UDC 551.24

STRUCTURAL MODEL AND TECTONIC EVOLUTION OF THE FAULT SYSTEM IN THE SOUTHERN PART OF THE KHUR AREA, CENTRAL IRAN

Arash SOHRABI [1], Alireza NADIMI [2], Irina V. TALOVINA[1], Homayon SAFAEI[2]
[1] *Saint-Petersburg Mining University, Saint-Petersburg, Russia*
[2] *University of Isfahan, Isfahan, Iran*

In the southern part of the Khur area, there is faults system with predominantly North-West strike. This network of tectonic disturbances is one of the most important fault systems in Central Iran which crosses Paleozoic metamorphic rocks, Cretaceous limestones, and Eocene volcanic rocks. Interpretation of satellite imagery ETM+ (Enhanced Thematic Mapper plus, Landsat) and field observations showed the presence of left-lateral shifts along with fault system. This formed the structure of the branch faults at the northeast end of the main fault. Another feature associated with shear dislocations is the rotation of blocks in the northeastern and southwestern segments of the area under study. There are several basins and positive structures within the area such as a series of uplifts and thrusts, indicating the presence of compressional and extensional tectonics.

Another part of the work is devoted to the study of the correlation between active faults and earthquakes. Processing of satellite images, field observations, records of micro-earthquakes within a radius of 17 km made it possible to analyze the earthquakes parameters and the position of tectonic disturbances, and, as a result, confirm the presence of active faults in the region. In addition, we have identified three successive stages of the Khur area tectonics: rifting, contraction, change of convergence and uplift direction.

***Key words*:** horsetail splay; block rotation; upthrust; overthrust; structures; earthquake; tectonic evolution; Iran; Khur; Ordib

***How to cite this article*:** Sohrabi A., Nadimi A., Talovina I.V., Safaei H. Structural Model and Tectonic Evolution of the Fault System in the Southern Part of the Khur Area, Central Iran. Journal of Mining Institute. 2019. Vol. 236, p. 142-152. DOI: 10.31897/PMI.2019.2.142

Introduction. The Alpine-Himalayan (Mediterranean) belt is one of the most significant intercontinental fold systems on the planet [15]. Iran and the surrounding areas are a mosaic of lithospheric blocks separated from each other by complex fold-thrust belts located within the Alpine-Himalayan orogenic system [5].

Central Iran is one of the main structural units, which is located in the north-east of the Urumieh-Dokhtar magmatic arc, as well as between the Arabian and Eurasian plates moving towards each other. This microcontinent is bounded by large faults and Mesozoic and Triassic ophiolite, which are fragments of the last generation of the Palaeo-Tethys Ocean [17]. Central Iran includes the following main blocks of the Earth's crust (Fig.1, from East to West): Lut, Tabas, Kalmard, Posht-Badam, and Yazd [1]. The Lut block is located between the Nehbandan faults in the East and Nayband in the West. The Tabas block is surrounded by the Nayband faults in the East and Kalmard and Kuhbanan faults in the West. The Yazd block is located between the Kuhbanan faults in the East, Ordib in the North and the Rafsanjan and Shahr-Babak faults in the South and West [13]. The Ordib area refers to the Yazd block and the Great Kavir Fault. The Ordib and Chapedoni faults are the largest tectonic disturbances of the area under study and one of the longest and most well-known faults of Iran, which cross alkali basalt intrusions and play an important role in regional tectonics [16].

In terms of tectonic settings, the Khur area is located on the North-Western edge of the Central Iranian microcontinent and in the North-Eastern part of the Urumieh-Dokhtar magmatic arc. This territory is characterized by the unique preservation of the Neo-Tethys back-arc rifting, the Late Jurassic – Eocene drift and collision, and syngenetic formation of igneous and metamorphic rocks. The complexity of Central Iran geological structure has no analogs in the region [3].

 DOI: 10.31897/PMI.2019.2.142

Tectonic disturbances of the region are large faults of the North-Eastern strike (Fig.1). These faults cross Mesozoic and Cenozoic sedimentary rocks, and in some places, Pliocene rocks up to Quaternary sediments. The majority of these faults are currently active. Due to shear dislocations – horizontal displacements of ridges, alluvial sediments, stream channels, and tectonic structures are observed along faults. Extended geological outcrops, located parallel to large faults, allow precise determination of the orientation of the slip plane, wih dip angles generally varying from 60 to 90°. The network of tectonic disturbances, formed in the Upper Cenozoic and Quaternary, is part of the Northeastern faults system – left-lateral shifts that cross the upper continental crust of the Iranian plateau. All faults of the Northeast strike within the Khur region are parallel to the Great Kavir Fault. The 160 km long Ordib fault, considered in this article, extends from the Northeastern Garmeh to the Southwestern Kabudan village [6].

Formulation of the problem. The article describes the main faults of the Northeastern strike, their geological and geomorphological characteristics. We have also indicated the shear components along the fault planes and structures associated with the shifts in Central Iran. This dislocation system was described for the first time and is considered taking into account the impact of the main fault systems located on the Northwestern margin of Central Iran (Fig.1).

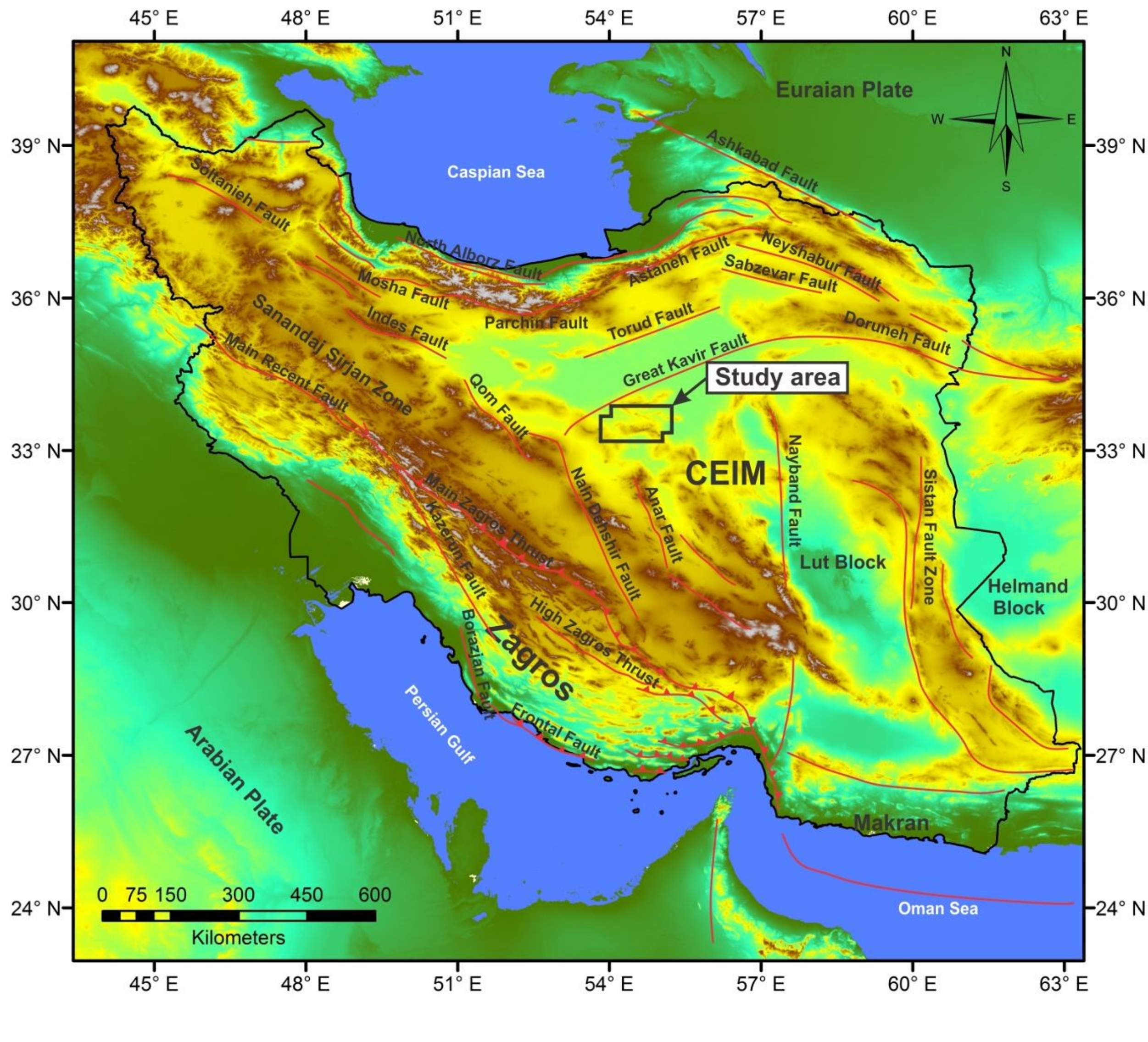

Fig.1. The main fault systems and the position of the Khur region in Iran's digital elevation model
CEIM – Central Eastern Iran microcontinent

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Research methods. The preparatory stage of the research included the collection of the previous studies results, remote sensing data, paleoseismological data, and the verification of these materials with geological maps. At this stage, we have used Landsat 7 satellite images (ETM +) with further processing in the ER mapping software (ER Mapper). This allowed us to mark lineaments and highlight active faults.

After collecting information in field studies, the following characteristics of large faults were studied based on the obtained satellite maps: geological features, such as slickensides along the fault planes, zone of crush and shift zone of rock blocks, the faults strike direction. The occurrence of the longest and most wide-open cracks was measured using a geological compass, while their coordinates were recorded using GPS.

Further, the obtained field data were analyzed along with other information. The fracture chart is depicted as a stereonet projection using the FaultKin5 WinBeta-e software to detect and analyze fractures and faults. Software for fracture chart construction allows us to distinguish preferential directions of tectonic stresses. To indicate the current tectonic activity of the area under study, a number of morphological and tectonic factors were studied, including: foothill ridges, the ratio of the width of the valley bottom to its height, the ratio of the valley width to its height, the displacement of rivers, terraces and eroded triangular elevations, the speed of tectonic activity.

Geological structure of the region. ***Stratigraphy.*** The Khur area is composed of various rocks with age varying from Upper Proterozoic to Cenozoic. The southern part of the region (the Cha Palang – Bayazekh zone) is characterized by the most complete stratigraphic sequence represented by the Proterozoic, Paleozoic, and Mesozoic rocks. In the South-Eastern part of the area, there is a folded region adjoining the periphery of the Posht-Badam complex, which consists of Upper Proterozoic and Lower Paleozoic marbles and dolomites. Almost half of the area is occupied by intermountain basins filled with Neogene-Quaternary sediments. The oldest rocks in the Khur area are Upper Proterozoic gneisses, schists, and other metamorphic rocks of the Agedoni and Jendek complexes. Young and less metamorphosed under the greenschist facies conditions, the Upper Proterozoic and Lower Paleozoic metamorphic rocks of the Anarak complex are subdivided into Chakh Gorbe, Kabudan, and Pateyar [18]. Late Paleozoic and Triassic terrigenous-carbonate formations (Niur, Padekh, Sibzar, Bahram, Shishtu, Sardar, Jamal) and other units characterized by strong facies variability and weak metamorphism are also common. In the southern part of the region, the Shemshak terrigenous formations of the Triassic and Jurassic are widespread. The Upper Jurassic-Neocomian formations of the Cha Palang zone are also exposed in the South of the region. The Early Cretaceous transgression covered the entire territory and led to the accumulation of terrigenous-carbonate and carbonate rocks of the Nogreh, Shah Kukh, and Bazyab formations, and the Biabanak and Mirza formations in the South-Eastern part of the region [10].

The Upper Cretaceous terrigenous-carbonate complexes of Debarsu, Khaftomun, and Farokhi formations are outcropped in the central and Northern parts of the area. The limestones of the Chupanan Paleocene-Early Eocene formation and the Dara Anji Lower Eoceneterrigenous formations are also exposed. Eocene volcanic rocks are widespread in the West, less often in the East of the region. In the North-Western part of the territory, they are overlapped and partially facially replaced by the gypsum-bearing rocks of the Pish Kuh stratum, forming diapir structures. The lower Kuma red sequences and the upper red formations are exposed in the limbs of the superimposed basins filled with Pliocene – Quaternary sediments [11] (Fig.2).

Tectonics. The Iranian segment of the Alpine-Himalayan orogenic system has a complex Permian-Quaternary history of sequential rifting and collision. However, most of the territory of Iran is represented by relatively conformable Paleozoic platform deposits, similar to the deposits of the Arabian platform. The area of research is characterized by a complex heterogeneous structure, a combination of ancient continental blocks, faults and narrow folds composed of rocks of the Meso-

DOI: 10.31897/PMI.2019.2.142

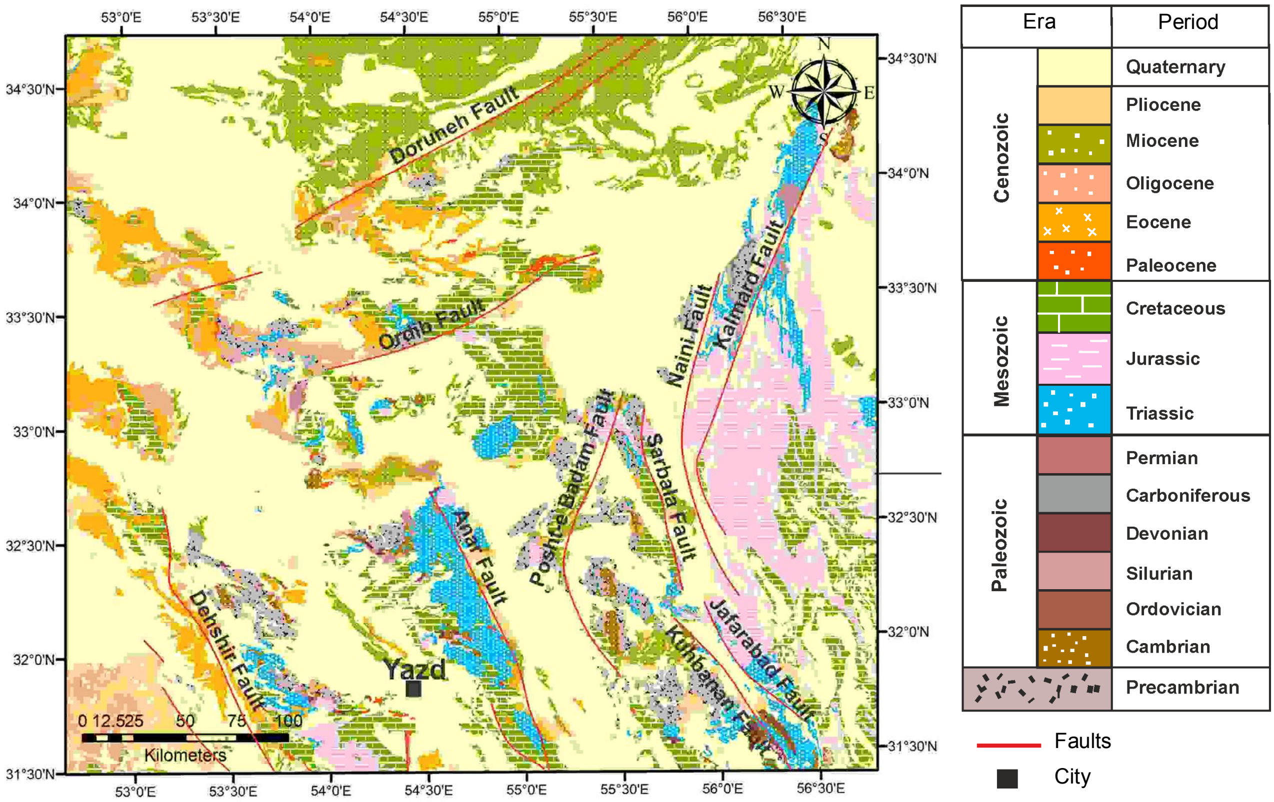

Fig.2. Major tectonic disturbances in the central part of Iran (the map of active faults within Iran territory (IIEES 2003) combined with the geological map of Iran [1])

Cenozoic complex [15]. The depressions and intermountain basins of the region were formed at a later Alpine time.

The Anarak-Khur massif is one of the main tectonic zones of the Yazd block. Central Iran as a typical junction structure was previously considered as a separate massif of medium size and, therefore, the zone itself was identified as the Khur platform [6]. The massif extends to the North-East for 250 km and reaches up to 75 km in width within the Khur region, where its central part is located. In the North-West, the massif is bounded by the Great Kavir fault, which separates the massif from the same-name depression, and in the South-East, it is separated from the Lower Cimmerian and Upper Alpine folded zones by the Ordib fault.

The faults play an important role in the formation of the tectonics of the region, dividing it into separate blocks. The main deep and long-lived faults divide the structural zones. They extend to the North-East, are clearly seen in the land topography and spread within hundreds of kilometers outside the region. Other faults, also classified as major, are not characterized by specific land topography and have a slight opening (Fig.2).

Models of tectonic structure of the Southern part of the Khur area. The tectonics of the Southern part of the Khur region is characterized by the major faults of the North-East strike, extending parallel to the Western part of the Dorune fault. The upthrow-shifts of the NW-SE trend are perpendicular to the Dorun fault. In the present article, we analyze the longitudinal dislocations identified within large faults, considering transverse uplifts and shifts as additional ones. Horizontal displacements of rocks, mountain ranges, alluvial sediments, stream channels, and tectonic structures associated with shear displacements were measured (Fig.2).

Major faults. *The Great Kavir Fault* is represented in the study area by its part of about 25 km in length. It is located to the North-West of the Pish Kuh Formation and in the South-West is buried under Quaternary sediments. The fault divides the Great Kavir depression and the Anarak-Khur massif. On the surface, it is a system of successive subparallel faults, forming in the Eocene-Miocene rocks a zone of 1-3 km in width, composed of narrow steep folds and small diapirs. The southeastern limb of the Great Kavir Fault is heavily distorted by a series of subparallel faults, some of which lie within the Middle and Upper Eocene rocks. Relicts of early Eocene andesite volcanism are also preserved on this limb. The North-Western limb of the fault consists of weakly deformed Miocene rocks that fill the depressions. Locally, the tectonic movements along this fault repeated in the Quaternary period [1].

The *Ordib Fault* borders the Anarak-Khur massif in the South-East. On the surface, the fault is represented by a series of subparallel vertical upthrusts, locally turning into steps falling to the north-west. The width of the fault zone ranges from a few hundred meters to 1.5-2 km. The size of the displacement decreases in the East, and the main branches of the faults transform into weak deformations that cut through almost all rock complexes from the Upper Proterozoic to the Neogene and even locally pass through Quaternary deposits [6].

Most of the *Chapedoni fault* is buried under the Pliocene-Quaternary sediments in the intermountaine basin. The directions of the fault's strike are N-NE. These faults extend to the South beyond the zone limiting the Posht-Badam complex in the West. On the surface, the rift coincides with a scarp. The Eastern raised limb is composed of the Upper Proterozoic schists and gneisses, and the lowered western limb is composed of Lower Cretaceous rocks and molasses of the Miocene [10].

Shear structures. *Ordib area*. Here, structures associated with shear displacements were detected using field data, geological maps, Landsat satellite images, and digital elevation models.

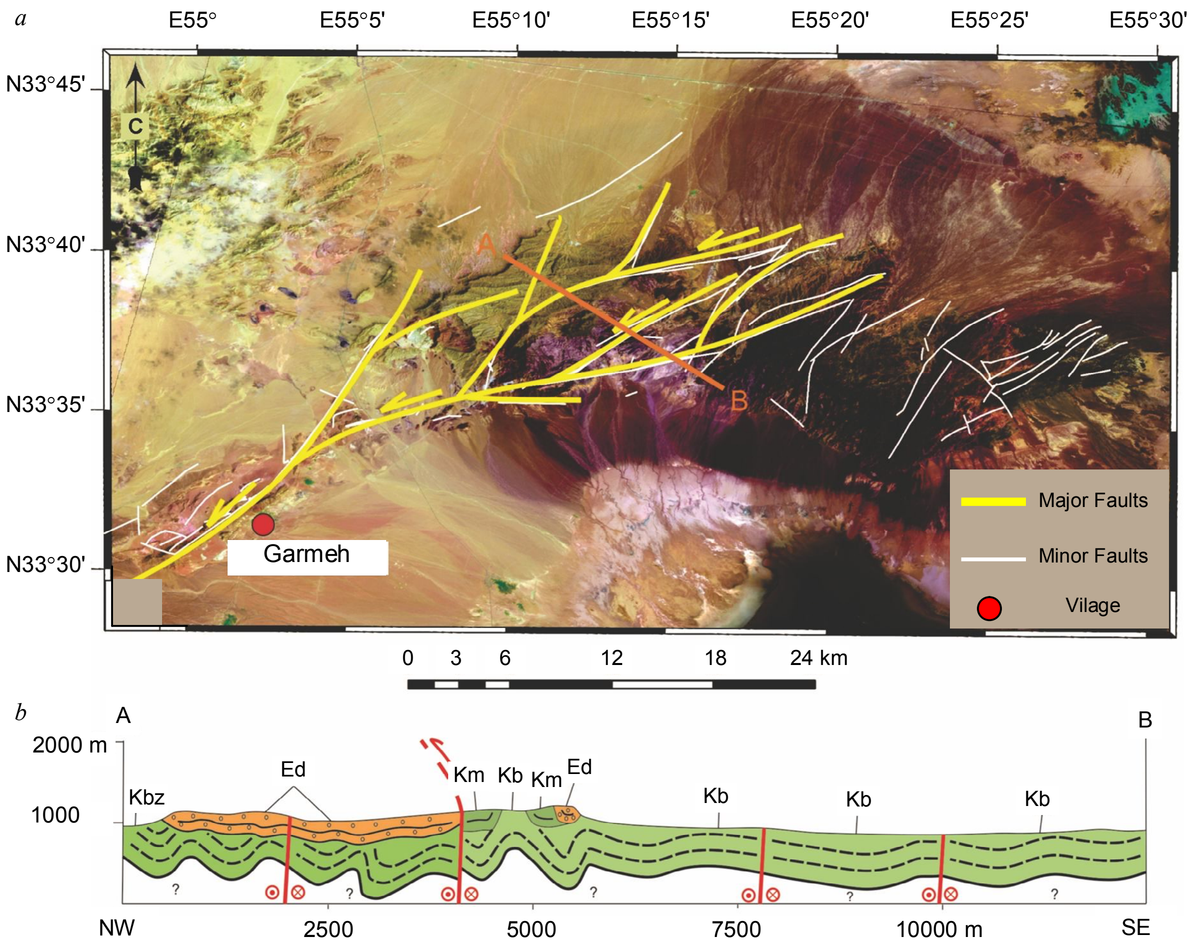

Fig.3. The position of major and minor faults on the ETM + map, which shows the horsetail splay in the North-East of the region
AB – the cross-section along the NW-SE direction; Kb – clay slates, laminated clay slates, marl, limestone; Kbz – Bazyab Formation, green-gray marl, mudstone, limestone, sandy limestone; Km – slate, limestone; shelly limestone and conglomerates at the base; Ed – gray conglomerates, sandstones, and marls

DOI: 10.31897/PMI.2019.2.142

The components of the shear displacements can be determined on the basis of various tectonic structures: rotation of blocks, branching faults, synthetic and antithetic faults on the periphery of major faults and horsetail splay faults.

Garmeh horsetail splay fault. Like any other dislocation, shifts may cease in zones of plastic deformation. In fragile rocks, the displacement is distributed along several branching faults. These minor dislocations, located obliquely to the direction of the main fault, form an open roof-tile-like structure called horsetail splay. Antithetic and synthetic faults formed on the periphery of major faults often have a slight vertical displacement in accordance with the divergent or convergent type of the fault system. A large divergent horsetail splay fault can be localized in sedimentary basins at the margins of major faults. Conversely, a convergent horsetail splay can display overthrusts and folds on the periphery of major faults [8].

The Ordib region consists of North-Eastern faults, which makes it possible to establish that most of them were formed and (or) reactivated during left-lateral shift along large faults. As a result of left-lateral shift, the horsetail splay structure was formed at the North-East margin of the Ordib fault (Fig.3).

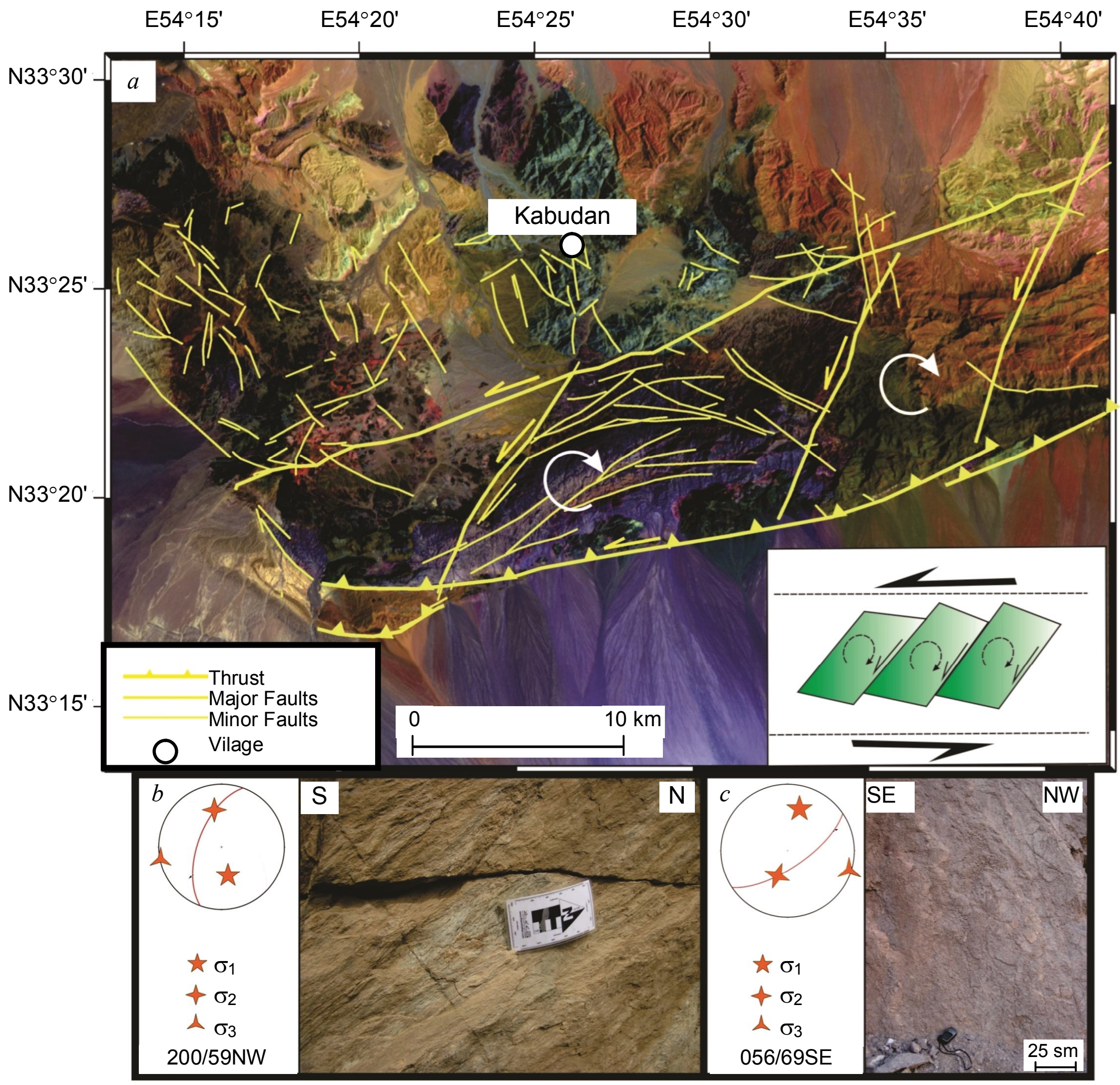

Fig.4. Kabudan tectonic area: *a* – model of the fault system and rotated blocks;
b and *c* – the stereonet projection of the fault plane (conjugate faults)
σ_1-σ_3 – main stress axes; the arrow shows the direction of movement along the sliding surface

Kabudan rotated block. As is known, the blocks separated by faults in shear zones in the continuation of the general shear movement should be rotated around the vertical axis. Two direct consequences of the deformation are possible: 1) shifting along each fault within the domain should be associated with the rotation of the blocks limited by these faults; 2) the faults themselves being the block boundaries should also rotate [12]. When the rotation becomes sufficiently intense, the shift on the rotating faults stops, because the allowed shear stress has decreased, and the normal stress has increased to a level when the friction resistance is too large for the further shift. To continue the Earth's crust deformation, it is necessary to form a series of new faults, more favorably oriented towards the direction of the regional stress field [9].

In the Kabudan region, the blocks rotate between faults clockwise around a vertical axis like dominoes of different sizes. This rotation is directly controlled by the orientation of the faults to the direction of tectonic compression (Fig.4).

Stages of the tectonic evolution of the Ordib area. According to the Allen et al. and Hogai et al. [2, 9, 14] data and the current analysis of the structures, three stages of the regional tectonic evolution were identified: rifting, convergence, change of convergence direction.

Rifting. In the Biabanak regions and north of Zabzevar, the rifting began in the Late Jurassic - Early Cretaceous and was evident by fractured zones and faults developed in parallel with the existing Dorun and Ordib Faults. In the Neocomian stage, the initial ocean began to open and take its present form. The study of pillow lavas and lamprophyres in the South-East of Nain [19] also shows that the Ordib Fault was associated with continental rifting (Fig.5).

Convergence. The oceanic crust was formed in the Albian stage and reached maturity at the end of the Cretaceous and Paleocene. In the middle of the Eocene, a subduction zone was formed with oblique motion at the southern margin of the oceanic crust under the Iranian plate. At the end of subduction and as a result of the Iran and Binalud plates collision at the end of the Eocene-Oligocene, the faults occurred in the Biabanak region were reversed [11] (Fig.6).

In addition, the collision of the Arabian and Eurasian plates caused the formation of a large folded belt between them. This is one of the youngest and most active collision zones that was formed after the closure of the Neo-Tethys Ocean [15].

The movement of the Arabian Plate during the Oligocene – Miocene was directed to the North-East. In Agard et. al. [4], it was shown that pushing the slab from the Sanandaj Sirjan Zone to the crushed zone from the beginning of the collision led to intracontinental compression of the subduction zone at least in a 50-70 km wide strip. The continuation of the Arabian plate movement to the Eurasian plate forms a compression and orogeny along the line of the main fault in the Zagros zone [14]. In the North-Eastern part of the Iranian plate, the faults and crush zones formed as a result of the collision of the Iranian and Binalud plates were more intensively exposed to the shift due to the convergence of the Arabian and Eurasian plates [14] (Fig.7).

In this regard, the Ordib fault of the North-East strike was affected, on the one hand, by the oblique movement of the plates during the convergence of the Iranian and Binalud plates at the end of the Eocene-Oligocene, and on the other, was compressed and aligned in the direction of the Arabian and Eurasian plates convergence in the Oligocene – Miocene. According to these data, shifting along the Ordib Fault occurred as shown in Fig.8.

The end of the collision between the Iranian and Binalud plates at the end of the Eocene-Oligocene and the movement of the Arabian plate in the North-East direction during the Oligocene-Miocene changed the Dorun fault from right to left-sided, which was caused by the rotation of the blocks between faults in this area clockwise (Fig.8).

Change in convergence direction and uplift. At the end of the Miocene, the directions of compression of the crust and the movement of the Arabian and Eurasian plates changed from North-West to meridional and due to this shear dislocations appeared in the Zagros belt [14] (Fig.9).

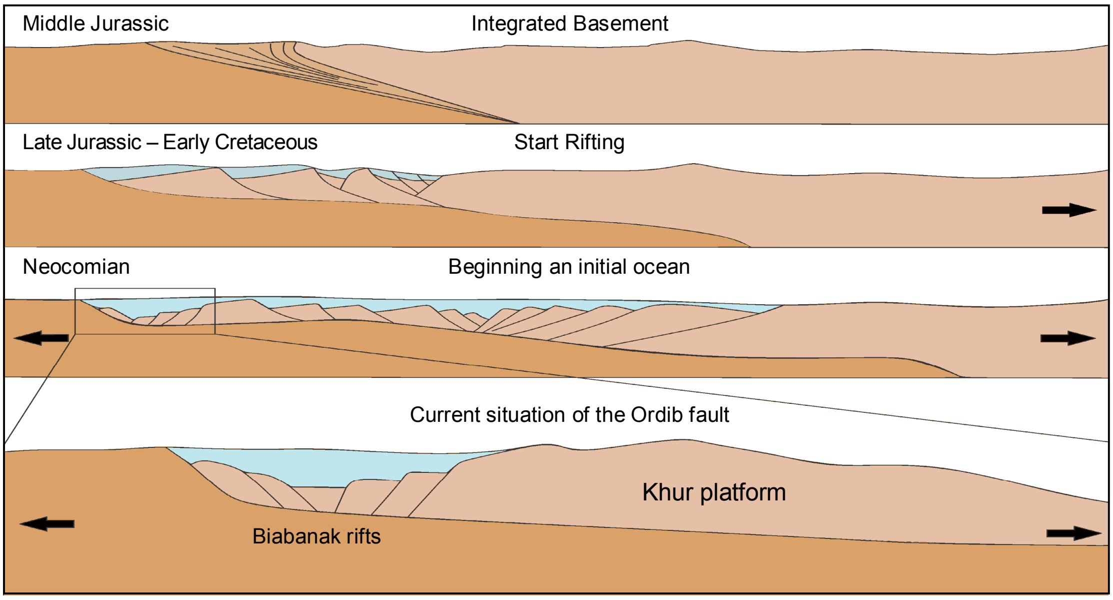

Fig.5. Stages of rift evolution in the Biabanak area (after Bagheri et al. [11])

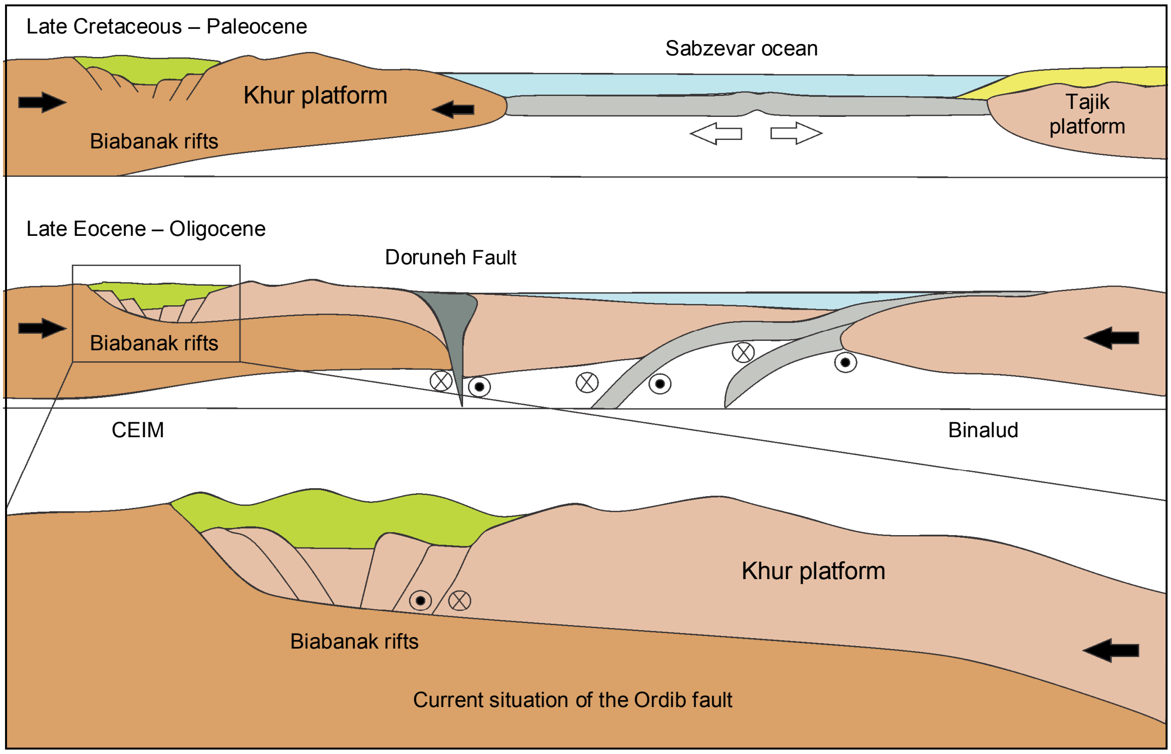

Fig.6. Oblique compression due to the shift of the Iranian and Binalud plates in the Biabanak area (after Bagheri et al. [11])

Due to the change of the Arabian plate convergence direction from the North-East to the North and increasing angle between the faults directions and the axis of convergence, the reverse mechanisms were formed with the formation of an uplift region in the central part of Iran [7] (Fig.10). In accordance with the direction of the Ordib Fault, its angle relative to the submeridional direction of convergence of the Arabin and Eurasian plates, in some fragments of the fault, the compression components and the uplift of the region dominated in the Pliocene-Quaternary time.

DOI: 10.31897/PMI.2019.2.142

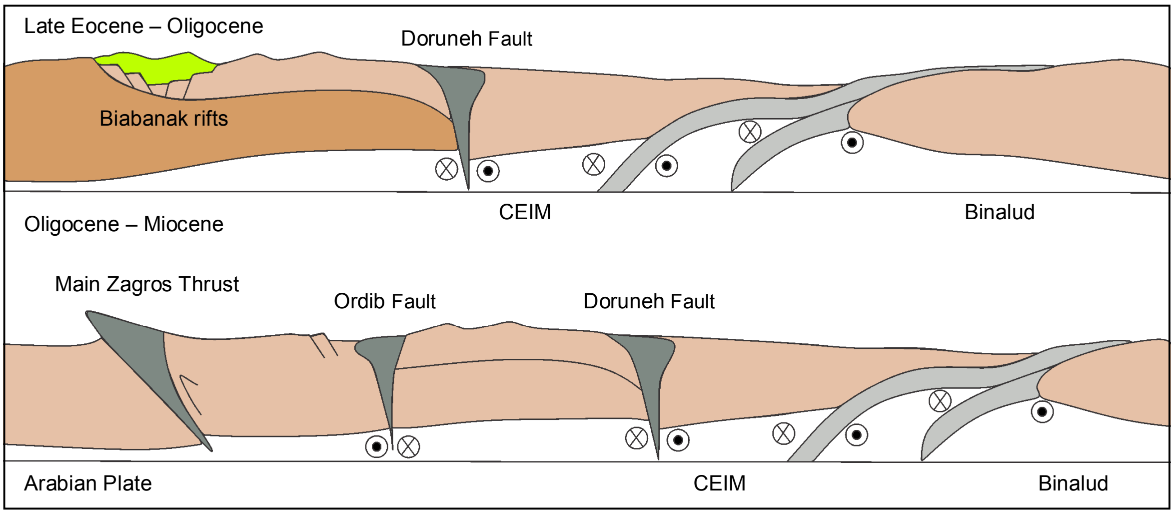

Fig.7. Compression movements in the Zagros zone and the creation of shear components in Central Iran (after Bagheri et al. [11])

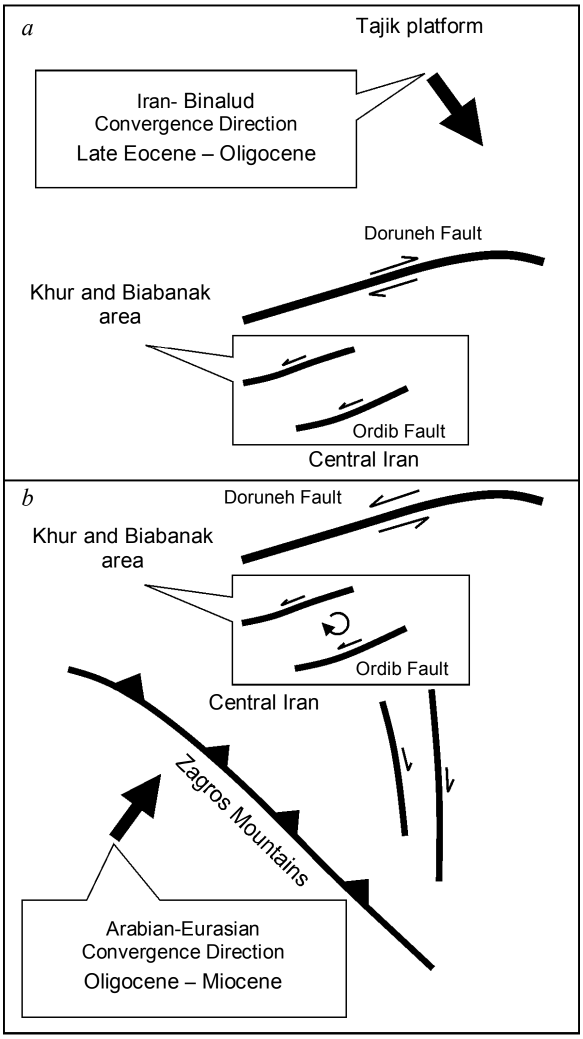

Fig.8. The structure of compression movements in the Zagros region and the occurrence of shear components in the central part of Iran, affected by the inclined movement of the convergence of Iranian and Binalud plates (*a*) and the collision of the Arabian and Eurasian plates (*b*) (using data from Bagheri et al. and Allen et al. [11, 14])

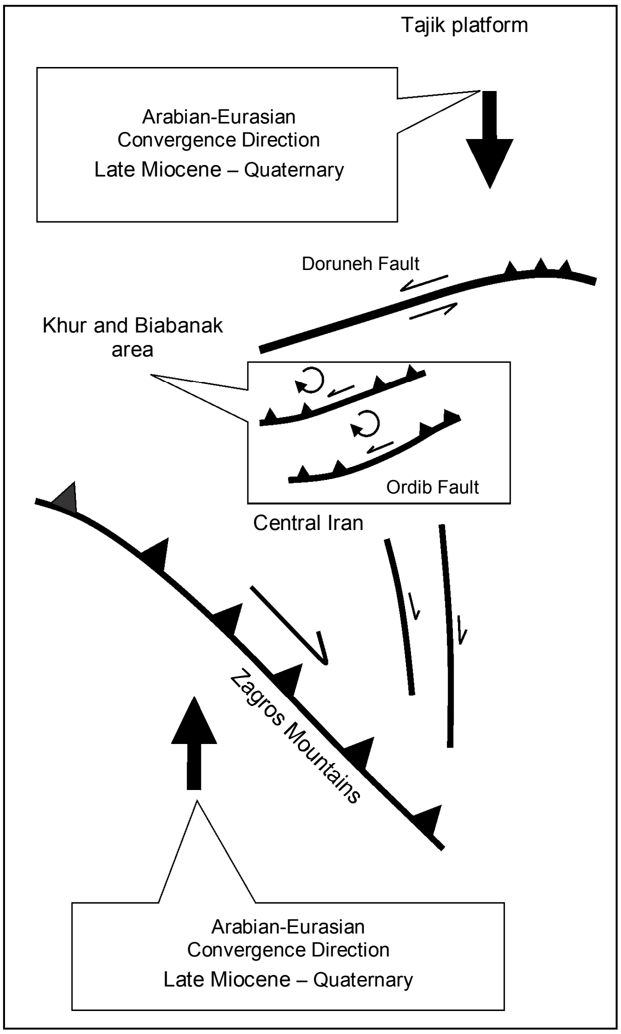

Fig.9. Changing the direction of convergence of the Arabian and Eurasian plates, the structure of shear movements in Zagros and the creation of compression components in the central part of Iran (after Allen et al. [14])

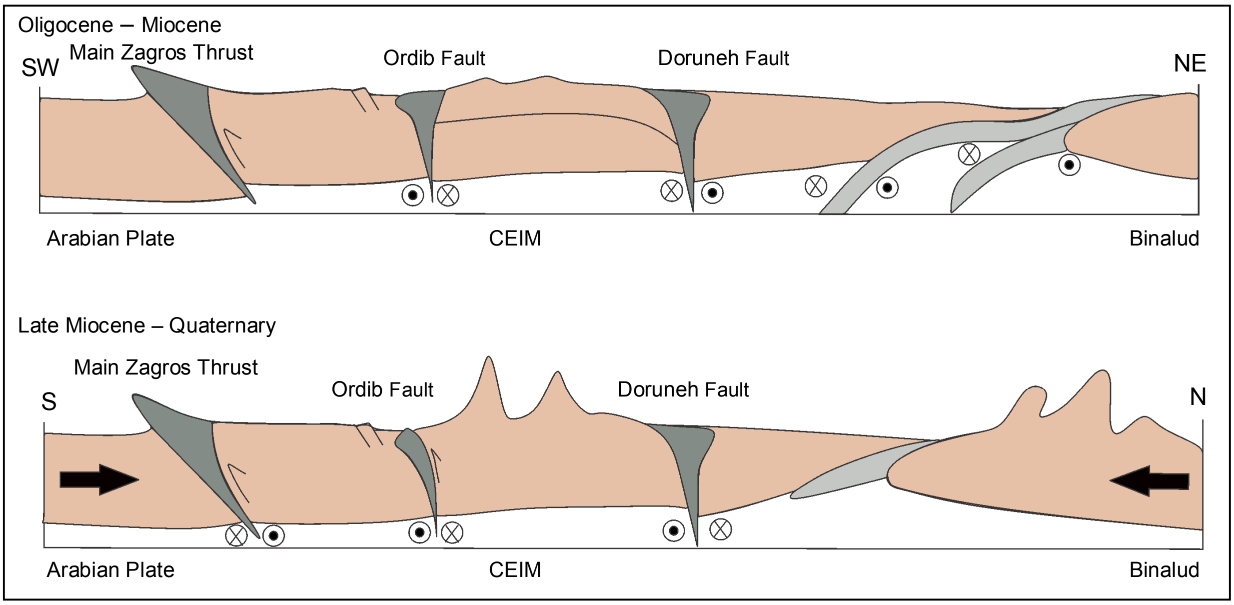

Fig.10. Changing the convergence direction of the Arabian plate and uplift of the region
(after Bagheri et al. [11])

Conclusions. We first described the structural elements and the tectonic evolution of the Ordib fault in the Khur region based on the analysis of various data. We have processed regional aeromagnetic data generated the set of maps, including: geological maps, topographic bases, satellite images, etc. As a result of a study of all available information, the following conclusions were made:

1. Analysis of magnetometer data shows that the Ordib Fault is a dislocation in the Khur region, breaking through the basement rocks.

2. In the region of Ordib, tectonic faults are represented by left-lateral shift of the North-East direction.

3. The stages of tectonic evolution in the Ordib region (Khur platform) include: 1) rifting processes in the area of Biabanak and in the North of the Zabzevar region took place in the Late Jurassic – Neocomian; 2) in the Albian – Oligocene, compression caused shifts along the Ordib Fault; 3) at the end of the Miocene, convergence of the Arabian and Eurasian plates changed the direction from the North-Western to the Northern, which led to the formation of the compression component of the fault and to the uplift of the Ordib region in the Pliocene – Quaternary time.

4. A new model of shift structures along the main fault includes the horsetail splay structure at the North-East edge of the fault, the probable rotation of blocks counter clockwise in the middle part of the fault and their clockwise rotation in the South-Western part of the fault.

Acknowledgments. *The authors thank the staff of the Geology Department of the University of Isfahan for providing geophysical data and assistance in conducting field research.*

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***Authors*: Arash Sohrabi,** *Postgraduate student*, *arashshrbi@gmail.com* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*), **Alireza Nadimi**, *Professor*, *Aldmi7660@gmail.com* (*University of Isfahan*, *Isfahan*, *Iran*), **Irina V. Talovina**, *Doctor of Geological and Mineralogical Sciences*, *Professor*, *i.talovina@gmail.com* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*), **Homayon Safaei**, *Professor*, *Homansafi44@yahoo.com* (*University of Isfahan*, *Isfahan*, *Iran*)

The paper was received on 5 December, 2018.

The paper was accepted for publication on 1 March, 2019.