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Modern Geodynamics and Focal Mechanisms of Earthquakes near the Bushehr Nuclear Power Plant

A. A. Lukk[a, *] **and Yu. L. Rebetsky**[a, **]
[a] *Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia*
**e-mail: lukk@ifz.ru*
***e-mail: reb@ifz.ru*
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Abstract—A method for determining the focal mechanisms of earthquakes using the *S*-wave polarization direction for weak close seismic events is developed based on the detailed seismological studies carried out by the seismological expedition of the Institute of Physics of the Earth of the Russian Academy of Sciences in 1999–2001 near the Bushehr nuclear power plant (NPP) in Southern Iran. The results of the reconstruction of such determinations are compared with the focal mechanisms of strong earthquakes determined in ISC catalogs using the standard method and with modern concepts of tectonic deformation of the earth's crust in a wide vicinity of the region under consideration. It has been established that this reconstruction is in good agreement with both the typification of movements in the foci of strong earthquakes and modern concepts about the nature of the deformation of the earth's crust within the observation network. This allows us to recommend this method for reconstructing focal mechanisms in other regions.

Keywords: tectonic deformations, geodynamics, focal mechanisms of earthquakes, kinematics of seismotectonic deformation

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ELEMENTS OF TECTONICS AND THE NATURE OF DEFORMATION IN A WIDE AREA NEAR THE BUSHEHR NUCLEAR POWER PLANT

The Institute of Physics of the Earth of the Russian Academy of Sciences carried out a detailed seismological study of the Zagros fold and thrust belt (FTB) in Southern Iran near the Bushehr nuclear power plant (NPP) in 1999–2001 (Fig. 1). The Zagros FTB extends from northwest to southeast and is the result of a collision of the Arabian and Eurasian plates. It is located on the edge of the Arabian Plate, which was passive in the past and which collided with the Eurasian Plate during the Mesozoic–Cenozoic along the suture zone, currently marked in the northwest by a right-lateral strike-slip fault called the Main Recent Fault (MRF in Fig. 1) and, in the southeast, by the Main Zagros Thrust (MZT in Fig. 1).

Zagros experienced its second deformation episode during the Neogene after the closure of the ocean basin. It led to the formation of High Zagros Mountains located between the MZT and the High Zagros Fault (HZF in Fig. 2). It was accompanied by intense folding, which led to the formation of the Simple Fold Belt (SFB in Fig. 2) located between the HZF and the coast of the Persian Gulf (Falcon, 1974; Berberian and King, 1981).

The Arabian Plate moves north-northeast near 52° E at a velocity of about 31 mm/yr in relation to Eurasia according to the Nuvel-1A model of tectonic plates (DeMets et al., 1990) based on the analysis of the seafloor spreading, fault systems, and slip vectors in earthquake sources. Geodetic data (for example, (Kreemer et al., 2003; McClusky et al., 2003)) show approximately the same orientation but with velocities of ~10 mm/yr or less. The Zagros earth crust is shortened by about 7–2 mm/yr in the north–south direction during these movements (Vita-Finzi, 1979). It is close to the total average spreading velocity of about 10 mm/yr of the Zagros deformation front after the Eocene (Hessami et al., 2001). This is manifested on the surface in a well-developed system of thrusts and folds, which were formed approximately in the mid- to late Eocene (Vernant et al., 2004).

The simple Zagros FTB consists of two different structures. The narrower West Zagros oriented obliquely to the direction of regional shortening in the process of lithospheric plate collision is associated with orogenic parallel thrust faults and folding that have been developing since the Mesozoic–Cenozoic (Falcon, 1974; Berberian and King, 1981). In addition, this part of the FTB is exposed to the influence of an active large right-lateral strike-slip Main Recent Fault (MRF) in the north. The plate convergence

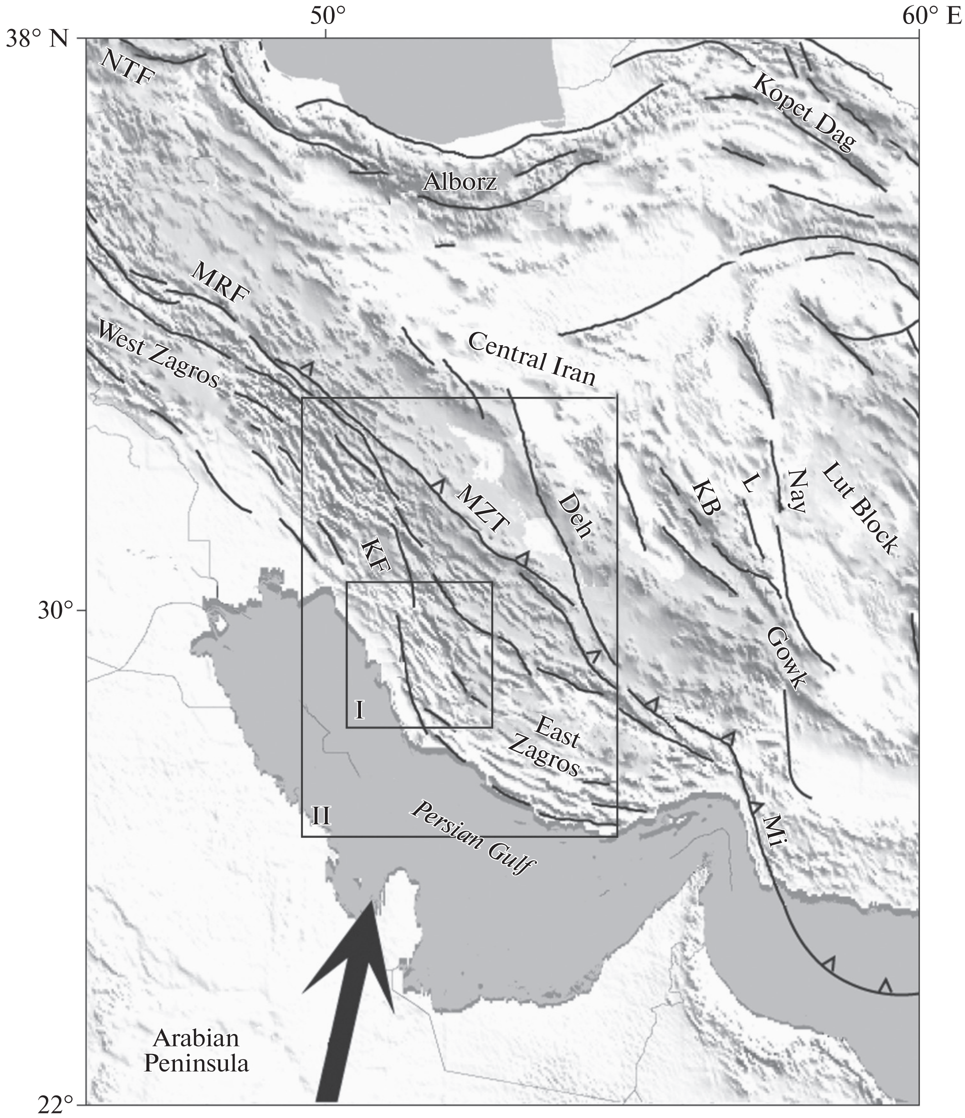

Fig. 1. Fragment of a simplified tectonic map of Iran ((Vernant et al., 2004), as amended). Abbreviations: Main Recent Fault (MRF), North Tabris Fault (NTF), Main Zagros Thrust (MZT), Kazerun Fault (KF), Dehshir Fault (Deh), Kuh Banan Fault (KB), Nayband Fault (Nay), Lakarkuh Fault (L), Gowk Fault (Gowk), and Minab Zendan Palami fault zone (Mi). (I) Region of detailed seismological studies in the area of the Bushehr NPP; (II) wide area of the assessment of the type of stress-strain state in the area of the Bushehr NPP (see Fig. 2). The arrow shows the direction of movement of the Arabian Plate relative to Eurasia according to the NUVEL-1A model (DeMets et al., 1990).

direction is about 45° to the strike of this fault. Therefore, the convergence velocity is 7 ± 2 mm/yr (Vita-Finzi, 1979; Vernant et al., 2004) and can be decomposed into components parallel to the fault and normal to it with values of ±5 ± 1.5 mm/yr each.

The existence of the first is evident from observations of geological and instrumental displacements along the MRF. The existence of the second is found by solutions of the focal mechanisms of earthquakes. Thus, in most cases, the coseismic slip vectors in earthquake foci to the southwest of the MRF are oriented normally to both the MRF strike and the strike of geological structures of this part of the Zagros FTB (Talebian and Jackson, 2004). At the same time, the focal mechanisms along the MRF show the predominance of pure strike-slip motions. All this suggests that the orogen-parallel component of convergence is associated mainly with the active strike-slip motion along the MRF, and the orogen-normal component of convergence is associated with the distribution of subducting orogen-normal thrusts in the FTB.

The wider East Zagros, oriented approximately perpendicular to the direction of shortening the distance between Arabia and Eurasia, is bounded in the north by a suture zone between colliding plates marked by the large MZT, which is currently inactive

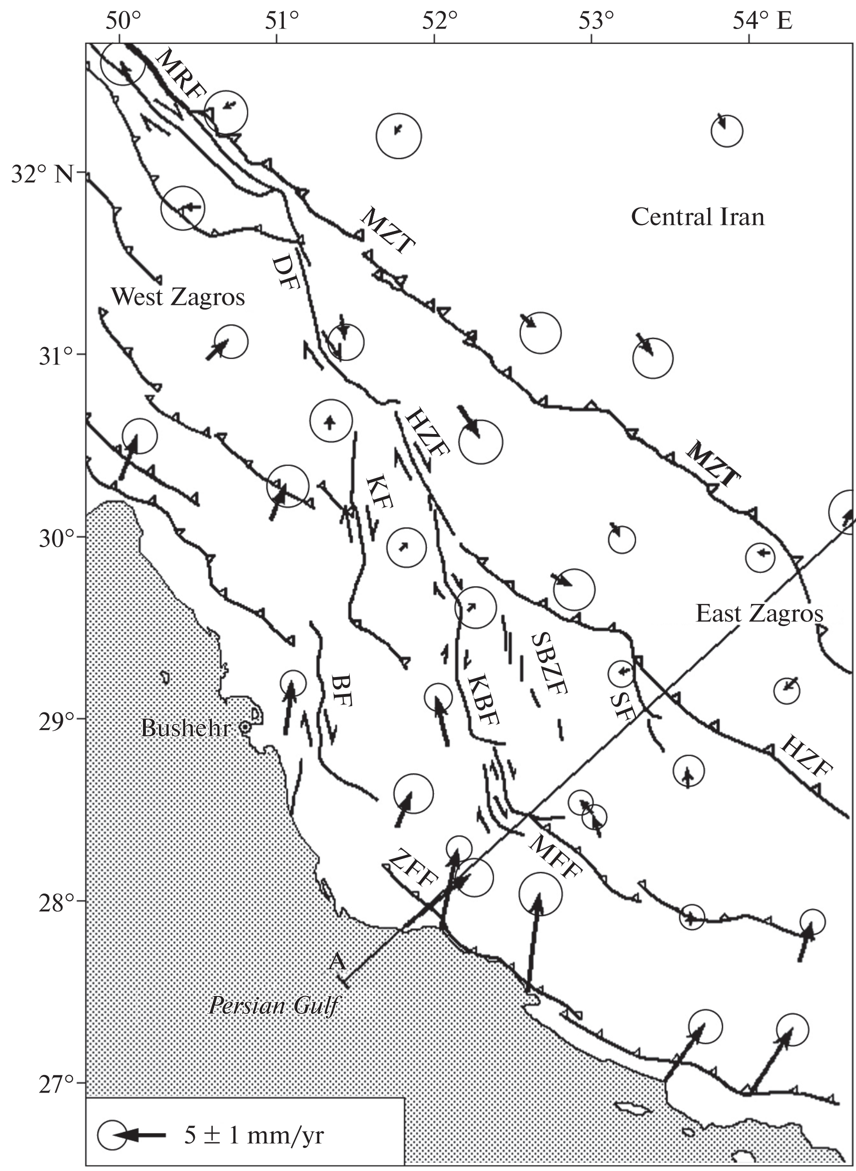

Fig. 2. Modern tectonics and the velocity field of the GPS points in the Kazerun County relative to Central Iran (Fig. 2 from (Tavakoli et al., 2008), revised). Abbreviations: Main Recent Fault (MRF), Main Zagros Thrust (MZT), Dena Fault (DF), Kazerun Fault (KF), Borazjan Fault (BF), Kareh Bas Fault (KBF), Sabz Pushan Fault (SBZF), Sarvestan Fault (SF), High Zagros Fault (HZF), Main Front Fault (MFF), and Zagros Front Fault (ZFF). **A–A'** is the geological profile across the Fars Province (according to (Allen et al., 2013)). The uncertainty in estimating the position of the velocity vectors shown by the corresponding circles at the ends of the vectors is 1σ.

(Berberian and King, 1981; Jackson, McKenzie, 1984; Tatar et al., 2002). The thrust became inactive with the onset of sliding along the MRF (Authemayou et al., 2006; Tavakoli et al., 2008). Apparently, this happened because both the fault and the thrust use the same lithospheric separator: the suture zone between Arabia and Central Iran. The faulting along this suture zone changed from a thrust in its eastern part to a strike-slip fault in the western part at the end of the Miocene (Tavakoli et al., 2008).

The HZF, Main Front Fault (MFF), and Zagros Front Fault (ZFF) play a major role in the deformation of the eastern part of the Zagros FTB. Their strike coincides with the strike of the belt (see Fig. 2), which shortens across them. The territory of the fold belt bounded by large ZFF and HZF is characterized by the largest values of the Earth's surface deformation (about 5–10 mm/yr) according to GPS observations (Tavakoli et al., 2008) (see the comparative values of the movement vectors of GPS points on Figure 2). Deformation values are noticeably reduced further north, in the High Zagros; even further north, within the plateau of Central Iran, the internal deformation is generally less than 2 mm/yr (Vernant et al., 2004; Tavakoli et al., 2008).

The main differences between the northwestern and southeastern parts of Zagros are in the orientation of the main right-lateral strike-slip faults and their correlations with the young thrusts and folds. Right-lateral strike-slip motions in Northwestern Zagros are focused on the MRF, while active thrusting and related folding spread to the south and southwest from it into the adjacent part of the Mesopotamian trough. In Southeastern Zagros, the main strike-slip faults are concentrated in the Kazerun zone, which strikes from north to south obliquely to the main strike of Zagros. All branches of strike-slip faults in this zone in their southeastern extremities are supported by thrusts striking in the sublateral direction (see Fig. 2).

The spatially separated equilibrium of transverse shortening and strike-slip displacement in Northwestern Zagros suggests that the interaction of the Arabian Plate with the Iranian block occurs mainly in the oblique collision regime, while in Southeastern Zagros the oblique interaction of the plates gives way to their normal collision. In this case, the separation of these parts of Zagros by the strike-slip fault zone extending from the north to the south of the Kazerun zone is most likely due to the change in the regime of long-term tectonics during the collision between the Arabian and Iranian (as the southern component of the Eurasian plate) plates.

According to current GPS measurement data (Tatar et al., 2002; Vernant et al., 2004; Hessami et al., 2006; Walpersdorf et al., 2006; Tavakoli et al., 2008), geological structures on opposite sides of Kazerun Fault zone are “crushed” in collision with different intensities: West Zagros with a velocity of ~4 ± 2 mm/yr in the north-northwest direction of 12° ± 8° and East Zagros with a twofold velocity (~9 ± 2 mm/yr) in the north-northeast direction of 7° ± 5° (Hessami et al., 2006; Tavakoli et al., 2008). The difference in collision rates is most likely due to significant strike-slip deformation along the MRF in Northwestern Zagros.

The strike-slip deformations are from 2 to 5 mm/yr in the same separation zone between these two Zagros structures, represented by the Kazerun (Kazerun–Borazjan) system of well-developed right-lateral strike-slip faults extending from north to south between the HZF and ZFF in the band between 51 and 53° E (see Fig. 2). The separation zone includes the short (~100 km) Dena, Kazerun, Borazjan, and Kareh Bas oblique strike-slip faults that spread in the southeastern direction and cross and break the folds of the Zagros Simple Thrust and Fold Belt (Berberian, 1995; Bachmanov et al., 2004; Authemayou et al., 2005; etc.).

It is assumed that this system is a southeast-trending fan-shaped fork of the strike-slip MRF (Talebian and Jackson, 2002; Bachmanov et al., 2004; Authemayou et al., 2005, 2006, 2009; etc.). It strikes from the southeastern tip of the MRF to the Persian Gulf. Geomorphological data, seismicity, and the results of direct observations of the movements along the fault during trenching show that the Kazerun zone and the associated right-lateral strike-slip faults are active both in the Zagros sedimentary cover and in its foundation (Baker et al., 1993; Bachmanov et al., 2004). All faults in this zone inherited from the Neoproterozoic tectonic phase go to the basement (Talbot and Alavi, 1996). The following characteristic feature of the strike-slip faults included in it should be noted: they all seem to be locked in the south by a relatively short southeast or even sublateral thrust (Authemayou et al., 2005, 2009) (see Fig. 2).

The total displacements of geological markers in the Kazerun Fault System are 8–27 km for the Neogene–Quaternary (2–3 Ma) (Authemayou et al., 2006, 2009). These estimates are based on the displacement of the topography and the evolution of folds on both sides of the main Kazerun Fault (KF). This age is similar to that of the MRF, which confirms the interpretation that the KF was reactivated as a modern fault as a result of MRF formation as a strike-slip deformation as a result of the collision between the Arabian and Iranian (as part of the Eurasian plate) plates and the transfer of this strike-slip motion to the Kazerun Fault zone (Talebian and Jackson, 2002; Authemayou et al., 2006, 2009).

The GPS measurement data show a decrease in the slip velocity on the Kazerun Fault System in the north–south direction. Thus, if this velocity in the zone of direct contact of this system with the strike-slip MRF is 3.5–12.5 mm/yr according to different estimates, then in the northern segment of the system the slip velocity decreases to 2.5–4.0 mm/yr and, in the middle part of the Kazerun Fault, it is 1.5–3.5 mm/yr and becomes quite insignificant in its southern segment (Authemayou et al., 2005, 2006, 2009; Tavakoli et al., 2008). At the same time, the role of thrusting on latitudinally striking thrusts that lock different branches of the strike-slip system from the south increases in the south. Such kinematics of faults suggests that the horizontal slip velocity along the Kazerun system of strike-slip faults decreases in the south due to the transfer of the collision motion from slipping to thrusting.

The final acquisition of strike-slip motion in the Zagros FTB by transferring the slip from the MRF to the KF is considered an effect of the regional reorganization of the Arabian–Eurasian collision that occurred 5 ± 2 Myr according to (Allen et al., 2004). This regional reorganization can be associated with the fracture of the Arabian lithospheric plate along the Kazerun Fault zone (Molinaro et al., 2005; Authemayou et al., 2006, 2009).

Thus, a number of researchers assume that the Kazerun Fault System plays a significant role in the transformation of collisional movements. The Arabian Plate appears to fracture and turn counterclockwise along it with an increase in the rate of strike-slip motion as it moves from the southern boundary of the Kazerun Fault System to the MRF (Talebian and

Jackson, 2002, 2004; Authemayou et al., 2005, 2009; Hessami and Jamali, 2006). Observed changes in the direction and magnitude of the velocity vector of GPS motions across Kazerun and Kareh Bas faults associated with the expansion of rocks near them to 4 mm/yr along the strike of the Zagros belt may indicate the possibility of such a turn (Hessami et al., 2006).

The tectonic transpression regime (strike-slip compression) caused by the collision of the Arabian and Iranian plates regulates the activity of all strike-slip faults in Iran (Hessami and Jamali, 2006). In addition, it transfers this activity through strike-slip motion along the MRF further northwest to the right-lateral strike-slip North Anatolian Fault (NAF), along which the Anatolian plate moves to the Hellenic collision zone (Authemayou et al., 2009).

NATURE OF THE DEFORMATION OF THE UPPER LAYER OF THE EARTH'S CRUST ALONG THE GEOLOGICAL PROFILE THROUGH THE ZAGROS FTB

There are two points of view on the nature of the deformation of the upper layer of the crust of the Zagros FTB as a result of the convergence of lithospheric plates. One of them suggests that the upper cover layers of sedimentary rocks of the Zagros earth crust with a total thickness of about 10 km are deformed independently above the cover of the Hormuz evaporite formation widely represented in this region (see, for example, (Ford, 2004; McQuarrie, 2004)). The second suggests that the foundation of the Zagros earth crust should also be involved in this deformation based on the interpretation of joint geological and seismic data on the basement structure (see, for example, (Mouthereau et al., 2007, 2011, 2012; Allen et al., 2013)). We favor the second point of view, and we will demonstrate this by an analysis of the geological profile through the Fars Province in the southeastern part of Iran (Allen et al., 2013).

The southwestern end of the profile (point A, see Fig. 2) is in the Persian Gulf at a distance of about 45 km from the coastline and at a distance of about 70 km from the Zagros Front Fault (ZFF in Fig. 2), which defines the southwestern end of the Zagros FTB. This regional southern end of Zagros is a distinct topographic front of the outcrops of the Oligocene–Miocene limestone called the Mountain Front (McQuillan, 1991). It was interpreted as indicating the position of a large, albeit segmented, axial front that runs along most of Zagros and is called the Zagros Front Fault (ZFF). The current activity of this fault is indicated by a fairly high level of seismicity in its immediate vicinity (Berberian, 1995).

The opposite, northeastern, margin of the Zagros FTB is represented by the HZF (Fig. 2). It is marked by outcrops of the Bangestan limestone. The early Tertiary layers break off to the northeast of it, and overlapping outcrops of Triassic–Cretaceous organogenic siliceous rocks are found on the surface (see radiolarite group, Fig. 3). The High Zagros Fault in this area is interpreted as a southwest-trending low-angle thrust fault under the base of a cover containing the radiolarite group and extending to the basement (Authemayou et al., 2006). The seismic activity of this fault is low.

The Zagros FTB is between these two faults. The upper ~10 km of the earth's crust belt, composed of Early Cambrian–Miocene sedimentary deposits, is represented in the surface outcrops of the Mesozoic–Cenozoic mixed carbonate–clastic sequence (McQuillan, 1991). These sediments contain layers of evaporites at different depths that separate the surface deformation of the belt from the basement (Barbarian, 1995).

This sedimentary layer is represented along the AA' profile by folds supporting each other and slightly overturned to the southwest. These folds are the result of subduction of the Arabian Plate under the Iranian Plate (as part of the Eurasian Plate). Small thrust faults that can be observed along the left sides of the folds (see Fig. 3) should be considered in our opinion as the northeast underthrusts of sedimentary material during this continental collision. The total shortening of the transverse dimensions of the FTB in the Fars Province on this profile is 65–78 km over the last 5–10 Myr according to (Mouthereau et al., 2007, 2011, 2012; Allen et al., 2013).

Limestone is exposed in the cores of the anticlines of the folds. The distance between the cores of the folds is on average about 15 km. The nature of orogeny at great depths remains unclear because, at depths of about 10 km, the fold belt is underlain by a 1–2 km layer of evaporite rocks of the Hormuz Formation, along which there is a fault of the folded cover relative to the basement according to some authors (e.g., (Ford, 2004; McQuarrie, 2004)).

However, the existence of a series of faults penetrating deeper into the basement (see Fig. 3) rather contradicts this assumption. Thus, for example, it is considered definitely established that the northern boundary of the fold belt in the form of the HZF fault penetrates to great depths down to the lower crust (see Fig. 3). The seismogenic MFF, with a depth of 20 km or more, stands out within the boundaries of the Zagros FTB, about 140 km south of the HZF fault. It is considered one of the most serious seismic thrusts in the Zagros basement (Berberian, 1995; Hessami et al., 2006).

Its trail on the surface roughly coincides with the regional topographic contour of 1250 m, which serves as the northeast boundary of the spread of active seismicity within the Zagros fold belt (Allen et al., 2013). There are a number of foci of quite strong earthquakes, up to $M \approx 6$, on the fault itself. Therefore, it is assumed that the fold belt zone, subjected to significant inelastic deformations, extends to the depth of penetration

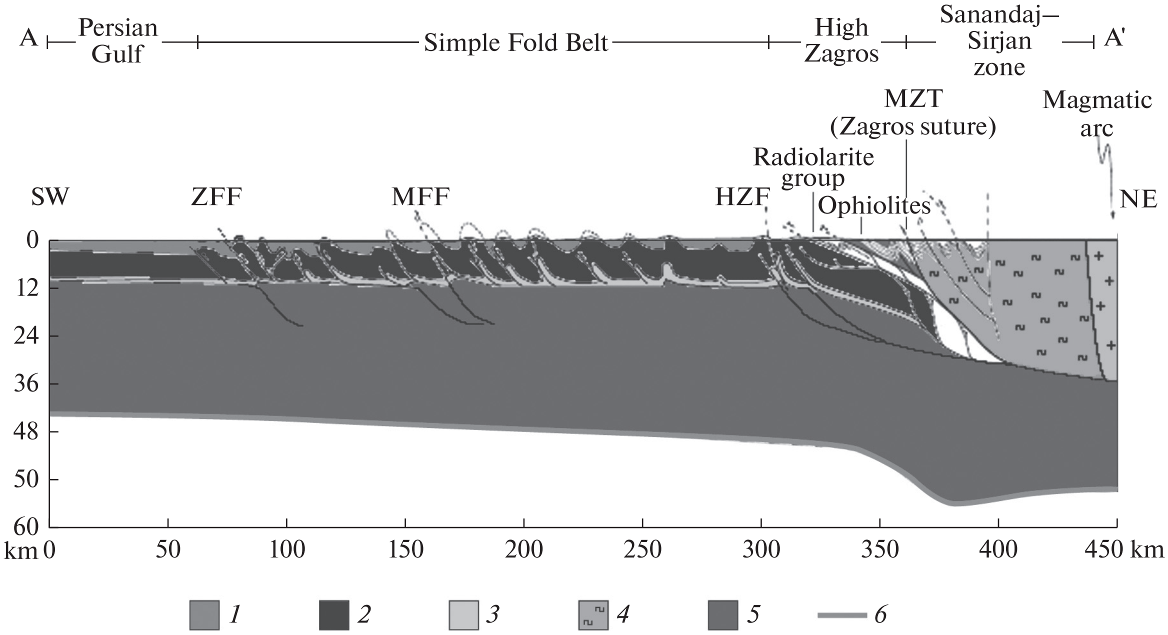

Fig. 3. Geological section through the Fars Province (fragment of Fig. 4 from (Allen et al., 2013), revised). (*1*) Quaternary rocks, (*2*) Miocene deposits, (*3*) Hormuz sequence of evaporites, and (*4*) metamorphic basement of the Sanandaj–Sirjan zone (Eurasia); (*5*) metamorphic foundation of the Arabian Plate; and (*6*) Moho boundary. The position of the section A–A' is shown in Fig. 2. The vertical scale is twice as large as the horizontal. Designations of faults are given in Figs. 1 and 2

of this fault, i.e., down to ~20 km (Adams et al., 2009; Nissen et al., 2011; Allen et al., 2013).

The middle part of the Kazerun–Borazjan strike-slip fault zone is also seismically active. There were strong (up to M8) earthquakes in the preinstrumental period and paleoseismic events in the Holocene–Paleogene within its boundaries (Berberian, 1994, 1995; Berberian, Geats, 1999). The maximum depths of earthquake foci in this zone are 23 km according to detailed high-precision observations near the Bushehr NPP (Rebetsky et al., 2017).

EVALUATION OF THE STRESS-STRAIN STATE OF THE AREA UNDER STUDY ACCORDING TO THE LITERATURE DATA

The current activity of the Kazerun Fault System (KFS in Fig. 2) is confirmed by data on historical and instrumental earthquakes that occurred here. The foci of these earthquakes are on different parts of the KFS (especially on the Kazerun and Kareh Bas faults) and are associated primarily with right-lateral strike-slip focal mechanisms (Berberian, 1995; Talebian and Jackson, 2004), which is in good agreement with right-lateral strike-slip tectonics within this system (see Fig. 2).

At the same time, it can be argued that the rest of Zagros (within the territory under consideration) is characterized mainly by thrust-fault focal mechanisms according to the seismological data from the Global CMT Project catalog (http://www.globalcmt.org/), which is in good agreement with tectonic movements along the faults in the form of thrust faults (underthrusts) within the western (Dezful province) and eastern (Fars Province) parts of Zagros (see Fig. 2).

Figure 4 shows the distribution of types of focal mechanisms of earthquakes with $M = 4.5–6.5$ for 1977–2015 according to the Global CMT Project catalog within a wide area near the Bushehr NPP (region II in Fig. 1) in the following coordinate system: angle of inclination with the horizon of the main pressure axis P along the X axis and the angle of inclination with the horizon of the main tension axis T along the Y axis. As follows from the data presented in Fig. 4, there is a clear clustering of focal mechanisms for the following types: thrust faults, strike-slip faults, normal dip-slip faults, and reverse dip-slip faults. At the same time, there are no mechanisms of intermediate types: thrust and strike-slip faults and oblique-slip faults. The number of mechanisms of different types for a total number of 191 events is as follows: about 72% are thrust faults, 24% are strike-slip faults, 2% are normal dip-slip faults, and 2% are reverse dip-slip faults. The apparent predominance of thrusts argues for the thrust tectonics in Zagros, which we have demonstrated in describing the tectonic situation in this region. The spatial distribution of earthquake epicenters with the prevailing types of focal mechanisms (thrust faults and strike-slip faults) is shown in Fig. 5.

As can be seen from the data presented in Fig. 5, the strike-slip faults are concentrated within the Kazerun zone of tectonic strike-slip faults that separates West and East Zagros. The thrust faults are dis-

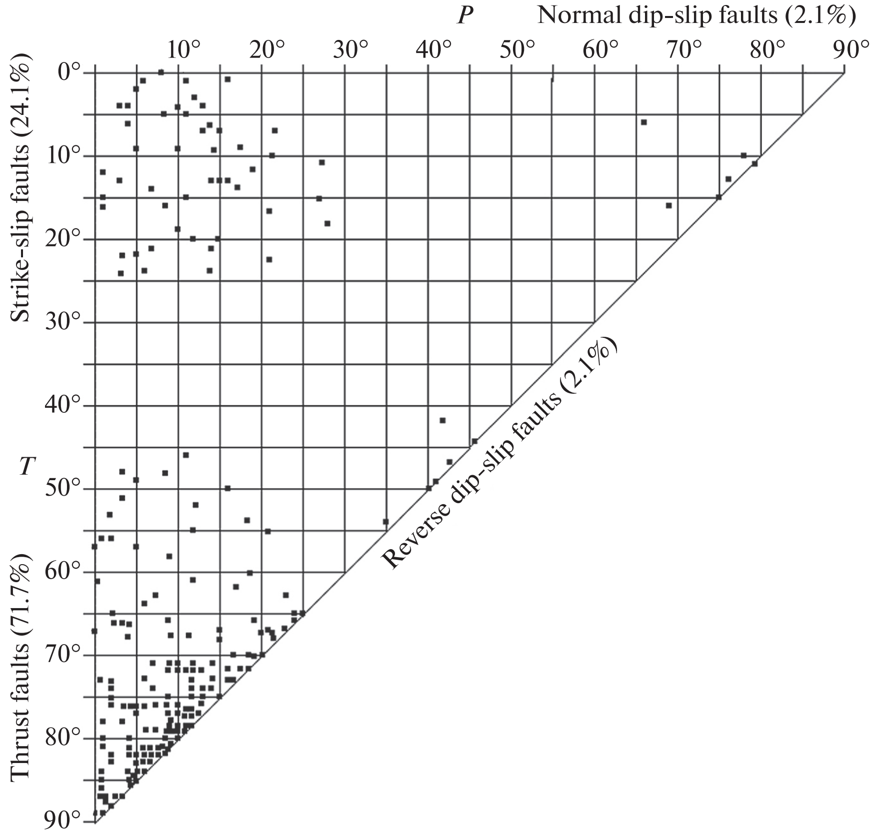

Fig. 4. Distribution of the angles of inclination with the horizon of the main axes *P* and *T* of the focal mechanisms of earthquakes with $M = 4.5–6.5$ for the period 1977–2015 according to the Global CMT Project catalog (http://www.globalcmt.org/) within a wide area of research near the Bushehr NPP (region II in Fig. 1). Total number of events, 191.

tributed approximately evenly throughout Zagros, which once again confirms that the Zagros Mountains are "crushed" and, accordingly, shortened in the process of convergence of the Arabian Plate and the rigid block of Central Iran. The same is evidenced by the type of the average mechanism constructed based on the complete set of all the focal mechanisms of Zagros earthquakes over a specified period of time using the method of S.L. Yunga (1979, 1990). The graphic view of this solution is presented in Fig. 6, and its design parameters are given in the upper part of the table.

The solution is determined quite reliably, which can be seen from the clear separation of the exit points of the individual axes of the main compressing and tensile stresses on the surface of the focal sphere. This is also indicated by the relatively high value of the coefficient *k* (0.69), showing a high degree of agreement of the individual focal mechanisms with the average solution obtained from them. Near-horizontal compression with a large thrust component (μ_M = +0.308) prevails in the Zagros earth crust according to Fig. 6 and Table 1, because the main tension axis *T* is oriented almost vertically in the case of the horizontal position of main pressure axis *P*.

An assessment of the types of average mechanism carried out separately for the thrust and strike-slip seismotectonic faults (this separation was carried out according to Fig. 3) is shown graphically in Fig. 7 and in the numerical values in Table 1. Both solutions turned out to be extremely stable, as is evidenced by both a clear separation of the exit points of the individual axes of the main compressive and tensile stresses on the focal sphere and high values of the coefficient *k* (0.81 and 0.67, respectively). The latter indicates a high degree of agreement of individual focal mechanisms with the average solutions obtained from them. The high stability of the determination of the azimuth of the main pressure axis *P* (29°–32°) regardless of the type of individual focal mechanisms in the three considered samples should also be noted. It is noteworthy that this azimuth is somewhat different from the direction of the displacement vectors (7°–12°) of the GPS geodetic points shown in Fig. 2.

It can be assumed that the solutions shown in Fig. 7 correspond to genetically different types of deformation of the earth's crust within the area under consideration. Thus, the solution in Fig. 7a describes the nature of the fold–thrust deformation of the cover of the earth's crust typical of Dezful and Fars Provinces

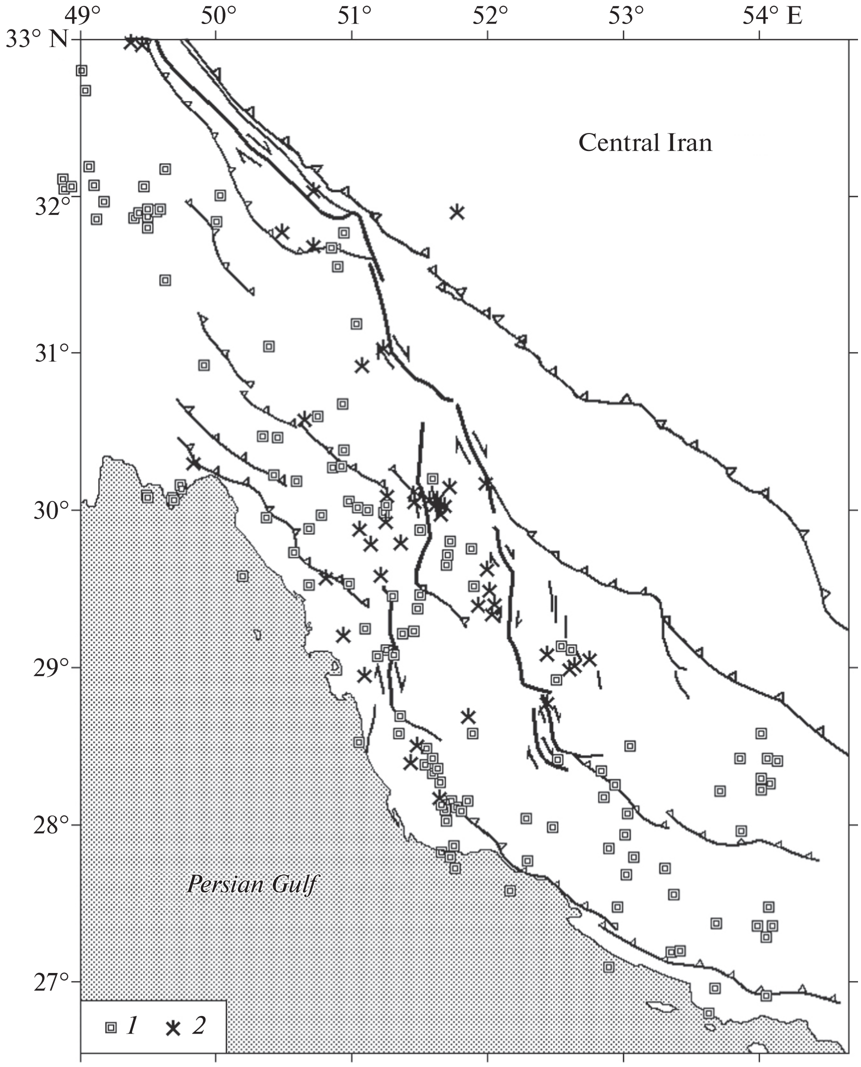

Fig. 5. Spatial distribution of earthquake foci with thrust and strike-slip mechanisms in the studied region for the period 1977–2015 according to the Global CMT Project catalog (http://www.globalcmt.org/). The tectonic base is given in accordance with Fig. 2. (*1*) Thrust faults and (*2*) strike-slip faults.

(shown on the geological profile transverse to the strike of folding in Fig. 3). In turn, the solution shown in Fig. 7b is characteristic mainly of the strike-slip zone directly near the Kazerun Fault. It is within this zone that the vast majority of earthquake foci with a strike-slip type of focal mechanism are concentrated (see Fig. 5).

RESULTS OF A RECONSTRUCTION OF EARTHQUAKE FOCAL MECHANISMS ACCORDING TO THE LOCAL NETWORK OF SEISMIC STATIONS IN A WIDE AREA NEAR BUSHEHR NPP

Special seismological studies were carried out by a research team from the Institute of Physics of the Earth of the Russian Academy of Sciences to assess the seismic hazard for the Bushehr NPP constructed on the Persian Gulf coast in 1999–2001. A network of eight seismic stations was established in the zone of convergence of Dezful and Fars tectonic provinces (north of the Bushehr NPP) in an area of 100 × 100 km (Fig. 8). One of the main results of this network is the reconstruction of earthquake focal mechanisms in the range of magnitudes $M_b = 0$–4.

Focal mechanisms were detected using a combination of signs of longitudinal waves *P* and the direction of polarization of transverse waves *S* according to the original method developed specifically for this purpose by Rebetsky et al. (2017). The use of this method has significantly expanded the possibilities of determining the focal mechanisms of low-magnitude seismic events and thereby expanded the statistics of such determinations at the site of the local seismic network aimed at solving a specific practical problem, i.e.,

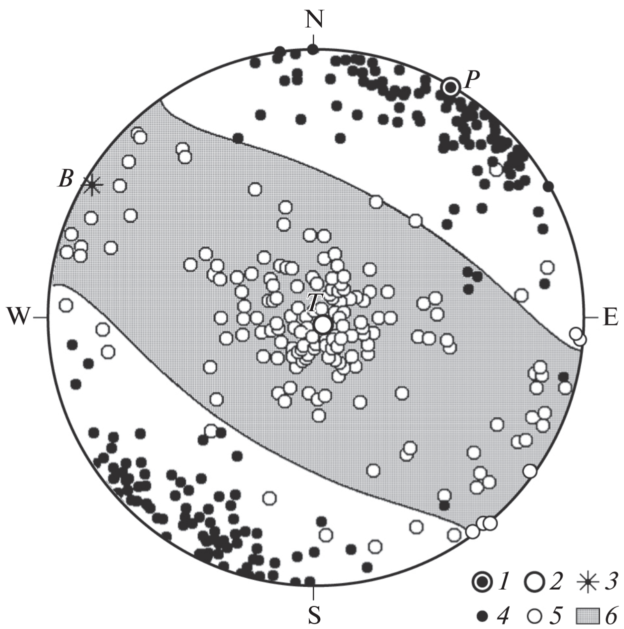

Fig. 6. Graphical solution for the average mechanism of Zagros earthquake foci (Iran) constructed based on the complete set of individual focal mechanisms for the period 1977–2015 according to the Global CMT Project catalog (http://www.globalcmt.org/). (*1*) Position of the axis of the main pressure load *P* on the lower focal hemisphere, (*2*) position of the main tension axis *T*, (*3*) position of the axis of the intermediate stress *B*, (*4*) position of the main pressure axes of the individual focal mechanisms on the lower hemisphere, (*5*) position of the main tension axes of individual focal mechanisms, and (*6*) tension region.

assessing the seismic hazard of the construction area of the Bushehr NPP. The degree of uncertainty in determining the onset of the *S*-wave was often quite high because we mostly used records of weak ($M_b < 4$) local events. Thus, it was impossible in most cases to measure the signs of the first onsets of *S*-waves. Therefore, only the direction of oscillations in the *S*-wave (polarization) calculated for different parts of the seismic recording of this wave was determined.

The location of the network of seismic stations, the results of the reconstruction of the focal mechanisms of weak nearby earthquakes for the period 1999–2001, and summary rose diagrams for azimuths and inclination angles of the axes *P* and *T* are shown in Fig. 8a. It can be seen that the most representative for the *T* axis pitch are the directions of 150° and 330°, and the most frequently encountered pitch angles are 10° and 55°. The 50° and 230° directions are the most representative for *P* axis traces. *P* axes have a low-angle pitch almost everywhere with the most pronounced value of 5°.

Figure 8b shows a diagram characterizing the distribution of different types of mechanisms in the kinematic (geological) interpretation, as well as a graphical method for separating mechanisms into kinematic types (six types). As can be seen, thrust faults (reverse dip-slip faults) and strike-slip faults are the most common. The same prevalence of types of mechanisms is also noted when considering the focal mechanisms from the Global CMT Project catalog (see Fig. 4). In general, the “kinematic portraits” of the sets of focal mechanisms of weak earthquakes (M_b = 1.5–3.5) near

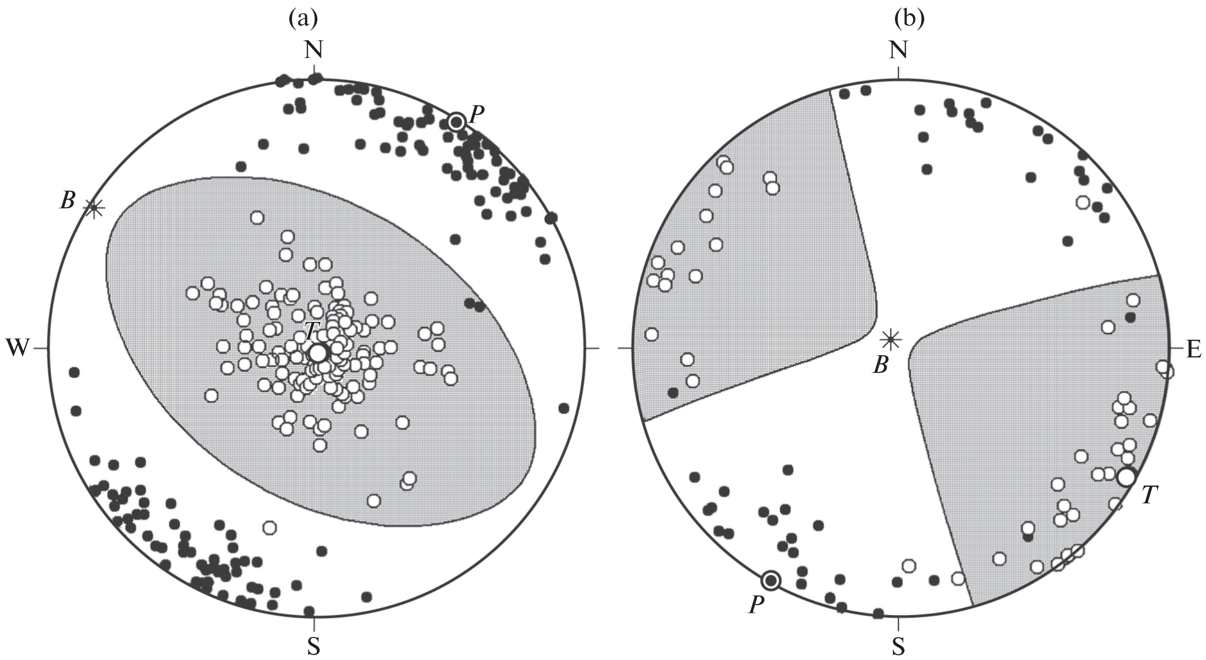

Fig. 7. Graphical solutions for average Zagros earthquake focal mechanisms constructed separately by sets of thrust (a) and strike-slip (b) individual focal mechanisms for the period 1977–2015 according to the Global CMT Project catalog (http://www.globalcmt.org/). Notation is the same as in Fig. 6.

Table 1. Main parameters of the calculated tensor of the average focal mechanism of Zagros earthquakes (Iran)

N	Orientation of the main axes of the average mechanism tensor, deg.						μ_M	*k*
All types of mechanisms								
	P		*T*		*B*			
214	Azimuth	Angle	Azimuth	Angle	Azimuth	Angle	+0.308	0.69
	031	01	135	87	301	03		
Thrust faults								
	P		*T*		*B*			
136	Azimuth	Angle	Azimuth	Angle	Azimuth	Angle	–0.061	0.81
	032	01	158	88	302	02		
Strike-slip faults								
	P		*T*		*B*			
67	Azimuth	Angle	Azimuth	Angle	Azimuth	Angle	–0.021	0.67
	209	02	119	04	320	86		

N is the number of individual focal mechanisms in a given sample; *P*, *T*, and *B* are the main axes of pressure, tension, and intermediate stress, respectively (their angles of inclination are measured from the horizon). The Lode–Nadai parameter (μ_M) describes the type of stress-strain state and changes from –1 (uniaxial tension) through 0 (strike-slip fault in the mechanical sense) to +1 (uniaxial compression). Coefficient *k* shows the magnitude of the correspondence of the aggregate of individual mechanisms to the average solution and varies from 0 to 1.

Bushehr (see Fig. 8) and relatively strong (M_b = 4.5–6.5) according to the Global CMT Project catalog are close to each other. Nevertheless, it should be noted that the distribution of the number of events according to the types of focal mechanisms is more diffuse for weak events (there are intermediate motion types, i.e., reverse dip-slip faults and normal dip-slip faults) when compared to those for stronger events. According to the results of calculations for weak events, no mechanisms were obtained in the form of pure normal dip-slip faults (a small number of which are among the strong seismic events according to Fig. 4). However, there were a sufficient number of weak events (six) in the form of dip-slip faults with mechanisms similar to them.

Note also the reverse dip-slip fault mechanisms (one of the nodal planes is subvertical, and the second is very flat) of weak seismic events, most of which are manifested in the crust of the coast of the Bushehr Peninsula. The possibility of their existence is indicated by geological structures such as reverse dip-slip faults, which are elongated latitudinally, with rather steep, almost vertical walls and a height of several tens of meters. A comparison of the solutions obtained by us for the focal mechanisms of weak earthquakes with these reverse dip-slip faults suggests that here the vertical nodal plane is implemented in the earthquake mechanisms; i.e., earthquake mechanisms are of reverse fault type.

DISCUSSION OF RESULTS

The results of calculations of the sets of focal mechanisms of earthquakes in Southern Iran showed that the kinematic types of mechanisms of earthquake foci in the crust of the region under study significantly differ on different sides of the Kazerun–Borazjan fault zone. Thus, the crust of the zone itself is predominated by strike-slip earthquake focal mechanisms. Modern concepts about the tectonic deformation of the Zagros earth crust outlined above make it possible to assume that the south and southeast movement planes were mainly implemented in these strike-slip fault mechanisms. Earthquake focal mechanisms in the form of thrust faults and reverse dip-slip faults are observed to west of the considered fault zone in the continental part of the coast of the Persian Gulf and near the Delvar–Mand fault zone (see Fig. 8). There is a combination of mechanisms in the form of strike-slip faults and reverse dip-slip faults for the Bushehr Peninsula in the zone of transition from the continental crust to the crust of the Gulf. Note that the presence of reverse dip-slip faults is not typical for other parts of the Zagros earth crust.

Such a division of the kinematics of seismotectonic deformation was noted by us earlier when discussing the spatial distribution of the thrust and strike-slip focal mechanisms according to the Global CMT Project catalog (http://www.globalcmt.org/) for stronger ($4.5 \leq M_b \leq 6.5$) earthquakes for the period 1977–2015 (Figs. 5, 7). This can indicate the general credibility of information about the nature of the deformation of the earth's crust obtained by us using the above-described method. Consequently, the proposed method for the reconstruction of focal mechanisms can be applied in other regions.

It follows from the faulting tectonics shown on the map (see Fig. 2) that the Kazerun Fault is a western boundary of the area of horizontal strike-slip faults,

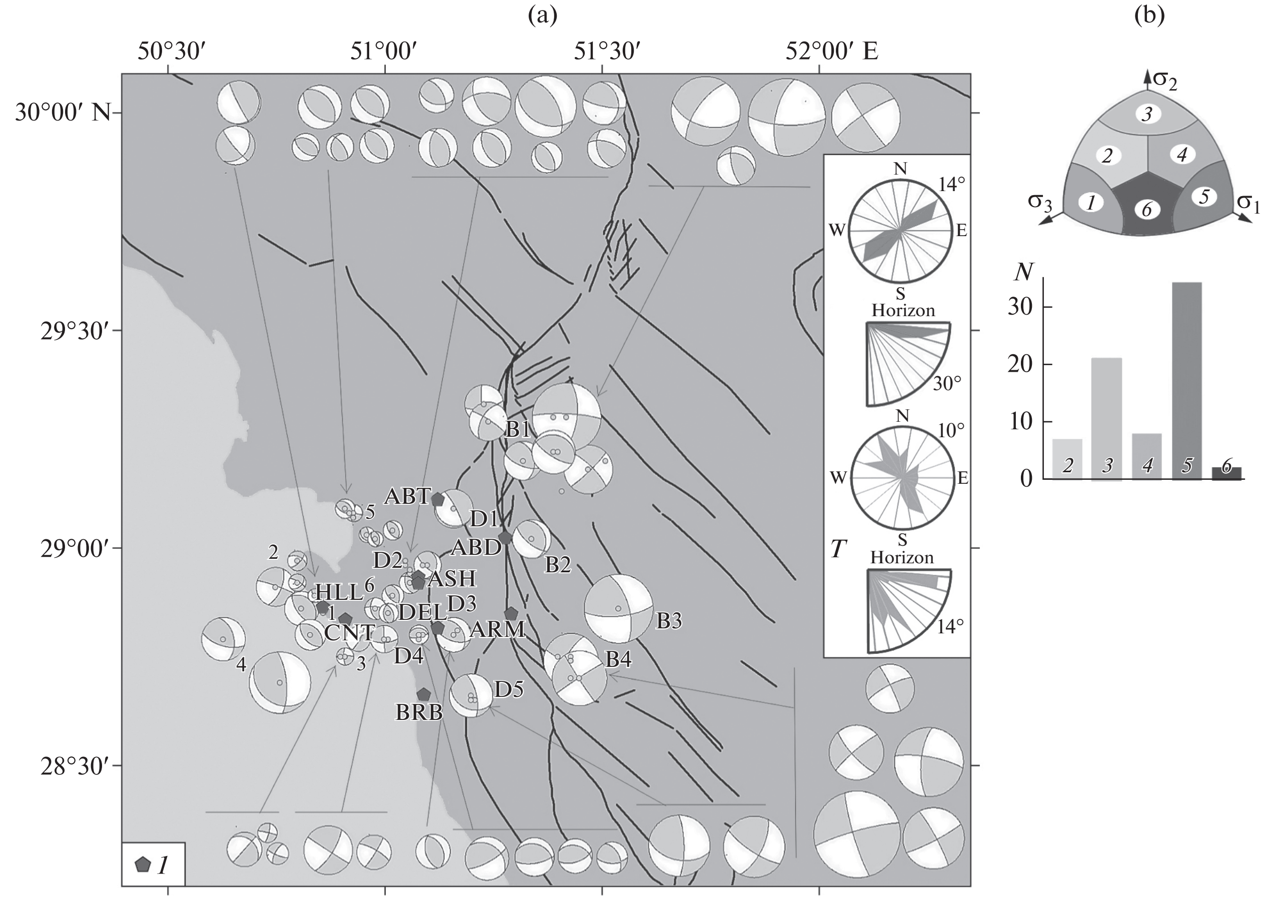

Fig. 8. Distribution of the mechanisms of earthquake foci with M_b = 1.5–3.5 in the studied area in the double dipole approximation for seismic event clusters (Fig. 5 from (Rebetsky et al., 2017), amended and revised). (a) Different clusters (*1–6*) of seismic events in the earth's crust in the immediate vicinity of the Bushehr Peninsula. B1–B4 are clusters of the Borazjan flexural fault zone. D1–D5 are clusters of the Delvar–Mand fault zone to the east of the Bushehr Peninsula. Some of the focal mechanisms for these clusters are given closer to the figure frame. Earthquake foci are shown above the mechanisms. (*1*) Seismic stations. The inset shows rose diagrams for the most representative strike angles and the pitches of axes *T* and *P*. (b) Graphical method for classifying mechanisms by kinematic types (areas of different colors determine the position of the axis to the zenith: (*1*) dip-slip fault, (*2*) normal dip-slip fault, (*3*) strike-slip fault, (*4*) reverse dip-slip fault, (*5*) reverse fault (thrust fault), (*6*) subvertical fault) and their representativeness diagram.

which descends from the foothills of High Zagros to the south and extends to the east in the form of a horse tail. The view of the zone itself and the earthquakes occurring in it (with a decrease in magnitude to the south) indicate that the intensity of the strike-slip faults is maximum in the north, in the foothills of the High Zagros, and gradually fades to the south. Here, the thrust component begins to prevail over the strike-slip one. As was already noted, each strike-slip branch of the Kazerun–Borazjan fault zone is, as it were, locked at its southern end by the corresponding thrust fault. It is likely that the thrust faults at the junction of the Kazerun–Borazjan strike-slip fault zone with the Major Front Fault (MFF) should be considered as the southern boundary of this regional strike-slip fault zone.

This complex combination of faults with significantly different kinematics of movement along them most likely determines the significantly greater variety of the abovementioned kinematic portrait of the sets of focal mechanisms of weak earthquakes compared with strong seismic events.

CONCLUSIONS

This paper compared the results of the reconstruction of focal mechanisms based on the algorithm developed earlier by Rebetsky et al. (2017) that uses *S*-wave polarization with modern concepts about the tectonic deformation of the earth's crust in a wide area near region under study. The need to develop such an algorithm arose due to insufficient information about the signs of the first arrivals of *P*-waves for determining the focal mechanisms of weak earthquakes (M_b = 0–4.0).

The specificity of the geodynamics of the area under consideration consists of the fact that the kinematic types of mechanisms of earthquake foci within the crust of the region under study differ significantly on different sides of the western edge of the Kazerun–Borazjan fault zone. This is established both by the focal mechanisms of weak earthquakes determined using the proposed method and by the focal mechanisms of relatively strong earthquakes ($M_b \geq 4.5$) determined using the standard method. Strike-slip mechanisms dominate in the crust of the fault zone itself and thrust mechanisms dominate to the west of it.

The coincidence of estimates of the motion type in the earthquake foci of the studied area for weak and strong earthquakes indicates the reliability of information that we obtained using the proposed method for determining the nature of deformation and the motion type of the earth's crust.

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