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Active Faults of the Arabian Plate Bounds, in Caucasus and Middle East

V.G. Trifonov[1], A.S. Karakhanian[2], M. Berberian[3], T.P. Ivanova[4], V.G. Kazmin[5], M.L. Kopp[1], A.I. Kozhurin[1], S.I. Kuloshvili[6], N.V. Lukina[1], S.M. Mahmud[7], G.A. Vostrikov[1], A. Swedan[8] and M. Abdeen[8]

1) *Geological Institute, Russian Academy of Sciences, Moscow*
2) *Institute of Geological Sciences, Armenian Academy of Sciences, Yerevan*
3) *Geological Survey of Iran, Tehran*
4) *Institute of Dynamics of Geospheres, Russian Academy of Sciences, Moscow*
5) *Institute of Oceanology, Russian Academy of Sciences, Moscow*
6) *Geological Institute, Georgian Academy of Sciences, Tbilisi*
7) *National Research Institute of Astronomy and Geophysics, Helwan, Cairo*
8) *Geological Survey of Egypt, Cairo*

Abstract. The paper presents general description of the large active faults bounding the Arabian plate (Egypt, Israel, Jordan, Lebanon, Syria, and Iraq) and in Lesser and Greater Caucasus (Armenia, eastern Turkey, Georgia, Azerbaijan, and Caucasus region of Russia), Iran, and Turkmenistan. The active tectonics of the region is shown to be controlled by the Arabian plate motion, and complex structural–dynamic relations between the fault zones and recent geodynamic provinces are discussed.

1. Introduction

The late Alpine structure of the region, whose formation was, on the whole, completed to the Pliocene, includes the following tectonic megazones (from south to north) [Khain, 1984; Bazhenov and Burtman, 1990]: (1) African–Arabian plate represented by the northern part of the African plate on the west, continued as the Levant Basin, Mediterranea Sea, and by the Arabian plate on the east; the major element of the intermediate zone between them is the Levant fault zone which inherits partly the Syrian folded zone; (2) neotectonic foldbelt of the northern and northeastern flanks of the Arabian plate, represented by Outer Zagros, Marginal folds of northeastern Turkey, and fold–thrust zone of northwestern Syria; (3) suture of neo–Tethys represented by narrow ophiolitic lenses in the zone of the Main Zagros thrust and boundary thrusts north of the Arabian plate and by the Kurd Dagh and Bassit zones in the northwestern Syria; (4) Taurus; (5) ophiolites and median massives of meso–Tethys; (6) Iran–Pontian megazone; (7) Rioni–Shirvan megazone including the Georgian block which separates obliquely the Rioni–Black Sea and Kura–Southern Caspian basins; (8) Caucasus flysch zone; (9) Major Caucasus Range; (10) Caucasus foredeeps. The present–day pattern and structure of the above megazones resulted from prolonged collision processes associated with the northward motion of the African and Arabian plates and from their

convergence with the north–lying tectonic zones of Eurasia. These processes persisted in the Pliocene–Quaternary time and were expressed most clearly by movements on active faults. The location of the largest faults was predetermined by structural and compositional features of the late Alpine megazones.

2. Northeastern Part of the African Plate

Beginning from the Oligocene, the Arabian plate moving faster than the African plate was separated from the latter by the rift zones of the Gulf of Aden and Red Sea. Both plates rotated slightly counterclockwise. The most intensive Late Quaternary and recent movements on their boundary occurred in the axial zone of the rift system where the continental crust was broken up, and the recent divergence rate exceeded 10 mm / yr [Kazmin, 1987]. The Red Sea rift spreading is oriented obliquely with respect to the rift axis, which produces a left–lateral relative movement of the rift walls, with its amplitude being lower than that of the spreading. Intermittent fault scarps parallel to the rift axis were recognized on the southwestern coast of the Red Sea. They separate Holocene and Late Pleistocene marine terraces.

Active faults in the western, platform part of Egypt are few and seemingly unrelated to the Red Sea rift, being caused by structural and compositional heterogeneities involved in the northerly drift of the African plate. Quaternary normal faults of WNW strike are found in the vicinity of Cairo, but most pronounced is the system of Quaternary faults southwest of the town of Aswan (Fig. 1) [Swedan and Abdeen, 1995]. It is represented by the west–trending Kalabsha and Seiyal faults associated with a system of north–trending young fault scarps on the east. A north–trending neotectonic normal fault of the Kharga zone is adjacent to the western end of the 200–km long

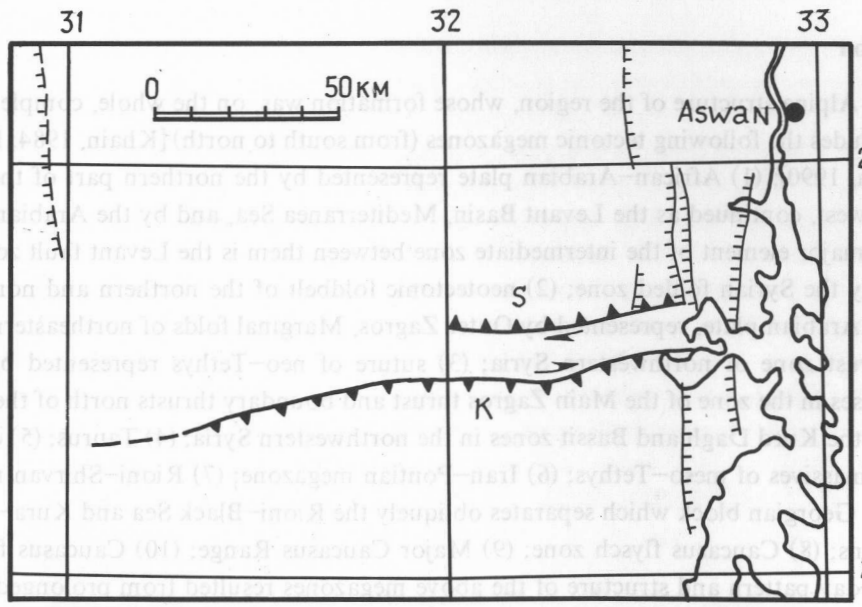

Fig. 1. Active faults west of the Aswan Reservoir [Swedan and Abdeen, 1995]. Faults: (K) Kalabsha; (S) Seiyal. For the legend, see Fig. 2.

Kalabsha fault on the north [Sigaev, 1967]. The Kalabsha and Seiyal faults are expressed on the surface as scarps, with the beds in the Kalabsha zone being bent near the fault, indicating the presence of a reverse–fault component. Moreover, the orientation of the drag folds is suggestive of a right–lateral component. Both fault zones were exposed by trenches which exhibit displacements of Quaternary to Holocene deposits and provide evidence of their seismogenic nature. Geodetic measurements, multiply repeated in the Kalabsha zone during 1986 to 1991, revealed right–lateral strike–slip movements of an amplitude above 10 cm [Vyskocil et al., 1991]. Probably they are related to the rotation of the inter–fault block under the action of north–trending compression.

3. Bounding Structures of the Arabian Plate

Western and northeastern boundary structures of the Arabian plate are represented, on the one hand, by the Levant and East Anatolian (EAFZ) fault zones and, on the other hand, by the faults of Zagros and of the eastern North Anatolian (NAFZ) zone (Fig. 2). The Main Recent fault of Zagros (Tchalenko and Braud, 1974) extends for 1500 km from the western Makran offshoots to the Van Lake area and, to a large extent, inherits the Main Zagros thrust existed earlier. Wellman [1966] described dextral bends and offsets of stream channels of amplitudes to 100 m along the fault. The Seliahor, 1909 earthquake near the town of Dorud gave rise to the 1–m subsidence of the eastern side, accompanied by a right–lateral slip [Tchalenko and Braud, 1974]. The active thrusts of the Outer Zagros occur in front of and parallel to the Main fault [Berberian, 1976–1977]. They disturb the detached sedimentary cover and reflect only indirectly the contemporary stress state of the basement, to which strong earthquakes of thrust type are confined [Nowroozi, 1972].

The NAFZ is the largest (over 1500 km) active right–lateral fault, with the amplitude of its vertical component being position–dependent. The NAFZ inherits the Early Cenozoic right–lateral fault [Bazhenov and Burtman, 1990] on the east and runs along the meso–Tethys suture on the west. Only the eastern NAFZ extends along the Arabian plate boundary. The ground motions of the strongest earthquakes of 1648 and 1930 occurred here, between the Lakes Resayegh (Urmie) and Van. Thus, the Salmas, May 6, 1930 earthquake with $M = 7.2$ produced a right–lateral slip as large as 4.1 m on a fault segment 30 km long and subsidence of the northeastern side with an amplitude of up to 5 m [Tchalenko et al., 1974]. A conjugate, northwest trending fault with left–lateral and normal motion components arose west. Further to the west, between the Lake Van and the NAFZ–EAFZ intersection, right–lateral motions with a vertical component occurred at the earthquakes of 1946, 1949, and 1966 [Ambraseys, 1975, 1988; Wallace, 1968]. Saroglu [1988] suggests the 18–km bend of the Murat River valley to be produced by a right–lateral motion. Dextral offsets of Late Pleistocene gullies by 350–400 m are found near the village of Tchmalliar northwest of the town of Varto [Trifonov et al., 1994].

The Levant fault zone detaches from the Red Sea rift and extends north from the Aqaba Gulf to Southern Taurus. The recent activity of the rift drops abruptly west of the Aqaba Gulf. Large pull–apart basins (Dead Sea, Tiberian Lake, and El Gaab) occur in the Levant zone. The Gulf of Aqaba appears to be a similar structure. The Israeli part of the Levant zone exhibits sinistral offsets of young stream channels, dry valleys, and other relief forms. Zak and Freund [1965] estimate the average rate of the Late Quaternary strike–slip movement to be 6–7.5 mm / yr, whereas other

authors [Gardosh et al., 1990] report smaller values. Thanks to the kind assistance of the Israeli geologists I. Karcz and A. Gelat, A.I. Kozhurin and V.G. Trifonov could survey the western coast of the Dead Sea and observed sinistral motion features to exist only along the main fault bounding

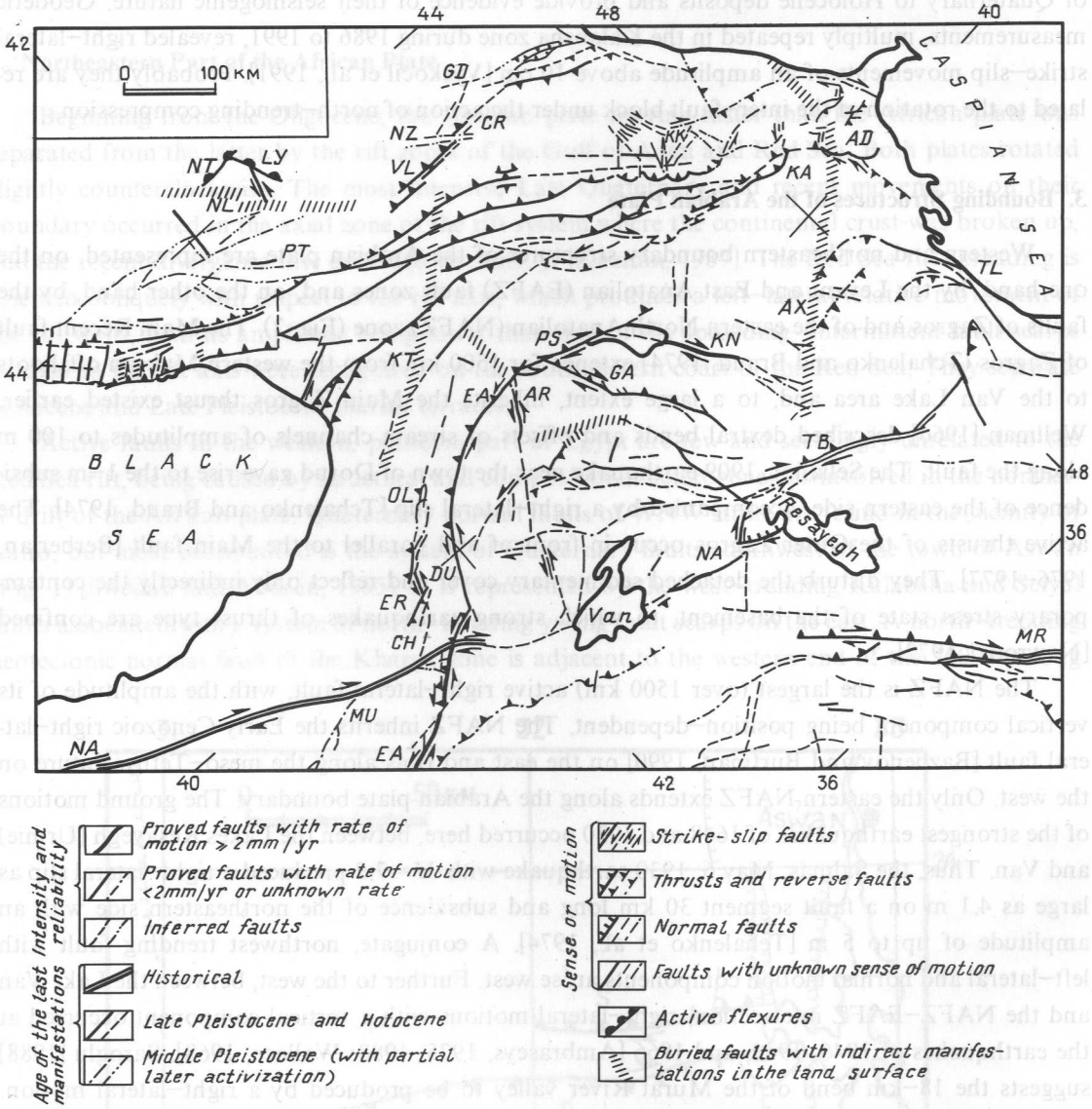

Fig. 2. Active faults in Caucasus and adjacent areas of Turkey and Iran [Trifonov et al., 1994b]. Faults, flexure, and fault zones: (AD) Adjichay (Salian–Lenghibiz) fault; (AR) Akhurian fault; (AX) Araks zone; (CH) fault of the southeastern side of the Chat basin; (CR) Chernogor flexure; (DU) Dumlu fault; (EA) East Anatolian zone; (GD) Gudermes fault; (KA) Karamarian fault; (KK) Kaflan–Kala fault; (KN) Khanarasar fault; (KT) Kazbek–Tshinval fault; (LY) Lysogor flexure; (MR) Main Recent fault of Zagros; (MU) Ovacik–Malatya (Munzur) fault; (NA) North Anatolian zone; (NL) Nalchik (Armavir–Nevinnomyssk) zone; (NT) Nagut flexure; (NZ) Nazran zone; (OL) Oltu fault; (PS) Pmbak–Sevan fault; (PT) Pshekish–Tyrnyauz fault; (TB) Tabriz fault; (VL) Vladicaucasus fault.

this pull–apart basin, while parallel faults inside the basin indicate normal fault movements only. Their mean rate on the western coast of the Dead Sea amounts to 1–2 mm / yr in the Pleistocene and 0.85 mm / yr in the Late Pleistocene and Holocene [Gardosh et al., 1990].

In the Lebanon territory, the zone assumes the NNE strike along with a shortening component of movements, which is expressed by a combined sinistral–reverse fault motions and by the development of compressed folds parallel to the fault. Smaller active faults with reverse and thrust components splay northeast off the Levant zone. Here also the Levant zone meets the Druz fault system, deforming its southeastern part. The Druz system consists of parallel tensile faults arranged often en echelon and including chains of Pleistocene and Holocene volcanoes [Ponikarov et al., 1968] whose youngest eruptions have ages of 4–4.5 thousand years [Trifonov and El–Khair, 1989]. Parallel to the system is the moderate–seismicity Erythrean fault zone branching off the Levant zone to the southeast in the Dead Sea area [El–Isa, 1992].

In its Syrian part, the Levant zone again trends north. Its segment near the town of Missif, studied in detail, has the form of a narrow graben. Numerous young sinistral offsets and bends of valleys and gullies are observed on both sides of the graben, with their amplitudes decreasing to the north on the eastern side and increasing on the western side, so that their net value remains constant. The average strike–slip rate is estimated to be 5–6 mm / yr in the Holocene and 4–5 mm / yr for the last 3.5 m.y. [Trifonov et al., 1991]. Holocene strike–slip amplitudes of movements on the El–Gab basin flanks are close to those measured in the Missif area, but their vertical component is larger.

Strong earthquakes of the 20th century are few in the Levant zone. However, historical chronicles report numerous earlier seismic events with intensity of 8–10. By preliminary estimates, strong earthquakes recurred every 200–300 years, and most catastrophic ones recurred every 500–600 years [El–Hakeem, 1986].

A moderately active fault is likely to extend along the continental slope of the Mediterranean. The fault is adjacent to the Levant zone, north of the Dead Sea, where it is known as the Roum fault [Girdler, 1990], and, like the Levant zone, joins the EAFZ on the north. South of the EAFZ–NAFZ intersection, numerous sinistral offsets of the Late Quaternary relief forms are discovered along the EAFZ segments [Saroglu et al., 1992; Trifonov et al., 1994]. The average rate of the movements is estimated from the 10–14 km bends of the Euphratus and Murat valleys. Assuming that the valleys originated in the Middle of Pliocene, we obtain the strike–slip rate to be 5–7 mm / yr.

4. Armenian Upland and Caucasus

The EAFZ continues as two northeasterly branches beginning from its intersection with the NAFZ [Trifonov et al., 1994]. The western branch known now as the Northeast Anatolian fault zone is represented by en echelon faults on the southeastern flanks of the Chat and Erzurum basins, the Dumlu fault, and faults near the Narman village and Oltu town. The faults include the epicenters of 20th century earthquakes with magnitudes of 5.5–6.2 and several stronger earthquakes of previous centuries [Bommer and Ambraseys, 1989]. Late Quaternary reverse movements are recognized along the faults, and sinistral movements on the Dumlu fault are more intensive. The zone is traced up to the town of Akhalkalaki, South Georgia, where it is replaced, in

an echelon–like manner, by the neotectonic Kazbek–Tshinval fault described by Milanovsky [1968].

In its northeastern part, the eastern branch, or the EAFZ proper, is gradually deflected to the east. Sinistral offsets of young relief forms are found in the Agakh River valley near the Zurashat village, being most pronounced at the northeastern termination of the zone where they reach 350 m with a reverse component of up to 70 m [Trifonov et al., 1994]. The fault plane dips steeply (50–60) to the northwest. The epicenters of the strong earthquakes of 1859 and 1924 are located in the fault zone. A sinistral motion of up to 1.2 m with a reverse component of up to 0.6 m took place on the fault at the Horasan, October 30, 1983 earthquake with $M = 6.9$. The seismic rupture extended for 8 km.

Northeast of the Gumri (Leninakan) town, the eastern end of the EAFZ joins the Pambak–Sevan–Khanarasar fault zone, both zones making an angle of 18°. The latter of them extends to the northeastern shore of the Lake of Sevan, crosses it, branches off in the southeastern Armenia, and dies out north of the Tabriz town. Main faults of the zone dip northeast at angles of 70–80°. They exhibit Middle–Late Pleistocene and Holocene dextral and much smaller reverse displacements. Thus, in the northwestern part of the zone, near the villages of Sarapat and Gogaran, a terrace aged about 70 thousand years is offset by 300 ± 20 m to the right, with its northeastern flank being uplifted by 20 ± 5 m, and the same parameters for a terrace aged 20–25 thousand years are 100 ± 20 m and 10 ± 5 m. The Middle Pleistocene Khanarasar volcano cone, lying 14 km southeast of Sevan, is displaced by 800 m to the right. These data yield 4–5 mm / yr for the strike–slip rate, whereas the reverse component rate is about 10 times smaller [Trifonov et al., 1990, 1994]. Chains of andesite–basalt volcanoes, with the age of their last eruptions being about 5 thousand years, and traces of several strong paleoearthquakes are found in a small pull–apart basin lying southeast.

The EAFZ and the Pambak–Sevan–Khanarasar zone form the North Armenian arc of active faults. It encloses an inner arc which contacts the outer arc in its apex and is represented by the Akhurian and Garni–Alavar fault zones [Trifonov et al., 1994]. The faults of the Akhurian zone forming the western part of the inner arc show evidence for the vertical and left–lateral movements. A number of strong earthquakes, including the notorious Leninakan earthquakes of 1926 are known. The Garni–Alavar zone includes several en echelon segments of NW strike, with each southern segment beginning east of the neighboring northern one. The segments are characterized by dextral movements with an average rate of about 2 mm / yr and by vertical movements of much smaller amplitudes. The segments are connected through shorter faults having a considerably greater reverse component. These peculiar structures of the segment junction coincide more or less with the epicenters of the strong earthquakes of (from south to north) 906, 1679, and 1827. The same structural position is characteristic of the Spitak, 1988 earthquake ($M = 7.0$) which occurred in the Garni–Alavar zone near its junction with the Pambak–Sevan–Khanarasar zone. The earthquake produced a 37–km long rupture with a maximum dextral–thrust movement of 2 m [Trifonov et al., 1990].

The Tabriz fault is the largest one between the North Armenian arc and NAFZ. It forks on the west and is characterized by right–lateral and subordinate vertical motions. The fault zone includes strongest earthquake epicenters. The earthquake of 1976 ($M = 7.3$) on the southern branch of the fault produced a 50–km rupture with a maximum dextral movement of 3.5 m and a vertical

component of up to 0.5 m [Toksoz et al., 1977].

The smaller Talysh arc which is also north–convex lies east of the North Armenian arc. It is represented by a zone of young faults showing evidence of sinistral motions and trending northeast along the Araks River and by the faults of the Talysh Mountains adjacent to the zone on the north. Reverse movements are recognized along this fault [Berberian, 1976–1977], but a right–lateral component is possible too.

The North Armenian and Talysh arcs reflect the contemporary deformation of the Iran–Pontian late–Alpine megazones. North–lying active faults form the northern front of this megazone and are particularly numerous in the southern foothills and on the southern slope of the Greater Caucasus, where they indicate the persisting underthrusting of the Rioni–Shirvan megazone beneath the flysch megazone and Major Caucasus Range. Thrust and reverse movements, occasionally associated with the formation of young asymmetrical fault–line anticlines, were observed by S.I. Kuloshvili in Georgia and by M.L. Kopp and V.G. Trifonov in Azerbaijan. The faults trend commonly west–northwest parallel to the Greater Caucasus axis. The faults that deviate northwest from the general trend show evidence of dextral movements. The strike–slip rate reaches 1 mm / yr on the Saliany–Lenghibiz (Adjichay) fault in the southeastern Caucasus area. Also there are recognized small sinistral faults concentrating along the continuation of the Araks fault zone. Moreover, normal faults and flexures trending N20°–40°E occur in the eastern Greater Caucasus.

The northern slope and piedmont of the Greater Caucasus are dominated by active faults of NW strike and of western or WNW strikes. The latter are commonly reverse. Seismogenic ruptures and landslides associated with the Daghestan, May 14, 1970 earthquake ($M = 5.7$) are described by Amirkhanov [1981] to occur along two reverse faults. Further to the west, the Vladicaucasus fault, crossing the river terraces of the earliest and latest Late Pleistocene ages, changes their heights by 40–70 and 15–25 m, respectively [Milanovsky, 1968]. The adjacent Balta fault changes the terrace heights in a similar way though by a smaller value. Movements on both faults are accompanied by anticlinal flexures of terraces. The northwestern structural trend is more often represented by deep zones of active faults, expressed on the surface only by indirect features such as young flexures and clusters of small faults and fractures. These are the Caspian coastal zone and the Gudermes, Nazran, Lysogor, and Nalchik (Armavir–Nevinnomyssk) zones. They are characterized by higher seismicity and occasionally by gas–hydrothermal activity. Faults of both trends combine into rhombiform patterns. The latter are most typical in the northern slope of central and northwestern Caucasus. Reconstructions of the stress fields from data on young tectonic fracturing suggest that the WNW–trending and W–trending faults are mostly reverse, while the NW trending faults have an additional dextral component [Rastsvetaev, 1989]. Also, normal faults with or without a strike–slip component, recognized most reliably from deformations of marine terraces, occur in the northwestern Caucasus [Ostrovsky et al., 1977].

5. Iran and the Turan Plate

In central and eastern Iran (Fig. 3), left–lateral motions on sub–west–trending faults occurred at the conditions of NE compression normal to the flank of the Arabian plate. The largest them is the Doruneh (Great Kevir) fault [Wellman, 1966; Mohajer–Ashjal et al., 1975]. Movements

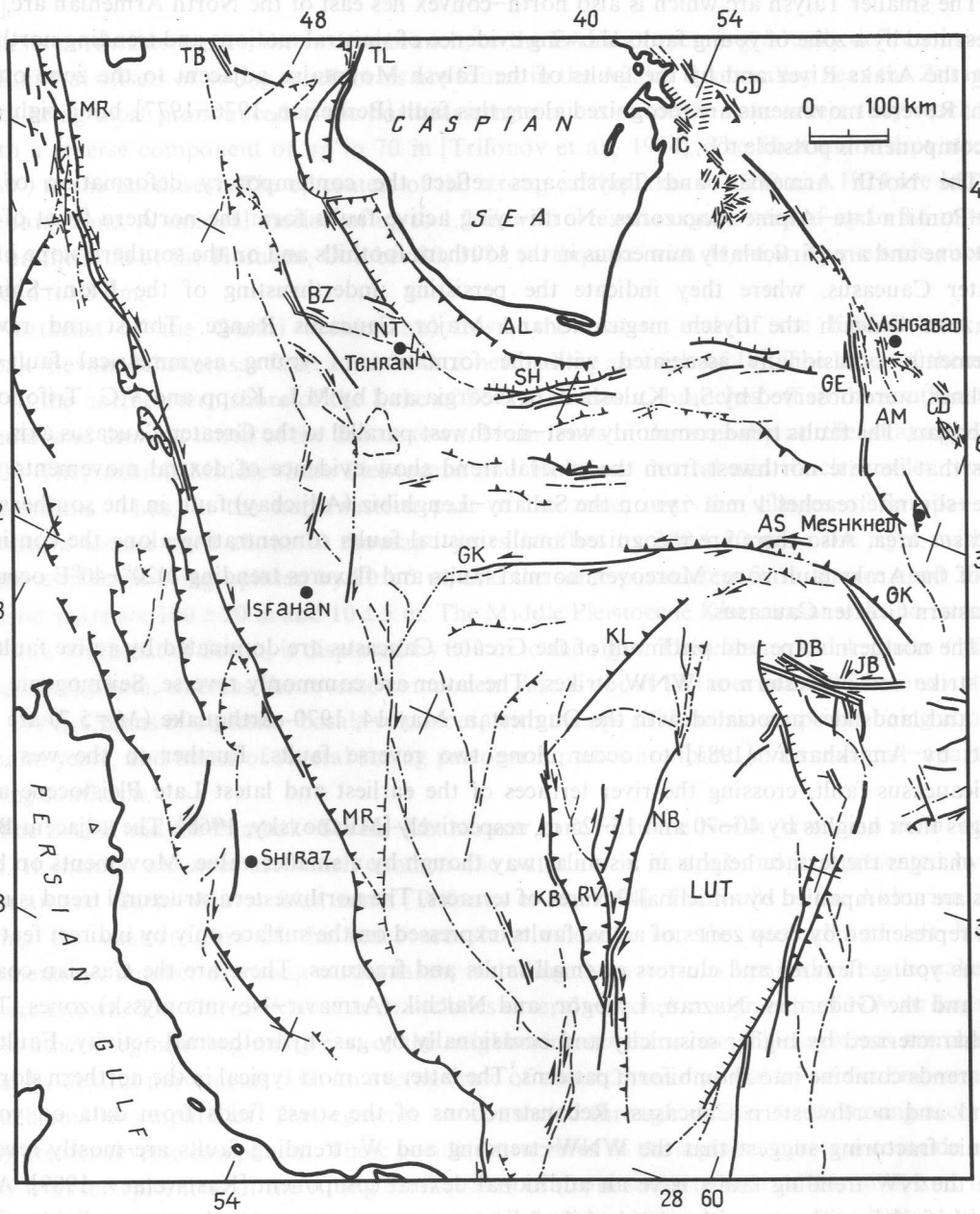

Fig. 3. Active faults in Iran and southern Turkmenia. The map compiled by M. Berberian with the use of data of N.N. Ambraseys, D. McKenzie, A. Mohajer–Ashjai, A.A. Nowroozi, J.S. Tchalenko, N.W. Wellman, and others, complemented by A. Karakhanian, V.G. Trifonov, and G.A. Vostrikov. Faults: (AL) North Alborz; (AM) Aselma; (AS) Asadabad; (BZ) Buyin Zara; (CD) Main Kopet Dagh; (DB) Dasht–e–Bayaz; (GE) Ghermab; (GK) Great Kevir (Doruneh); (IC) Isak–Cheleken; (JB) Jabbar; (KB) Kuh Banan; (KL) Kalmard; (MR) Main Recent of Zagros; (NB) Nayband; (RV) Ravar; (SH) Shahrud; (TB) Tabriz; (TE) North Tehran; (TL) Talysh. For the legend, see Fig. 2.

of the same direction (sinistral amplitude of up to 4.5 m and vertical amplitude of up to 2.5 m) took place on a 80–km fault activated at the Dasht–e–Bayaz, 1968 earthquake ($M=7.2$) [Tchalenko and Ambraseys, 1970; Tchalenko and Berberian, 1975]. Dextral movements with or without a thrust component are present along the faults that trend northwest near Zagros (Kuh Banan fault) and almost in the northern direction further to the east (Nalband, Ravar, and Jabbar faults) [Wellman, 1966; Mohajer–Ashjai et al., 1975; Berberian, 1976–1977].

The active faulting in eastern Iran reflects the relative movements of the separate Lut block. The Ala Dagh–Benalud fold arc before its front originated as a result of the northerly movement (along with some counterclockwise rotation) of the block. The arc forces the thick sedimentary cover of the folded area between the arc and the Turan plate (consolidated at the end of the Paleozoic) to move westward, to an area of lower pressure. On the north, the squeezed–out triangle block is bounded by the Kopet Dagh Range with the dextral–reverse Main Kopet Dagh fault on its northeastern flank [Rastsvetaev, 1972]. The Late Quaternary dextral movements in the zone of this fault have a rate equal to or greater than 2 mm / yr, and their amplitude is about 5 times higher than that of their reverse–thrust component [Trifonov, 1983]. Conjugate sinistral faults active on certain segments detach from the dextral–reverse faults. The zone of the latter continues on the northeastern slope of the Great Balkhan and is complemented here (in West Kopet Dagh) by the parallel Isak–Chelekan fault zone, along which both purely dextral and strike–slip reverse motions occurred at the Kum Dagh, 1983 and Burun, 1984 earthquakes [Trifonov et al., 1986]. The Late Pleistocene–Holocene movements were also revealed there. The WSW–trending sinistral–reverse Shahrud fault extends along the southern edge of the wedge–shaped block [Wellman, 1966]. To the west, both slopes of the Alborz Mountains include sublatitudinal faults showing evidence of the Late Quaternary and Recent seismogenic reverse–thrust motions with a sinistral component [Ambraseys, 1963; Berberian, 1976–1977; McKenzie, 1972; Nowroozi, 1972; Tchalenko, 1975].

6. Conclusion

The Late Quaternary movements on the Red Sea rift provide evidence for the northerly motion of the Arabian plate relative to Africa at a rate of about 10 mm / yr. To a small degree, this motion is accommodated by the intraplate deformations, but mainly it is represented by 5–7 mm / yr strike–slip movements on the western, northwestern, and northeastern flanks of the plate. Within the Alpine orogenic belt, this northerly drift of the plate encounters a rigid lithospheric block of the Black Sea with a somewhat uplifted cold mantle and, as a result, transforms into two lithospheric mass flows. One of them, moving to the west, is best defined by the right–lateral movements on the NAFZ, while the other produces the north–south compression and shortening of the Lesser Caucasus. They reveal themselves first of all in the North Armenian fault arc as strike–slip movements accommodating the rotation of small blocks and rock mass flow away from the zone of highest compression rather than as underthrusting of the southern flank of the plate. Also, the Lesser Caucasus drifts northward, which is expressed as the Quaternary overriding of the Rioni basin by the northern flank of the Lesser Caucasus on the west and as underthrusting of the Lesser Caucasus and its frontal Dzerula block beneath the upper–crust structures of the Greater Caucasus on the east. This underthrusting results in the uplift of the Greater Caucasus and development of thrusts, reverse faults, and dextral–reverse faults. The intensity of young movements

attenuates to the north, being lower on the northern slope of the Greater Caucasus as compared with its southern slope. The northerly drift of the Arabian plate produces compression of central and eastern Iran normal to the northeastern flank of the plate, the compression being accommodated mainly by the strike–slip fault movements. These deformations and movements in their turn result in the north–south compression of the Alborz and Ala Dagh–Benalud structures and the Turan plate lying north. The compression is manifested by thrust strike–slip movements along the Kopet Dagh. The brief description of active faults presented in this paper is not complete because some areas such as Karabakh and its vicinities or Limestone Daghestan at the boundary between Daghestan and Chechnya are not studied. However, additional data on these areas are unlikely to have an essential effect on the general kinematic and dynamic pattern.

Thus, the active fault tectonics of the region considered is controlled by the northward drift of the African plate and by the Arabian plate divergence from it. The associated local transformations of the stress field and diversity of its structural manifestations are related to inhomogeneities of the structure and physical properties of the lithosphere, largely dependent on the geological evolution.

Acknowledgments

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