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A comparison between the Kazerun (Iran) and the North Anatolian (Turkey) fault systems in fault interaction and seismicity migration based on the spatiotemporal analysis of earthquakes

Hasanlou, A.[1*] and Hashemi, N.[2]

1. M.Sc. Expert, Geological Survey of Iran, Tehran, Iran
2. Assistant Professor, School of Earth Sciences, Damghan University, Damghan, Iran

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Abstract

The Kazerun Fault System (KFS) is a right-lateral strike slip fault system in the middle part of the Zagros seismogenic zone in Iran. Historical and instrumental earthquake data catalogs of this fault system show good evidence of fault interactions and seismic migrations. This study provides evidence for the migration of seismicity in the middle part of the Zagros region along the segments of the KFS, as well as, among the Kazerun fault segments. North Anatolian Fault System (NAFS) is similar to the Kazerun Fault System (KFS) and there are also interactions among the segments of the NAFS. In this paper, we have described the fault interactions and seismic migrations in the KFS and NAFS based on the spatiotemporal analysis of the earthquake data of these two regions in a period of 5 years (from 2005 to 2010). The obtained results indicate that these migrations mainly occur along the trend of these fault systems. Additionally, we found a good agreement between these seismicity patterns and the overall ongoing plate tectonic movements in these parts of the World.

Keywords: Fault interaction, Kazerun fault system, North Anatolian fault system, Spatiotemporal analysis, Seismicity.

1. Introduction

The Zagros fold-and-thrust belt is located within Iran at the edge of the Arabian plate (Fig. 1). It is 1200 km long with NW–SE trends in eastern Turkey. Its width varies from 200 km in the west to 350 km in the east. The Zagros mountain belt is resulted from convergence between Arabia and Eurasia plates. The Zagros is classically described in terms of longitudinal units separated by lateral discontinuities. The High Zagros is comprised of highly deformed metamorphic rocks of Mesozoic age; it is bounded to the NE by the Main Zagros Thrust (MZT). This is the highest part of the Zagros, with maximum elevation more than 4500 m above sea level. The High Zagros is overthrust in the south part of the Zagros Fold Belt, in a 10 km thick Palaeozoic–Cenozoic sequence of sediments. Longitudinally, the Zagros is divided into two geological domains, the North Zagros (and the Dezful embayment) to the west and the Central Zagros (or Fars) to the east are separated by the north–south-trending strike-slip Kazerun Fault System (KFS) that cross-cuts the entire belt. The Kazerun Fault is considered as an active and basement fault that reactivates frequently in different modes (Baker et al., 1993). Significant differences in mechanical stratigraphy exist between the North and the Central Zagros; the sedimentary cover of the latter has been deposited on top of the infra-Cambrian Hormuz Salt layer, whereas this layer is absent in the North Zagros (Hatzfeld et al., 2010).

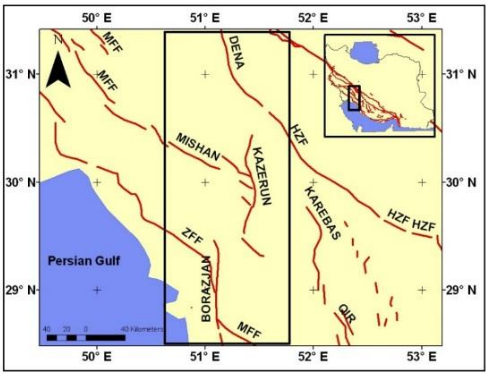

Fig. 1. Map showing the Kazerun Fault System and other main faults in the central part of Zagros (Iran).

*Corresponding author: E-mail: azrahasanlou@gmail.com

The Kazerun Fault System separates the North Zagros from the Central Zagros and crosscut the entire Zagros belt at a high angle. It is comprised of several roughly north–south-trending right-lateral strike-slip faults. The Kazerun Fault itself is composed of three north–south-trending segments: the Dena, Kazerun and Borazjan segments, which all terminate to the south with a north-dipping reverse fault (Authemayou, 2005, 2006; Falcon, 1969) with equivalent length (~100- km-long). They have similar shapes with a general N170°– 180°E trend and southern terminations bent southeastward (Authemayou, 2005). On the basis of geological maps, present morphotectonic features of the region and field evidence, the Kazerun Fault Zone has an N-S trend. These are distinguished on the basis of their geometry and their effect on the Zagros sediments and adjacent structures. The segments from north to south are termed the Sisakht, Yasuj, Kamarij, and Burazjan segments. All but the Yasuj sector act as transfer faults or lateral ramps making connection among the different segments of the Zagros deformation fronts, i.e., the High Zagros and Mountain Front faults (Sepehr and Cosgrove, 2005). The Sisakht, Kamarij, and Burazjan segments are characterized by a major downwards to the west and also by the termination of folds against the fault zones. The Kazerun Fault is associated with exhumation of Hormuz Salt (Talbot and Alavi, 1996) and modifies the trend of folds adjacent to it. The KFS and the other north–south-trending faults are probably inherited from a Cambrian tectonic event that affected the Arabian platform because it controls the distribution of Hormuz Salt, which is present to the east of the fault system but not to the west (Talbot and Alavi, 1996; Sepehr and Cosgrove, 2005). It was reactivated as early as in the Middle Cretaceous (Koop and Stoneley, 1982). The total offset along the Kazerun Fault is a matter of debate, varying from 5 km (Pattinson and Takin, 1971) or 8.2 km (Authemayou 2006) to 140 km (Berberian, 1995), depending, on the markers used to quantify strike-slip motion. This large difference in displacement results in inferred slip rates of 1–15 mm a^{-1}. Careful mapping of the active faults and of the lateral offsets along the various segments of the fault together with precise dating of fans yields a slip rate of 3.1–4.7 mm a^{-1} on the Dena Fault and 1.5–3.2 mm a^{-1} on the Kazerun Fault (Authemayou et al., 2009). The southernmost segment, the Borazjan Fault, seems to have a dominant dip-slip motion (e.g., Oveisi et al., 2009). East of the Kazerun Fault, the Kareh-Bas Fault is very active and is accommodated with 5.5mm a^{-1} of right-lateral strike slip; the Sabz-Pushan Fault in contrast appears inactive, and the Sarvestan Fault is also accommodated only with little motion.

The onset of strike-slip motion on the main recent Fault is probably of Late Miocene age and therefore synchronous with an increase in the shortening rate within the Zagros and the general tectonic readjustment observed throughout Iran (Allen et al., 2004). The onset of motion on both the Dena and Kazerun segments is more recent, probably c. 3 Ma and it is much younger (c. 0.8–2.8 Ma) for the Kareh-Bas Fault (Authemayou, 2006; Authemayou et al., 2009).

The Borazjan segment, with a length of about 180 km, is located south the Kazerun segment with a right– stepping gap. Hessami and Jamaly (1996) consider the Borazjan fault zone and the Kazerun fault as two segments of a single structure (Fig. 1). The Borazjan segment of the KFS system has a left stepping arrangement and does not overlap the Kamarij segment. It acts as an oblique lateral ramp, decoupling the deformation to its west from that in the Fars Borazjan Fault. The only possible way to estimate net lateral displacement along the zone is to correlate it with about 10 km of lateral bending of the Gisakan - Takab anticline between terminations of the Kazerun and Borazjan zones (Bachmanov et al., 2004). The KFS is seismically active (Baker et al., 1993; Berberian, 1995; Talebian and Jackson, 2004). Clearly, most of the seismicity and especially the earthquakes with the largest magnitude are occurred on the central segment of the Kazerun Fault. The three largest (M>6) instrumental earthquakes were located on the Kazerun segment and the Kareh-Bas and Sabz-Pushan faults. Very little activity is observed on both the Dena and Borazjan faults, and no activity is associated with either the High Zagros Fault or the Sarvestan Fault. The depth of the reliably located earthquakes associated with the KFS is 9±4 km, which probably makes them connected to the basement. Most mechanisms are strike-slip on the Kazerun, Kareh-Bas and Sabz-Pushan faults. Reverse mechanisms are associated with the Mountain Front Fault, on both sides of the KFS. A few reverse mechanisms are also associated with the Borazjan segment, which suggests that it is not an active strike-slip fault but more probably a trans-pressive lateral ramp (e.g., Oveisi et al., 2009). The KFS is seismically active with a peak activity along its central part, where I > VIII, the historical earthquakes have been reported (Berberian, 1981).

These inherited fractures were activated during Permian and Mesozoic sedimentation. This results in a change of the mechanical behaviour of the lithostratigraphic horizons. Because the KFS marks the boundary of the Hormuz Salt layer in the Central Zagros, during collision, the fault plays the role of a lateral ramp for the Fars arc. A lateral ramp generally implies transpressional motion as observed along the Borazjan segment. This can be interpreted as the active part of the Kazerun Fault lateral ramp. The southward propagation of this segment can be detected by a structural study of the Mand anticline. The bending of this large coastal anticline suggests the presence of a hidden segment of the KFS bounding in the Mand fold to the west. As the Mand anticline is a Plio-Quaternary fold, the propagation of the Kazerun Fault lateral ramp must be very recent (Hatzfeld et al., 2010).

If the Kazerun Fault is a lateral ramp of the Fars arc, the fault motion must be restricted to the cover. However, the seismic activity localized along the Kazerun segment implies basement faulting because earthquakes are probably located in the basement and, thus, it plays an important role in the Kazerun Fault System in the Zagros deformation.

In comparision, the dextral North Anatolian Fault System (NAFS) extends for over 1000 km from the compressive tectonic domain of eastern Anatolia to the broad and diverse tectonic domain of the western Anatolian, Marmara and Aegean regions (Fig. 2). For most of its length, the transform has a typical strike– slip fault zone morphology, charactrized by a narrow rift zone (Sengor, 1979).

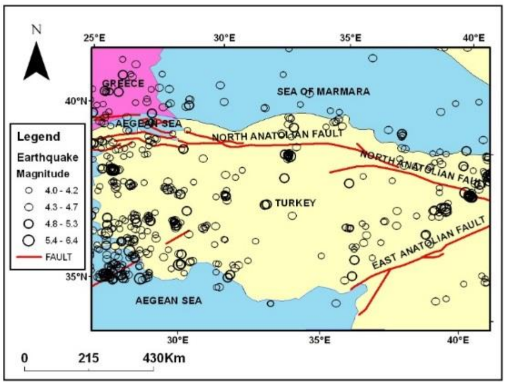

Fig. 2. Seismotectonic Map of Turkey showing the major active faults of the region and the epicentral distribution of earthquakes.

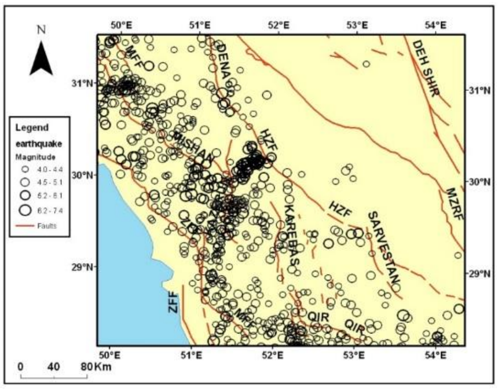

Fig. 3. Seismotectonic Map of southern Zagros (Iran) showing the major active faults of the region and the epicentral distribution of earthquakes.

In the west of Bolu, the NAFS splits into northern and southern sub-parallel branches in a broad extensional deformation zone incorporating the Marmara- northern Aegean region (McClusky et al., 2000). Sengor et al. (2004) suggested that the NAFS has displayed cyclical seismic behaviour, with century – long cycles beginning in the east and progressing westward, since the seventeenth century.

The NAFS is separated into two segments. One of them is Elmali Segment in east Yedisu Basin and Kizilcubuk village. The other is Kargapazari Segment, located in the Elmali Segment and Karliova Triple Junction. The Elmali segment is begun from east of the Yedisu Basin and continues 30 km, where it is elongated with N70W / E-W orientation. Two sub-segments are defined for Elmali segment based on the surface rupture geometry. The western sub-segment is elongated with N70W orientation about 15 km long. Kaynarpinar, the eastern subsegment, is also elongated with E-W orientation about 15 km long. The 25 km-long Kargapazari segment is oriented in N65-70 direction between Kizilcubuk village and the Karliova Triple Junction (Sancar et al., 2008)

Okay et al. (2000) proposed that the Northern strand is consisted of three segments under the northern Marmara Sea. These are, from west to east, the submarine part of Ganos Fault (15 km), Central Marmara Fault (105 km) and North Boundary Fault (45 km).

The main goal of this article is a comparison of seismic data to find fault interaction and migration between the segments of KFS and NAFS by spatiotemporal analysis of earthquakes.

2. Geology and Tectonic Setting

The general tectonic setting of the Iranian and Turkey regions and the tectonic displacements vectors at different parts of these two regions are shown in Figure 4. Iran is located within the interaction zone between the Arabian and Eurasian plates currently converge at 30 mm/yr. Since the Miocene, continental collision resulted in formation of the NW-trending Zagros fold-thrust belt that accommodates c.a. 10 mm/yr of NNE-trending shortening. The present morphology of the Zagros region is the result of a geological history including a platform setting during the Paleozoic; a Tethyan rifting phase in the Permian-Triassic; a passive continental margin setting (with seafloor spreading to the northeast) in the Jurassic-Early Cretaceous; Tethyan subduction to the north-east and obduction in the Late Cretaceous; and finally Arabia-Eurasia collision during the Neogene.

The KFS is generally interpreted as an inherited fracture of an old tectonic event affecting the Arabian platform. Such inherited fractures are observed in several places in both the Zagros and the Arabian platform across the Persian Gulf, whereas we observe motion and seismicity only on parts of the fractures located within Zagros and only around the Kazerun zone. This focus of seismicity could be either due to a non-homogeneous state of stress within the Zagros or to the fact that the Zagros part of the Arabian platform is more brittle (it is thinner) than the remaining parts. The thick sedimentary sequences of the Zagros basin contain rocks ranging in age from the Cambrian to the present. The geological evidence also suggests that the region was a part of the passive continental margin, which subsequently underwent rifting in the Permo-Trias and collision in the Late Tertiary (Berberian, 1981; Beydoun et al., 1992; Stocklin, 1974).

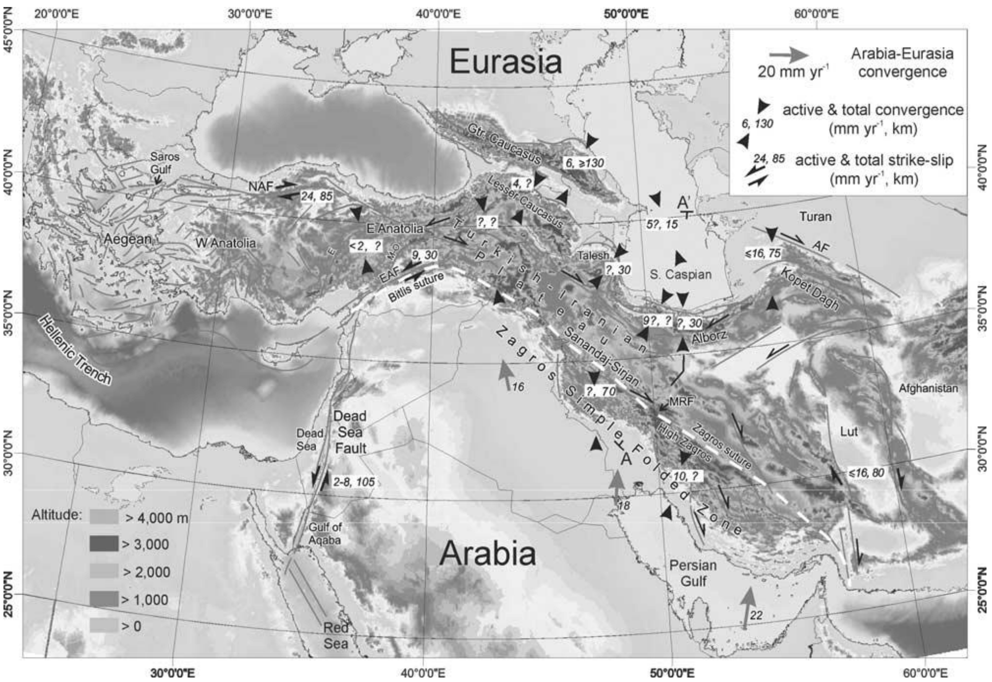

Fig. 4. Map showing the general tectonic setting and the direction of tectonic displacement vectors within Iran and Turkey (Vernant et al., 2004).

During the Palaeozoic, Iran, Turkey and the Arabian plate (which now has the Zagros belt situated along its northeastern border) together with Afghanistan and India, made up the long, very wide and stable passive margin of Gondwanaland in the Paleo-Tethys Ocean to the north (Berberian and King, 1981).

By the Late Triassic, the Neo-Tethys Ocean had opened up between Arabia (which included the present Zagros region as its northeastern margin) and Iran, with two different sedimentary basins on either side of the ocean (Berberian and King, 1981). These two plates later converged as a result of the north- easterly subduction of the Neo-Tethys oceanic crust, a process which led to the Tertiary continent–continent collision between Arabia and Iran and the formation of the present day Zagros Mountains. In the Zagros belt, the approximate locations and geometries of the basement faults have been defined using geodetic survey, more or less precise epicenter/hypocenter locations, as well as topographic and morphotectonic analyses (Berberian, 1995). The southeastern part of the thrust belt is affected by the north-trending, right lateral Kazerun Fault System (KFS) stretching from the Main Reverse Fault. GPS measurements indicate that the Arabian and Eurasian plates converge at 21 mm/yr around 50◦E (Authemayou, 2005).

At this longitude, the Zagros records a NNE trending shortening rate of about 10 mm/yr that is oblique with respect to the main fold-and-thrust belt strike (Vernant et al., 2004). The inversion of focal mechanisms from small and moderate earthquakes shows a consistent N020°–030° compression with a low ratio between differential stresses (Lacomb et al., 2011; Talebian and Jackson, 2002, 2004). The mean direction of the P axes, which could be associated with the shortening, is deduced from all the focal mechanisms, with trends consistently in a NE- SW direction (Tatar et al., 2004) and the direction ~ N 10° of Nuvell Arabian plate motion relative to Eurasia. This does not take into account the motion of Central Iran with respect to Eurasia.

The roughly east–west trending NAFS is a 1,500 km-long dextral transform fault that accommodates western extrusion of the Anatolian plate resulting from the collision of the Arabian plate in the eastern Anatolia along with the sinistral East Anatolian Fault Zone. Geological and morphological evidences suggested that NAFS is originated 10 Ma ago in eastern Anatolia and has propagated westward over the past 10 Ma (Sengor et al., 1985; Barka, 1992; Armijo et al., 1999, 2002; Hubert-Ferrari et al., 2002).

The North Anatolian Fault Zone (NAFZ) developed during the Neotectonic period in response to intra-continental convergence following the Late Miocene collision of the Arabian promontory with Eurasia (McKenzie, 1978; Dewey and Sengor, 1979; Sengor et al., 1985; Barka, 1992).

It extends from Karliova Triple Junction (KTJ) in the east to the Northern Aegean Sea. The NAFS and the conjugate East Anatolian Fault delimit a block, Anatolia, which is moving westward, pushed by the collision between Arabia and Eurasia. The most recent GPS data suggest a rate of 22 ± 3 mm/yr for the NAFS (Straub et al., 1997; McClusky et al., 2000).

The NAFS is a significant plate boundary and is active with destructive earthquakes at the western end near Istanbul metropolis. The observation and location of the micro seismic activity as well as monitoring other physical changes in the upper and lower crust in the area is a prerequisite for monitoring and possible prediction of destructive future earthquakes (Bekler et al., 2008). The North Anatolian transform fault system appears to have originated as a consequence of the Arabia- Anatolia collision during the Late (or Middle) Miocene, when the Anatolian Plate formed and was wedged out into the oceanic tract of the eastern Mediterranean from the converging jaws of Arabia and Eurasia to prevent excessive crustal thickening in eastern Anatolia. The westerly motion of Anatolia, with respect to Eurasia and Africa, caused a great change in the tectonic evolution of the eastern Mediterranean, giving rise to the Aegean extensional regime and to internal deformation of Anatolia (Sengor, 1979). He added that the crust along the fault zone is thinner than normal. The transform probably originated sometime between the Burdigalian and the Pliocene and has offset about 85 km.

These different tectonic regimes are the result of diffential indentation of the Anatolian accretionary collage by the northward movement of the Arabian Plate and the tectonic escape of these terranes by a combination of westward push and suction into the southward-retreating Aegean Trench (Bektas et al., 2007). Zhu et al. (2006) suggest that there is general trend of westward crustal thinning from 36 km in central Anatolia to 28-30 km in the central Menderes.

3. Interactions between Adjacent Faults

The segmentation of strike-slip fault systems plays a critical role in controlling the location, orientation and length of fault splays (Segall and Pollard, 1980). These splays, in turn, impact the distribution of damage and the geometrical and statistical properties of secondary fault networks around strike-slip faults (Flodin and Aydin, 2004; Myers and Aydin, 2004). Moreover, the fault architecture affects the repartition of slip and stress along fault systems, with important consequences for damage zone distribution (Cartwright et al., 1995; Knott et al., 1996; Finzi et al., 2009). Finally, fault segmentation controls the development of fault core formed preferentially in stepovers because of high strain levels therein. This is critical for fluid flow in the subsurface since damage zones have typically higher permeability than the parent rock whereas fault cores have usually lower permeability (Caine et al., 1996; Jourde et al., 2002; Aydin and Schultz, 1990; Odling et al., 2004).

Fault interactions can increase or decrease stress at other faults, and thereby trigger or delay earthquakes on them. This is called the effect of earthquake triggering or delaying (King, et al., 1994; Hodgkinson, et al., 1996; Zhang, et al., 2003).

It is now widely accepted that brittle faults start from a series of short en echelon arrays and grow by linkage of the neighboring segments (Segall and Pollard, 1980; Cartwright et al., 1995; Myers and Aydin, 2004; Kim et al., 2004). It then follows that steps are destroyed by through-going planar surfaces to produce more continuous and smoother fault segment geometry at larger scales while new segments achieve a greater capability to interact with each other at a greater distance (Aydin and Schultz, 1990; Scholz, 2002).

When considering the possibility that an earthquake may propagate from one fault to the next, it seems reasonable to conclude that this will depend on how strongly the faults are interacting. Geological studies of faults especially in geometrical analysis have been proposed different parameters which govern fault interactions. Each parameter will have a special effect on the geometrical relationship between faults and iteration between the faults. Effective parameters in fault interaction include the geometry of each fault and rheological properties of rocks.

Since earthquake interactions between faults are scale invariant (Mouslopoulou and Hristopulos, 2011), a better understanding of the occurrence of large earthquakes in fault systems may be achieved through further analysis of micro-earthquake data sets. This is what we propose to do here.

In this article, we discussed about fault interactions and relationship between seismicity and faults. We want to show that fault interaction can trigger earthquake and seismic energy near other faults. This kind of interaction is stress triggering. We have stress transfer and change. The effect of the stress change on time of earthquake recurrence can be cast as a change in the probability of further events. Cumulative stress changes are resulted from large earthquakes and steady deep slip on the North Anatolian fault since 1939 (Stein et al., 1997).

Harris and Day, (1993) suggested that earthquake ruptures can spontaneously be propagated across both dilatational and compressional steps, concurring with field observations of strike – slip faults and the maximum step-over width which can be jumped by a propagating rupture. This appears to depend on whether or not the rupture velocity on the first fault segment is supershear. More precisely, the parameters which control rupture velocity also influence the maximum step-over width. Aydin and Schultz (1990) looked at the fault interaction problem in an attempt to quantify the relationship between fault step-over width and overlap for en echelon strike-slip faults around the world.

Therefore, the field observations of

Knuepfer (1989) and Wesnousky (1988) appear to indicate that fault steps with stepover widths greater than 8 km have never been jumped, and most likely 5 km is an upper limit for this critical distance.

Knuepfer (1989) notes that in his data collected from world-wide field observations of strike-slip faults, no rupture has ever jumped a compressional step wider than 5 km and no rupture has ever jumped a dilational step wider than 8 km. Barka and Kadinsky-Cade (1988) showed evidence that the 1939 Great (M=8) Erzincan earthquake rupture on Turkey's North Anatolian fault jumped a dilational step 4 km wide. The length of fault rupture often determines the magnitude of a strike-slip earthquake. Therefore, it is critical to determine what factors control the length of fault rupture.

The size of the stress drop is somewhat significant to determine the magnitude of the stepover distance which could be jumped. It also appears that the jump distance is sensitive to the model parameters which control rupture velocity. Gupta and Scholz (1999) showed that the interacting tips were, in fact, propagating into progressively higher stress drop regions, while developing progressively more deformed displacement profiles. They also analyzed many other cases and showed that this systematics is general. They also found that there is a critical stress drop at which the tips become fully pinned. At about that point, minor fractures begin to develop in the interaction region, progressively linking the two faults. The summed displacement profiles of the two main faults plus the minor faults begin to approach the profile expected from a single fault of the length equal to that of the combined lengths of the interacting faults; this indicates that they are starting to act as a single mechanical unit (Dawers and Anders, 1995).

The interaction between the two faults is unquestionable if the end of the first fault resides in the streeses drop levels of the second fault. For these parameters, faults should have overlap (Scholz and Gupta, 2000). Another important parameter is the direction of the step-over with respect to the sense of slip on the strike-slip faults: right-lateral faults with right step overs and left-lateral faults with left step-overs produce dilation in the step-over region, whereas left-lateral faults with right step-overs and right-lateral faults with left step-overs produce compression in the step-over region. The studies indicate that it is much easier for rupture to jump across dilational step-overs than compressional step-overs (Segall and Pollard, 1980). The degree of overlap between strike-slip fault segments affects the ability of rupture to propagate across the step-over. Another important parameter is linking faults in strike slip step overs.

The studies carried out on strike-slip faults with step-overs and linking dip-slip faults indicate that the presence of a linking fault can greatly increase the ability of earthquake rupture to propagate across the step-over and lead to a larger event. This effect is even stronger for dilational step-overs than compressional step-overs owing to the sign of the normal stress increment on the linking fault: slip on the strikeslip segments tends to unlock a linking normal fault in a dilational step-over, while it tends to lock up a linking thrust fault in a compressional step-over (Oglesby, 2005). Due to the fact that the linking fault has a nonzero static stress drop, this gives support for the ability of a rupture to propagate large distances for faults with high step-over widths.

Sibson (1985) showed that at dilational step-overs the rupture jump of interactions should act to terminate earthquake ruptures. He proposed that the effect of the reduced normal and mean stress at a dilational step-over would be the reason that the extension fractures would suddenly open. The fluid pressure in these extension fractures would not have time to be re-equilibrated during the time of the earthquake. Therefore, the effective normal stress would suddenly increase and lead to an increase in material strength at the step-over area. Sibson envisioned that this scenario would at least temporarily delay ruptures at dilational step-overs. The changes in pore pressure greatly reduce the dilatational step-over distance which could be jumped by a propagating earthquake reupture. The elastic and poro-elastic interactions are necessary to explain the evident spatial and temporal migration of seismicity.

For seismic fault interactions studies, these faults and seismic migration are investigated by spatio- temporal analysis. Spatio-temporal analysis of seismicity and seismic migration in this area, the type of faults mechanism and tectonic movement of the region show fault interactions between these faults.

To find interaction between faults, we used the spatiotemporal technique. Interaction of faults to express the amount of energy released by seismic earthquakes for 5 years to the six-month intervals has been used. These data on the network are considered appropriate amount of energy per cell according to the number of earthquakes. Total amount of energy in any cell earthquakes has also been calculated. High-energy cells per six-month period based on the position of network have purposed the location of maximum energy and migration of these cells as the basis of seismic migration in the region. If we compare maps of periods, we can find relationship between faults and migration of seismic energy. This migration has been occurred in the fault systems, the Kazerun fault system and the North Anatolian fault system. We want to show this migration and interaction in both systems.

4. Methodology

The earthquake data used in this research are retrieved from the Iranian Seismological Center Online Databank and Europian – Mediterian seismology center databank. The data cover a time period of nearly 5 years from 2006 to 2010. From 2006 to 2010, approximately 1612 earthquakes occurred in the Kazerun fault system region and 644 earthquakes in North Anatoly Fault system. We only consider the events in this study with magnitude greater than 4 Richter. The largest earthquakes are M=6.1 for Kazerun fault system (near the big bend of Kazerun fault or Kamarij segment) and M=6.4 for North Aatoly Fault System (near the Hellenic arc).

In order to characterize the spatio-temporal evolution of the seismic activity of the regions for a given time, the epicentral regions were divided into equal areas (we call cells). These cells are square-shaped with a dimension of 10 km. We extracted earthquakes for each cell. The seismicity parameters of the cells are analyzed based on temporal approaches. For temporal analysis, we divided the overall time period into equal time spans of six months. To detect the interaction of two active faults, we should find a reliable parameter to be monitored. Seismic energy released is a good parameter for this spatio – temporal analysis. We overlay maps of every two successive six-month seismicity parameters, and finally we find the seismicity migration. The amount of seismic energy released by the earthquakes is directly related to the size of the events. The following formula was used to calculate the seismic energy (Gutenberg and Richter, 1954):

$$\text{Log } E = 4.8 + 1.5\, M \tag{1}$$

where M and E represent local magnitude (Richter) and seismic energy (J), respectively. According to this formula, we calculated seismic energy of each earthquake and, finally, the total seismic energy released in each cell was computed. In each 6-month seismicity map, the cell with the highest seismic energy release was found. Comparing the successive 6-month seismicity maps, the major seismicity migration trend were found for each two successive periods. The cell with the maximum seismic energy released in each seismicity map is called the seismic hot spot. Figures 5 and 6 show the seismic migration pattern of major earthquakes, during a period of 5 years, for the Kazerun Fault System (Iran) and the North Anatolian Fault System (Turkey), respectively.

Figure 5 shows that the highest concentration of earthquake locations is found near the Borazjan and Kazerun faults. If the location of seismic hot spots for each 6-month seismicity map is compared to the next 6-month period seismic map, the change in the location of hot spots can be presented as migration trends. Figure 7 simply shows the migrational pattern of the seismic hot spots on the Kazerun Fault System (Iran). This was deduced from the analysis of earthquake data for 6-month periods in 2006–2010. In this figure, A and B refers to the first and second 6-month period of each year, respectively. Based on the maps presented in this figure, it is concluded that most of the migration trends are located between the Kazerun and Borazjan faults.

Additionally, in order to provide an

overall view of the directional pattern of seismic migration in this region, the Rose diagram of the directional pattern of these migrations is presented in Figure 8. From this diagram it can be seen that in the middle parts of the Zagros range and within the Kazerun Fault System, the seismic migration trends are mainly Northeast– Southwest. This direction is nearly parallel to the direction of movement of the Arabian plate.

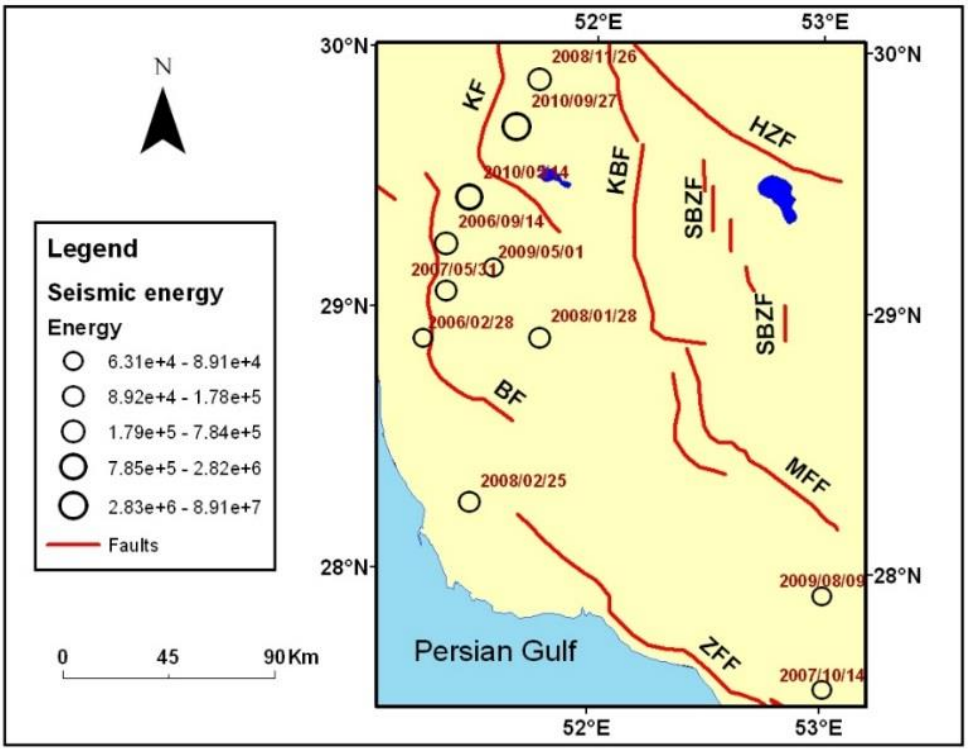

Fig. 5. The spatial pattern of the earthquake migration along the Kazerun Fault System (KFS).

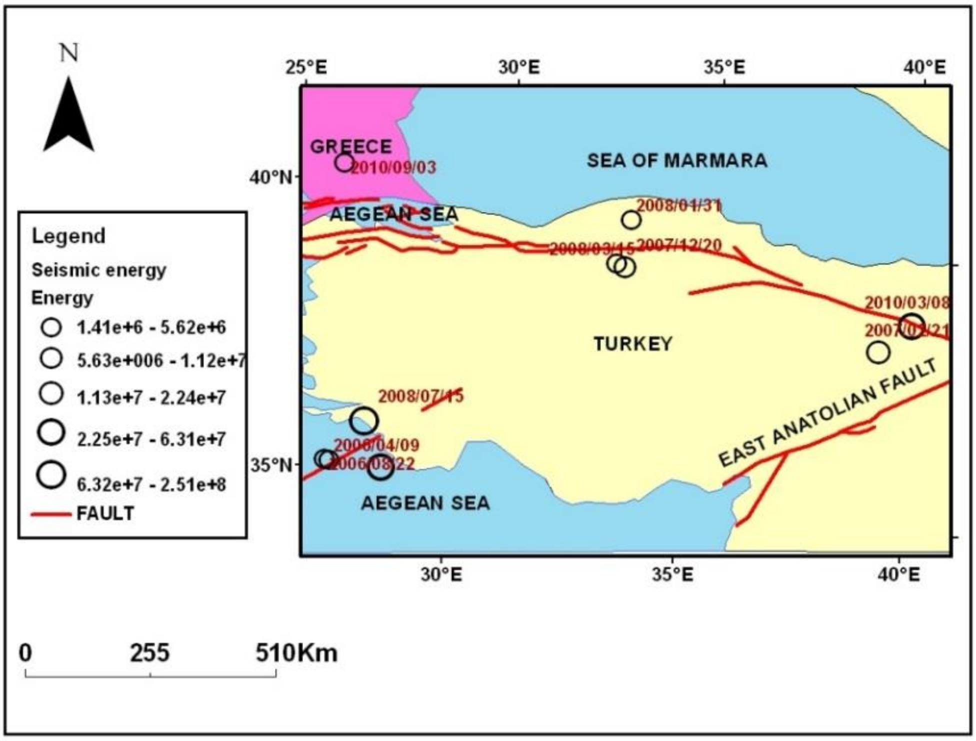

Fig. 6. The spatial pattern of the earthquake migration along the North Anatoly Fault System (NAFS).

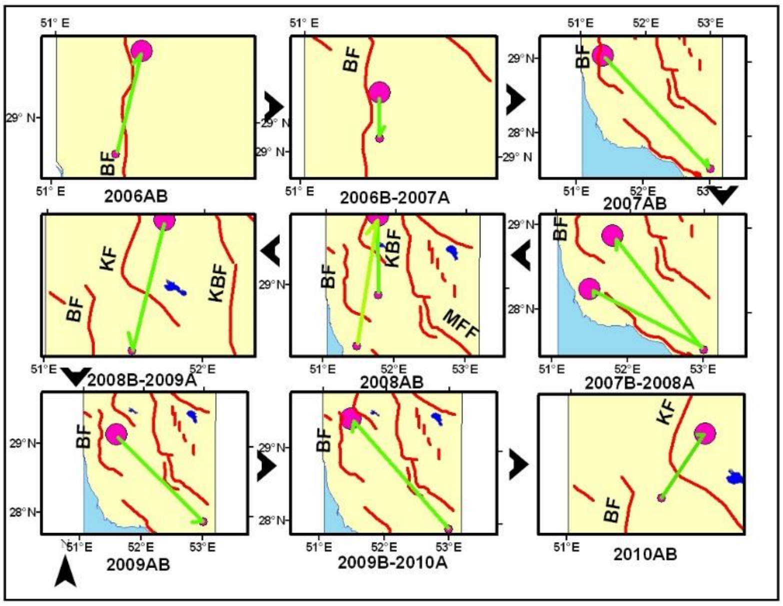

Fig. 7. The migrational pattern of the seismic hot spots on the Kazerun Fault System (Iran) deduced from the analysis of earthquake data for 6-month periods during 2006–2010 (A and B refers to the first and second 6-month period of each year, respectively).

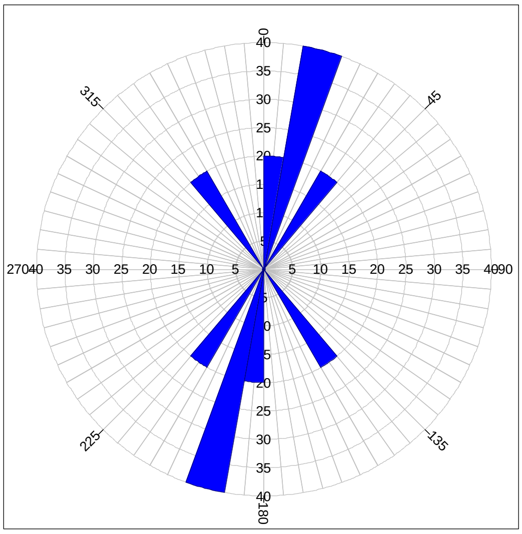

Fig. 8. Rose diagram of the directional pattern of migrational trends of seismic hot spots over the KFS.

The same procedure was carried out for the NAFS. The results are shown in Figures 9 and 10. Accordingly, the highest concentration of seismic energy release is found near the North Anatolian Fault system and a minor concentration is also found near the Helenic Arc. The Helenic Arc, in southern Turkey shows a left– lateral strike slip mechanism. Based on the maps presented in Figure 9, we can conclude that most of the migration trends are nearly East-West. This mean direction, observed in the Rose diagram presented in Figure 10, is the same as the direction of movement towards the Eurasian plate.

5. Discussions

In seismicity studies, we can outline the seismic migration and fault interactions in a fault system, and also find the highly seismogenic areas by using spatiotemporal analysis of earthquake data. In this study, we compared two fault systems: the Kazerun Fault System (Iran) and the North Anatolian Fault System (Turkey). We determined the seismicity relationships between fault segments of each fault system. The Kazerun Fault System is located in the middle part of Zagros that include three segments. The North Anatolian Fault System is a main fault of Turkey. In both regions, there are several parameters that can affect the occurrence of earthquakes and the pattern of seismic migrations. The transfer and migration of seismic hot spots can occur across the front and retreat bulge of fault segments in a fault system (Harris and Day, 1993). It is known that the jumps occur preferentially near the free surface. This is because dynamic changes in normal stress may be large compared to initial stresses near the free surface. Therefore, the effect of dynamic normal stress change at a fault bend should be investigated. Rupture area and overall slip distribution on the fault vary with the initial stress field, which depends on strike change at the bend. Earthquake faults sometimes have bends, and the bends act as geometrical barriers to earthquake rupture (King and Na´beˇlek, 1985). Rupture velocity changes of a bend depend principally upon the initial strength excess and stress drop heterogeneities, which in turn are related to static stress variations induced by fault geometry. In a restraining bend, normal stress (positive in compression) dynamically increases due to slip behind the bend. Thus, the interaction of active faults and fault bends should also be considered.

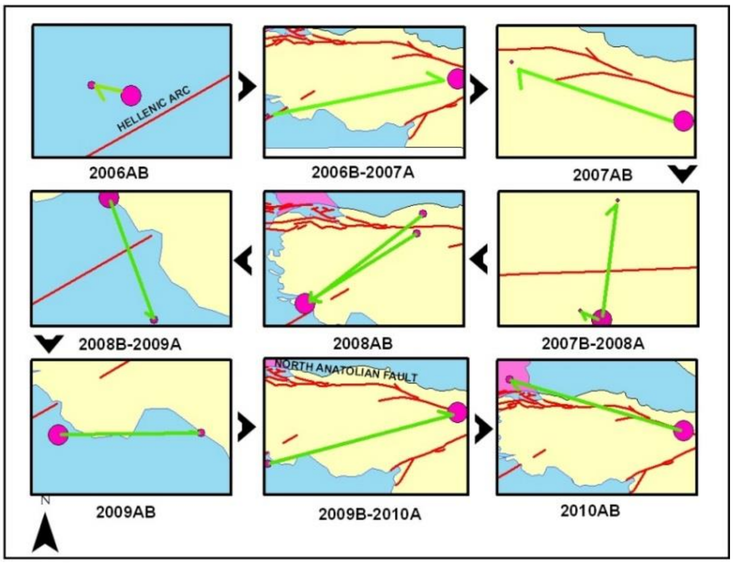

Fig. 9. The migrational pattern of the seismic hot spots on the North Anatolian Fault System (NAFS) deduced from the analysis of earthquake data for 6-month periods during 2006–2010 (A and B refers to the first and second 6-month period of each year, respectively).

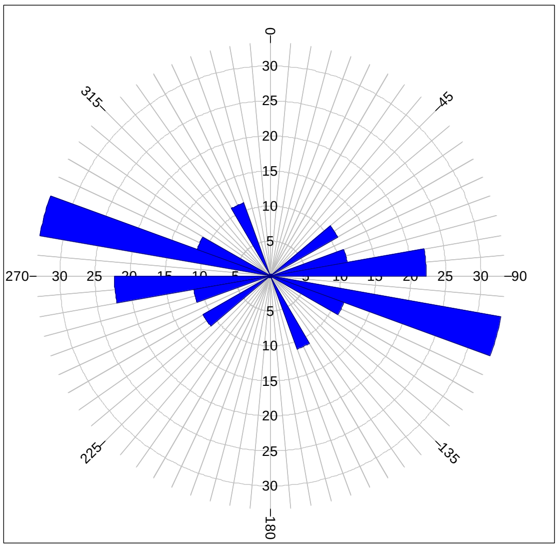

Fig. 10. Rose diagram in the directional pattern of migrational trends of seismic hot spots over the NAFS.

Seismic migration is a process that removes distortions from reflection records by moving events to their correct spatial locations, and by collapsing energy from diffractions back to their scattering points. In several neighboring faults ruptured sequentially, earthquake epicenters migrated progressively along fault zones. Lack of migration trends along some fault planes does not necessarily suggest lack of interaction. Fault interactions may also lead to chaotic rupture of a fault plane at various localities simultaneously, as opposed to a progressive migration away from a seismic source; very likely this was the case for the faults (Mouslopoulou and Hristopulos, 2011). Earthquakes may rupture fault-sections larger than previously observed, making it essential to develop predictive rupture models. Damage in step-overs greatly affects earthquake rupture propagation and arrest.

A glance at the Kazerun and Borazjan fault traces indicates that many bends can be observed in the horizontal traces of these two faults (Fig. 11). Most of the seismic energy released across the active fault segments belongs to the segments with complex geometry. Near the bend, the amplitude of the fault-normal component is larger in the bending part of the fault than in the straight parts (Kase and Day, 2006). For a high bending angle case, rupture terminates the bend because of the large strength excess and negative stress drop beyond the bend.

In Figure 11 the major bends located along the KFS are shown. In order to show the role of this bends in seismicity concentration and migration, on both sides of each fault, the bends are illustrated by a measured angle and also the value of the seismic energy released.

Most of the bends in the Kazerun fault have small angles towards East that cause accumulation of seismic energy in this segment of fault (Kamarij segment). There are also 5 bends to the West that will cause accumulation of seismic energy between two faults (Fig. 11). This accumulation along with the major migration trend (Fig. 8) represents the fault interaction and migration in the range of extentional step between Kazerun and Borazjan faults.

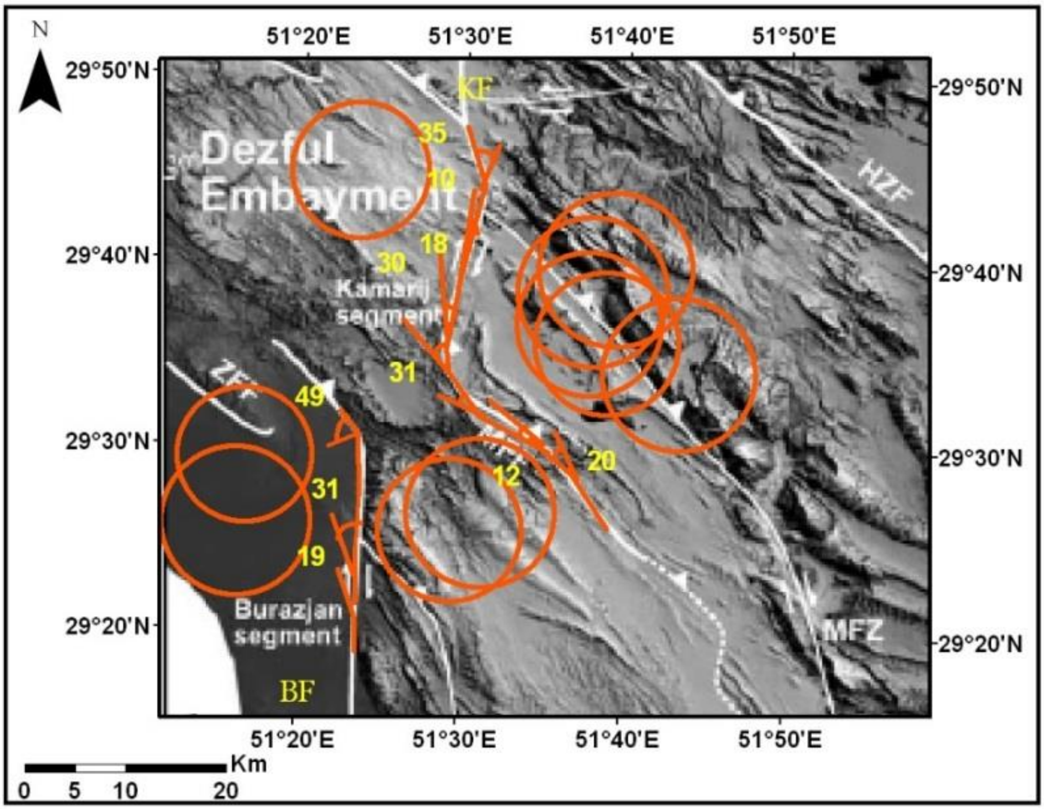

Fig. 11. Accumulation of seismic energy released in step-overs and bending parts of the Kazerun and Borazjan faults

Similar evidence of fault interactions and seismic migrations has been reported for the NAFS. Roy & Royden (2000) suggested that brittle failure in a high viscosity crust is primarily focused on the narrow strike-slip fault zone forming earthquake series regardless of the time of the earthquakes. In contrast, when the elastic upper crust is underlain by a low-viscosity lower crustal layer, the deformation zone is broadened in time to encompass many parallel strike-slip faults in an interacting network and their earthquake pairs. They emphasize the effects of lower crustal flow on the faulting at strike-slip plate boundaries. They show that when a low-viscosity lower crustal layer underlies a primarily elastic upper crust, the deformation zone is also broadened in time to encompass many parallel strike-slip faults in an interacting network such as the Marmara region of the NAFS. Spatiotemporal variations of seismicity in the North Anatolian Fault System reflect different crustal rheology and stress transfer by this idea that all faults are connect to a detachment at the base of the seismogenic layer (Cai and Wang, 2001).

6. Conclusions

In this study, we analyzed the earthquake data of the KFS and NAFS regions, with magnitude equal or greater than 4 Richter, and for a time period of 5 years (2006-2010). For this purpose, the study regions were divided into equal area rectangular cells with 10 by 10 km dimensions. We calculate seismic energy released for each earthquake and determined the maximum energy released for each period by providing seismic maps. The spatiotemporal analysis of the data along with the study of the geometry of the active faults in both fault systems were related to the tectonic regime within the middle part of Zagros (Iran) and the Anatoly block (Turkey).

The results obtained in this study show that the seismicity migration and fault interaction is strongly ongoing between the Kazerun and Borazjan segments of the Kazerun Fault System (KFS). The dominant direction of this migration is NE-SW, prependicular to Main Zagros Reverse Fault and more or less parallel to the direction of the Arabian plate motion towards the Eurasian plate.

In addition, the existence of many bends in the Kazerun and Borazjan faults (especially on Kazerun fault) is a good explanation for energy jump in seismic migrations. The mean direction of seismic migrations in North Anatolian Fault System is E-W. According to this study and the studies carried out by previous researchers, the seismic migrations and fault interactions along the segments of NAFS are justified by the westerly motion of Anatolia block, with respect to the Eurasian and African plates. This causes a great change in the tectonic evolution of the eastern Mediterranean, giving rise to the Aegean extensional regime and to internal deformation of Anatolia.

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