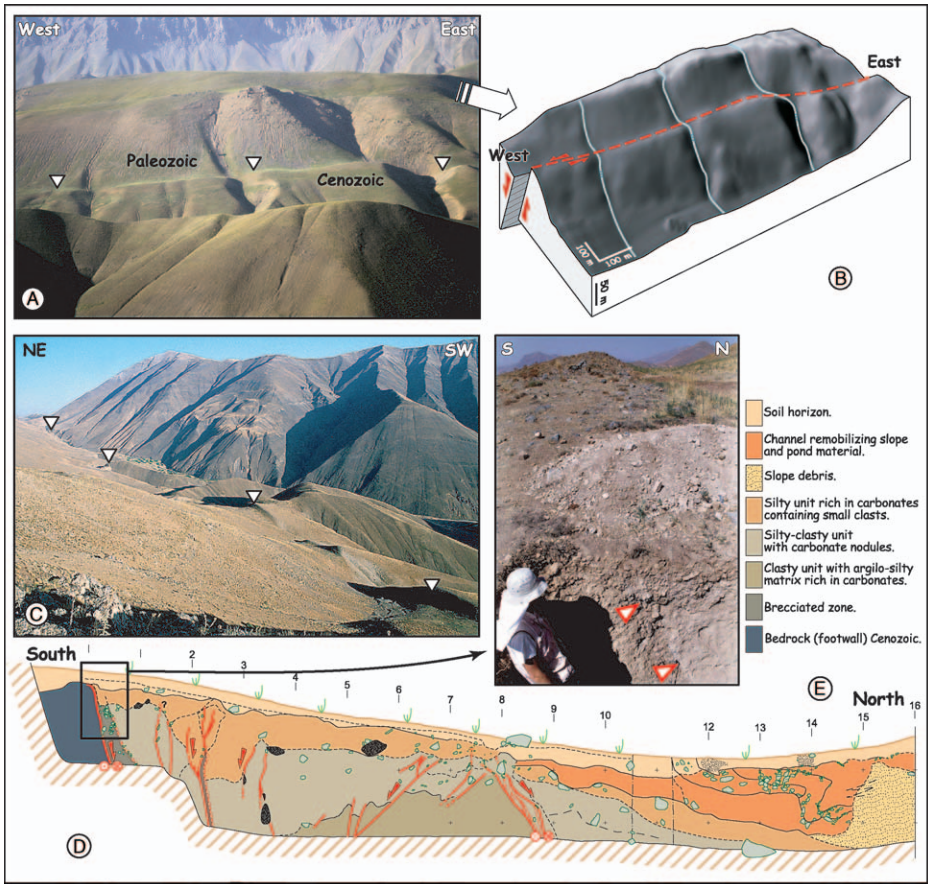

Figure 3. A: Eastern Mosha fault scarp in landscape. B: Corresponding digital elevation model (DEM) obtained by global positioning system (GPS) kinematics survey. C: Picture of fault scarp. D: Log of one of trenches dug across fault scarp (modified after Ritz et al., 2003). E: Picture of main rupture.

we estimated a ratio of $H/V = 0.6$ between the horizontal ($H = 15$ m) and the vertical ($V = 25$ m) components for the main stream displacement. This is consistent with the geometrical and kinematical parameters measured along the Taleghan and eastern Mosha faults, also taking into account the NE-SW trend of the Firuzkuh fault.

Put together, the recent morphological and structural features observed along the Taleghan, eastern Mosha, and the Firuzkuh faults characterize an active transtensional deformation occurring in the internal domain of central Alborz. The constant WNW-ESE direction of slip vectors throughout the studied area shows that this transtension is not related to the apex of the curved Alborz Mountains. Moreover, this transtension regime does not accumulate enough deformation to reverse the large-scale topography associated with previous thrusting movements. This suggests that the transtensional tectonic events along these faults are recent.

How recent? From paleoseismology, Ritz et al. (2003) estimated an ~2 mm/yr horizontal slip rate along the eastern Mosha fault over the Holocene and a ratio $H/V = 5$ between horizontal and vertical components. This ratio is also obtained if we use larger-scale morphological features, such as left-lateral shifted streams and the corresponding accumulated vertical offset of the mountain slopes (Fig. 5): From the satellite image (Fig. 5A), we measured an ~2 km accumulated horizontal displacement for the stream shown in Figure 5B, corresponding to accumulated vertical offset of ~350 m (the accumulated vertical displacement along the Taleghan fault is also ~350 m). This yields a ratio $H/V = 5.7$, suggesting that the kinematics of the fault have remained stable through the time.

On the satellite picture (Fig. 5A), the largest shifted drainage that we can observe is displaced a maximum of 3 km. Consequently, assuming a 2 mm/yr horizontal slip rate stable through the time, this yields an age of 1–1.5 Ma for the beginning of the transtensional regime along the Mosha fault.

DISCUSSION

Our observations show that the present general left-lateral shear observed inside the central Alborz mountain range is associated with transtensional deformation. These observations are supported by microseismic data recorded along the eastern Mosha fault showing steep north-dipping, N100°E-trending left-lateral strike-slip focal mechanisms associated with normal components (Ashtari et al., 2005). Moreover, the analysis of Shuttle Radar Topography Mission (SRTM) images in western Alborz suggests that the same kind of features (normal movements associated with left-lateral wrenching) are occurring along the Rudbar fault. Compared to the cumulative transpressive deformation and the large-scale topography associated with the Neogene structures (e.g., geological maps; Allen et al., 2003), our observations show that there has been a transition of the internal domain of the central Alborz from transpression to active transtension in very recent time.

This transtension is tightly associated with the geometry of pre-existing faults that are involved in the general left-lateral shear inside the range. Meanwhile, the borders are still affected by a transpressive regime. The whole kinematic picture is compatible with a general strike-slip regime (with σ1 and σ3 trending horizontally NNE-SSW and WNW-ESE, respectively) and the permutation of σ1 with the vertical stress axis between the borders and the internal domain (Fig. 6).

Our results show that the highest reliefs in the internal part of the range are decreasing. This appears to be consistent with the reconstruction of sedimentation history in the South Caspian Basin (Brunet et al., 2003), which suggests a recent diminishing of the sedimen-

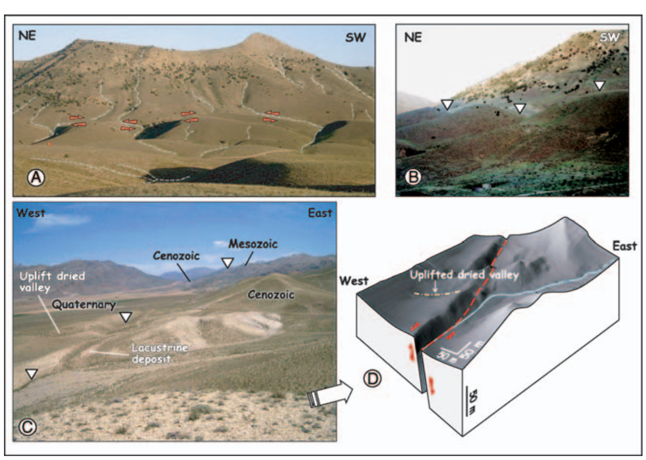

Figure 4. A–B: Firuzkuh fault scarp in landscape. C: Picture of fault scarp studied north of Firuzkuh. D: Corresponding digital elevation model (DEM) obtained from global positioning system (GPS) kinematics survey.

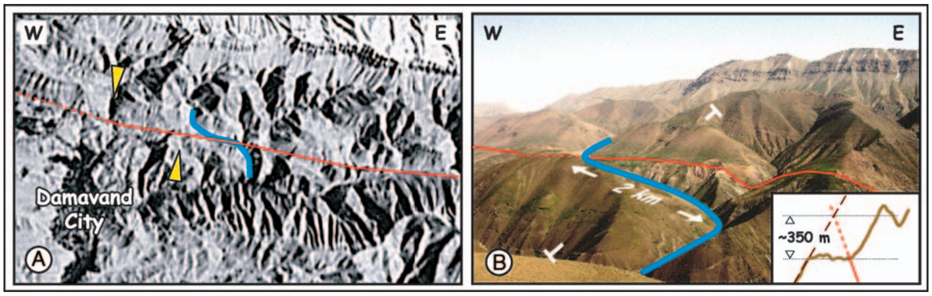

Figure 5. A: Iconos satellite image showing eastern Mosha fault and offset streams (stream underlined in blue is the one shown in B); yellow arrows show largest shifted stream (3 km). B: Picture showing cumulative horizontal and vertical displacements within an offset stream.

tation rate between the Pliocene (when the Alborz was higher and under compression) and the Pleistocene.

This recent kinematical change in the Alborz has to be considered also with the present deformation in the Talesh at the southwestern border of the Caspian Basin, where GPS measurements show the occurrence of a NNE-SSW extension (Masson et al., 2005). All these new observations tend to show that a recent regional kinematic reorganization has occurred at the scale of the South Caspian Basin and its surrounding mountain ranges.

According to our estimates, the transtension started between 1 and 1.5 Ma and appears to be contemporaneous with the Damavand volcanic activity, dated between 1.8 Ma and 7 ka (Davidson et al., 2004). The transtension is clearly linked to the partitioning of deformation in the central Alborz, which is itself associated with the westward component of the South Caspian Basin motion with respect to Eurasia (Jackson et al., 2002). It could also be proposed that the general left-lateral shearing in Alborz is related to the clockwise rotation of the South Caspian Basin (Fig. 6B). Therefore, our results suggest that the latter events could be at least three times younger (middle Pleistocene) than has been previously proposed (middle Pliocene), which used interpretations of industry-image subsurface growth structures in the northwestern South Caspian sedimentary stack (Devlin et al., 1999).

CONCLUSIONS

Our results suggest that the beginning of the South Caspian Basin northwestward motion to Eurasia and/or its clockwise rotation is Pleistocene in age. This motion provoked not only the change from a general N-S compression to a general NNE-SSW transpression in Alborz but also the expression of transtension in the internal domain of the range. Not only have the horizontal movements along the strike-slip faults in the western Alborz been reversed but also the vertical component of the thrusting faults in the internal part of the range; this is an outstanding example of extensional phenomena occurring within a compression-dominated region.

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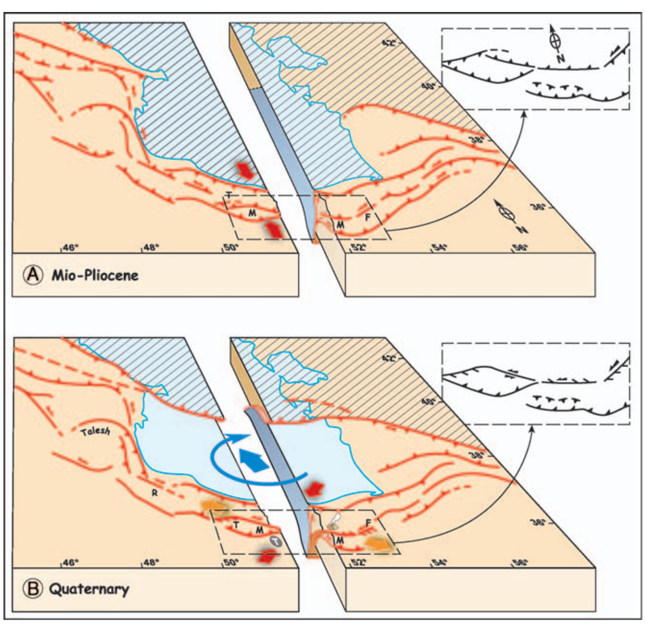

Figure 6. Three-dimensional sketches illustrating recent change of kinematics in central Alborz associated with northwestward motion of South Caspian Basin (blue arrow) and/or its clockwise rotation. Red arrows indicate general compressive axis across central Alborz; orange arrows indicate extensional axis in internal domain of range along range-parallel left-lateral shear zone. Symbols are same as Figure 1. Faults with small dashes indicate predominant normal faulting along Taleghan and Firuzkuh faults. T—Tehran city.

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