

A comprehensive analysis of the Sistan Suture Zone: tectonic implications and stress dynamics

Mahnaz Sabahi¹, Mohammad Mahdi Khatib², Yahya Djamour³, Seyed Morteza
Mousavi⁴, Abass Amini⁵

1- PhD Candidate, Department of Geology, Faculty of Science, University of Birjand, Birjand, Iran

2- Professor, Department of Geology, Faculty of Science, University of Birjand, Birjand, Iran

3- Associate Professor, Department of Geology, Faculty of Science, University of Birjand, Birjand, Iran

4- Associate Professor, Faculty of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

5- Associate Professor, Australian College of ACK

Received: 2024/12/08

Accepted: 2025/04/29

Abstract

The Sistan Suture Zone (SSZ) in eastern Iran is a significant tectonic boundary separating the Helmand Block from the Central-East Iranian Microcontinent (CEIM). This study provides a comprehensive review of its tectonic framework by integrating structural, geodynamic, and seismic data. The aim is to clarify stress distribution, fault dynamics, and deformation patterns in the region. The SSZ is primarily characterized by N-S trending right-lateral strike-slip faults, which exhibit no rotational deformation and facilitate differential motion between adjacent tectonic blocks. In contrast, the Dorouneh Fault System shows left-lateral motion with clockwise rotation, reflecting the region's tectonic complexity. The Qasr-e Qand Fault is identified as a crucial boundary marking the transition to the Makran Subduction Zone, where compressional forces dominate, and a steep lithospheric dip is observed. Additionally, the Lut Block experiences counterclockwise rotation and heightened fault activity under regional stress. Quantitative analyses reveal variations in fault slip rates, with active faults effectively accommodating strain across the zone. This synthesis underscores the SSZ's critical role in regional tectonic processes, linking surface deformation to deeper subduction mechanisms. The findings enhance our understanding of the SSZ's evolution, its implications for seismic hazard assessment, and its broader geodynamic connections to the Makran Subduction Zone and adjacent tectonic systems.

Keywords: Sistan Suture Zone, tectonic framework, stress distribution, Eastern Iran

1. Introduction

The closure of the Neo-Tethys Ocean created several major orogenic belts, many of which experienced lateral movement of the upper plate lithosphere. Notable examples include the westward motion of Anatolia away from the Arabia-Eurasia collision zone (Jackson & McKenzie, 1984), the escape of the eastern Alps and northern Pannonian Basin from the Adria-Eurasia collision (Ratschbacher et al., 1991, 1989), and the eastward shift of Indochina due to the India-Asia collision (Tapponnier et al., 1982; Richter and Fuller, 1996; Li et al., 2017). These lateral movements accommodate crustal shortening and are guided by major strike-slip faults, which also pose significant seismic risks when active. Another region that may have experienced similar lateral escape lies west of India and Tibet, covering much of Afghanistan and eastern Iran. Tapponnier et al. (1981) observed that the strike-slip faults around the Helmand Block in Afghanistan show evidence of westward movement. However, due to limited geological data, the full extent of this motion remains unclear. The geology of eastern Iran, especially the Sistan Suture Zone (SSZ), offers valuable information to better understand this lateral motion.

The SSZ is a N-S trending structure, roughly 800 km long, that separates the Helmand Block from the Lut Block in central Iran (Figure 1). This orientation is unusual because most Neo-Tethyan subduction zones during the Mesozoic and Cenozoic were E-W trending. Structural and metamorphic evidence suggests different possibilities for the subduction polarity

in the SSZ, with researchers proposing either westward or eastward subduction (Agard et al., 2009; Angiboust et al., 2013; Arjmandzadeh et al., 2011; Bröcker et al., 2013; Pang et al., 2011; Saccani et al., 2010; Tirrul et al., 1983; Bagheri and Damani Gol, 2020). Estimates for the timing of closure range from the Late Cretaceous to the Late Eocene or Oligocene (Bröcker et al., 2013; Tirrul et al., 1983; Zarrinkoub et al., 2012). Some studies even suggest that subduction began in the Jurassic, based on magmatic and metamorphic evidence from the eastern Lut Block (Beydokhti et al., 2015; Esmaeily et al., 2005; Karimpour et al., 2011; Nabiei & Bagheri, 2013; Pang et al., 2013; Stöcklin et al., 1972). If E-W convergence caused the SSZ to close, the Lut and Helmand Blocks must have interacted significantly. This would restore the Helmand Block to an eastern position, potentially into the Karakoram-Tibetan realm. However, the extent of this movement remains uncertain due to limited kinematic data. Bagheri and Gol (2020) proposed an alternative hypothesis that the SSZ was initially an E-W trending Neo-Tethyan trench, which later bent into an N-S orientation through oroclinal buckling. If correct, this scenario would clarify the timing and extent of lateral motion while connecting the tectonic history of Iran with the western Tibetan Plateau. The oroclinal bending hypothesis suggests a tightly curved structure linking the eastern Lut Block to the western Helmand Block. This is consistent with paleomagnetic data showing counter-clockwise rotation of the Lut Block from the Triassic to Paleogene (Bina et al.,



1986; Davoudzadeh et al., 1981; Soffel et al., 1996). Alternatively, if the SSZ was always N-S trending, it may extend farther north than currently mapped (Rossetti et al., 2010) or end against a transform boundary to the north, encompassing the Helmand Block and Farah Basin. Both interpretations suggest significant westward motion for the Helmand Block but differ in timing. For instance, if the SSZ acted as a back-arc basin that closed during N-S subduction, evidence of high-pressure/low-temperature metamorphism (~90 Ma, Bröcker et al., 2013) implies this motion began in the Late Cretaceous, well before the India-Asia collision.

In contrast, the oroclinal bending model may connect to the collision, similar to the case of Indochina (Li et al., 2017). This study investigates the northern termination of the SSZ through field observations, focusing on the subduction zone's location, the presence of curvilinear structures or strike-slip faults, and the timing of deformation. Stratigraphic and magmatic evidence is used to determine whether the northern SSZ exhibits features of a tight orocline. The Sistan Suture Zone (SSZ), located in eastern Iran, is a Cretaceous-Tertiary orogenic belt commonly referred to as the Eastern Iranian Ranges. This north-south elongated belt spans approximately 900 km in length and 200 km in width, consisting primarily of Cenozoic rocks. It serves as a tectonic boundary, separating the Gondwana-derived Afghan Block to the east from the Lut Block in central Iran to the west (Stöcklin et al., 1968; Tirrul et al., 1983; Samimi et al., 2020; Bagheri

and Gol, 2020). The northern end of the SSZ becomes splayed due to strike-slip fault activity, trending towards WNW and extending to the south of Birjand and Basiran. Towards the south, its N-S trends curve southeastward and continue in an east-west direction into Pakistan. The flysch basin in eastern Iran has been categorized as a transform fault basin influenced by the Nahbandan and Harirud fault systems, along with the rotational movements of the Lut and Helmand blocks (Samani and Ashtari, 1992; Bagheri and Gol, 2020).

2. Geology setting

Geologically, the SSZ comprises three main units, representing distinct stages of an accretionary prism during the closure of the Sistan Ocean (Tirrul et al., 1983). The Ratuk Complex, located in the eastern part of the suture zone, is the oldest segment, preserving evidence of early east-directed subduction beneath the Afghan Block. This complex includes Cretaceous flysch, ophiolitic rocks, and a metamorphic mélange. The Neh Complex, situated to the west, records a later phase of east-directed subduction following the migration of the subduction zone westward (Rad et al., 2009). It consists of Late Cretaceous to Eocene flysch interspersed with ophiolitic materials. The Sefidabeh Basin, which unconformably overlies the Ratuk and Neh complexes, contains unmetamorphosed sediments dating from the Maastrichtian to Eocene, interpreted as representing a fore-arc basin (Tirrul et al., 1983). The final stages of oceanic closure and suture formation in the SSZ were associated

with calc-alkaline and alkaline volcanic activities, alongside minor granitoid intrusions, occurring between the Late Cretaceous and the Quaternary (Camp and Griffis, 1982; Pang et al., 2013; Walker et al., 2009). The timing of the Sistan Ocean's existence remains uncertain, but radiolaria in pelagic cherts suggest that deep-water marine conditions were present as early as the Early Cretaceous (Babazadeh and De Wever, 2004a, b). Although the details of the closure history are not well-constrained, it is widely accepted that the ocean was fully closed by the Late Paleocene to Early Eocene (Tirrul et al., 1983).

Numerous studies have examined the geology, petrology, and geochemistry of the SSZ (Angiboust et al., 2013; Camp and Griffis, 1982; Fotoohi Rad et al., 2005; Saccani et al., 2010; Tirrul et al., 1983). This summary focuses on the key geological and structural features of the SSZ that are most relevant to the present study.

3. Active Faulting in Sistan Suture Zone

The map illustrates the widespread distribution of active faulting across the Sistan Suture Zone, emphasizing its significant seismic potential (Figure 2). Among the identified faults, Sefiedabeh, Zahedan, Nehband, Nayband, Abiz, and Gazik are particularly notable due to their heightened potential for generating large-magnitude earthquakes. These faults, located in a tectonically dynamic region, play a crucial role in shaping seismic hazards and contribute to our understanding of the region's geodynamic behavior. To provide context for seismic activity,

the map incorporates the epicenters of 180 seismic events ($M_s \geq 4$) recorded between 1900 and 2022, compiled from the International Seismological Centre (ISC) and the United States Geological Survey (USGS) datasets. Active faults are delineated by red lines, while the epicenters of the 1997 Zirkuh earthquake (M_s 7.3) and the 2013 Saravan earthquake (M_s 7.7) are highlighted with red circles.

4. Active Faulting and Deformation in the Northern Sistan Suture Zone

Active faulting in the Birjand region of NE Iran by Walker and Khatib (2006) provides a detailed schematic representation of faulting patterns in northeastern Iran, as depicted in Figure 3. The diagram emphasizes the accommodation of N-S right-lateral shear across the region through a range of fault systems. In the southern segment, this shear is predominantly absorbed by the N-S right-lateral faults of the Sistan Suture Zone, where deformation is primarily nonrotational. Moving northward, the shear transitions to E-W left-lateral faults, which are characterized by clockwise rotation around vertical axes. The Giv and Nauzad thrusts, situated at the eastern termination of the Sistan right-lateral faults, are interpreted to undergo anticlockwise rotation. This rotational behavior facilitates the transition to E-W thrust faulting near Birjand, which is likely linked to the clockwise vertical-axis rotation of crustal material around the Dasht-e Bayaz fault in the northern region. These interactions highlight the dynamic interplay between thrust and strike-slip faulting, underscoring the complex shift

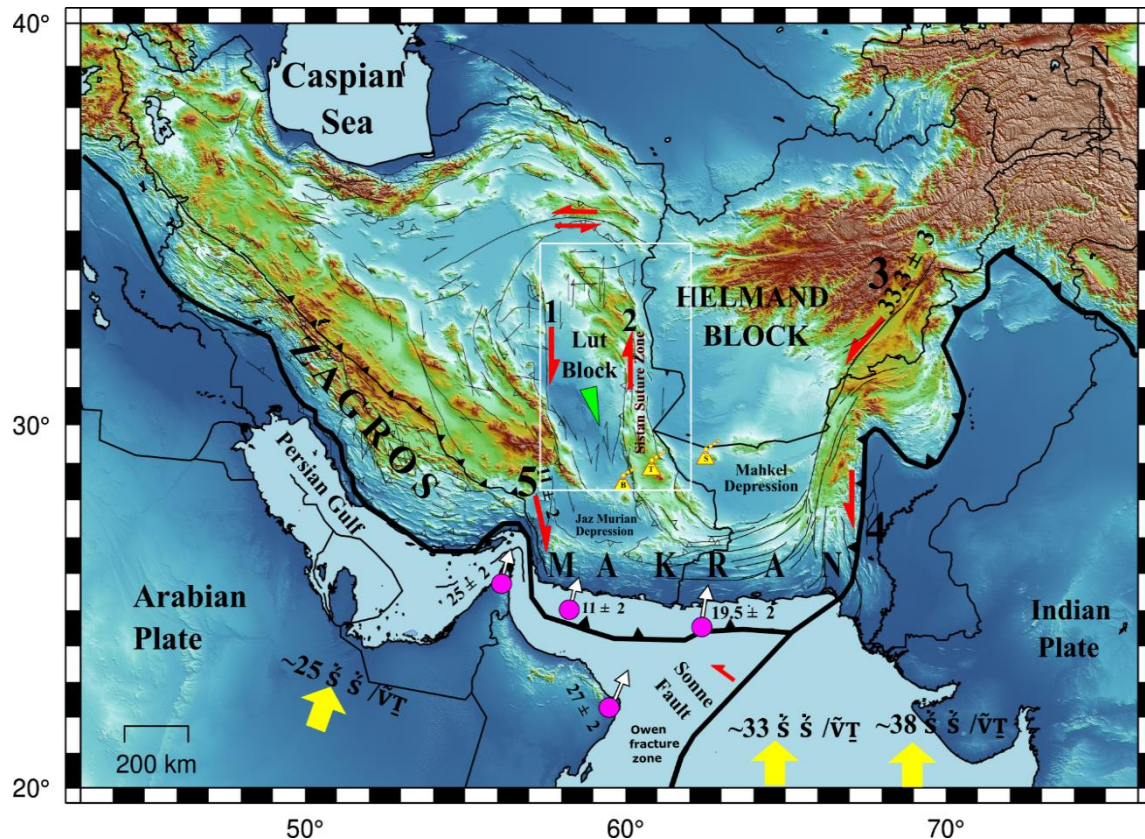


Figure 1. Tectonic map of the Makran region, illustrating primary tectonic features, fault systems, and geological boundaries. The Lut Block's boundaries are emphasized, with the western boundary (No. 1) and eastern boundary (No. 2) defined by major dextral strike-slip fault systems. The Chaman Fault (CF, No. 3) and Ornach Nal Fault (OF, No. 4) are sinistral strike-slip faults, with the movement rate of the CF derived from geomorphological analyses (Snead, 1990). The Minab–Zendan–Palami (MZIP) fault system (No. 5) is depicted along with its motion rates based on Vernant et al. (2004). The map also highlights the Main Zagros Thrust (MZZT) and key geological features such as the Jaz Murian Depression and Mashkel Depression. The Sistan Suture Zone is identified as a critical tectonic boundary between the Lut and Helmand Blocks. Quaternary volcanic centers, including Bazman (B), Taftan (T), and Sultan (S), are shown as yellow triangles (Afaghi & Salek, 1977; Dykstra & Birnie, 1979; White, 1984). A green symbol within the Lut Block indicates counterclockwise rotation, supported by GPS measurements and paleomagnetic interpretations (Mattei et al., 2012; Walpersdorf et al., 2014). Pink circles represent GPS stations recording movement velocities related to the convergence of the Arabian and Eurasian plates (Vernant et al., 2004), while white arrows show the relative motion of the Arabian Plate with respect to the Eurasian Plate, derived from the GEODVEL-2010 model (Argus et al., 2010).

between rotational and nonrotational deformation in the area (Walker and Khatib, 2006; Bayasgalan et al., 1999 a and b). This faulting pattern illustrates the intricate seismotectonic environment of northeastern Iran, where deformation accommodates

N-S shear while contributing to the region's seismic hazard potential.

4. Variation in Fault Slip Rates and Strain Distribution in the Lut Block, Eastern Iran

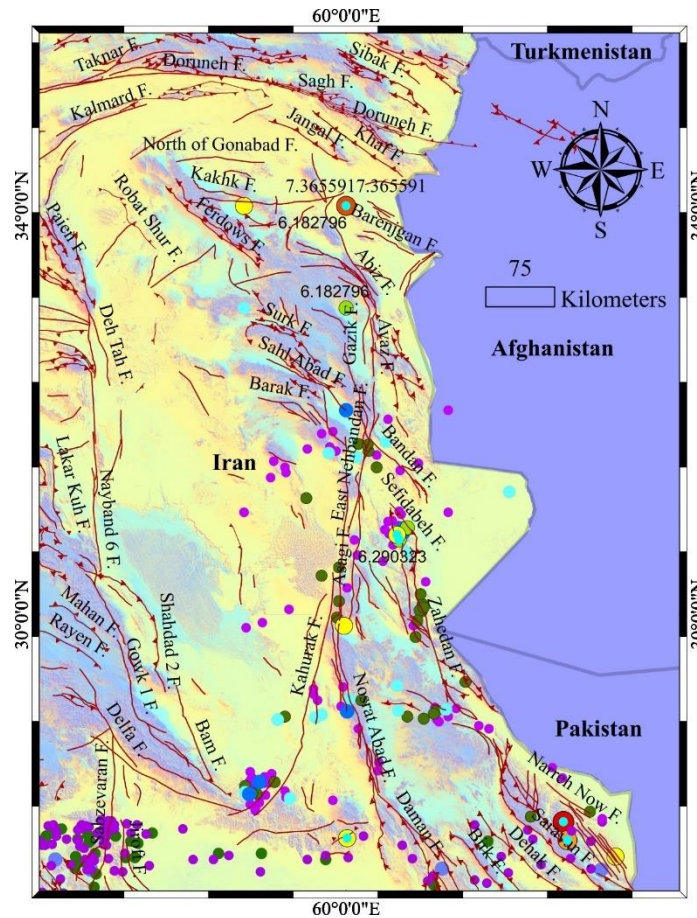


Figure 2. The structural map depicts active faults within the Sistan zone. Earthquake magnitudes are denoted by circles with the following color scale: green ($4.5 \leq M_s < 5$), cyan ($5 \leq M_s < 5.5$), blue ($5.5 \leq M_s < 6$), light green ($6 \leq M_s < 6.5$), yellow ($6.5 \leq M_s < 7$), orange ($7 \leq M_s < 7.5$), and red ($7.5 \leq M_s < 8$), based on data from the ISC Catalogue (1900–2023).

Yazdanpanah et al. (2015) studied fault movements in the Lut Block, a region in eastern Iran, where the speed of fault slipping changes from west to east. Over the last five million years, right-lateral faults have become active in and around the Lut Block. During the Quaternary period, the Nehbandan fault system in the east was measured to have a slip rate of about 5 mm/year, while the Nayband fault system in the west had a rate of 1.7 ± 0.3 mm/year. This shows that faults in the east move faster than those in the west. The high activity of these faults has created a zone where the amount of movement varies. Using tools like satellite images, field studies, magnetic

data, and lab experiments, Yazdanpanah et al. (2015) examined how strain and fault movement are spread across the Lut Block. They discovered that areas with more movement directly relate to changes in fault slip rates.

5. Competing Tectonic Models for the Northern Termination of the Sistan Suture Zone

Rojhani et al. (2020) conducted an in-depth study of the tectonic evolution of the abrupt northern termination of the Sistan Suture Zone in eastern Iran. Their work explores two contrasting hypotheses to explain this phenomenon. The first hypothesis,

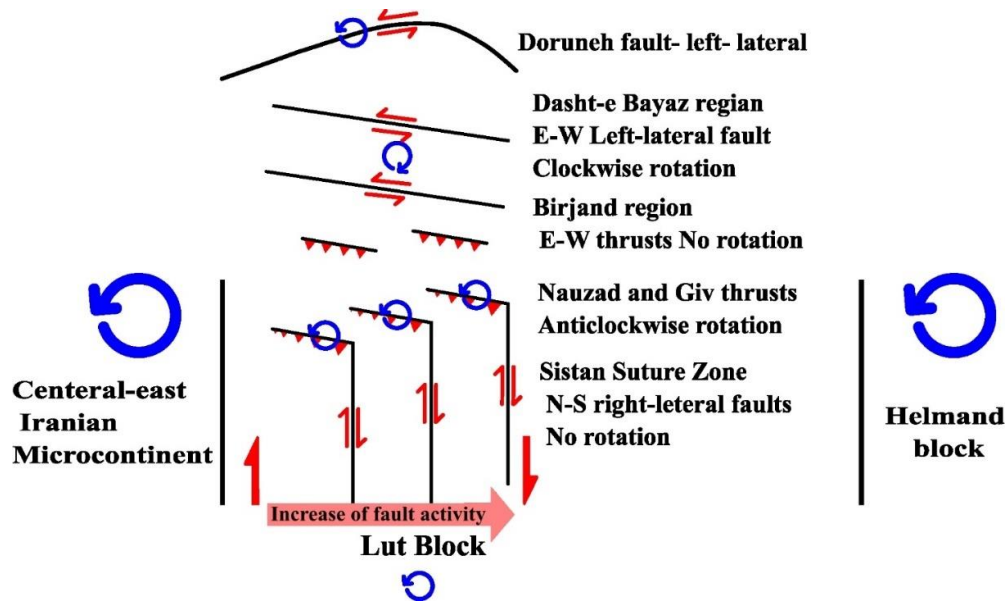


Figure 3. presents a schematic map of faulting in northeastern Iran, illustrating the occurrence of N-S right-lateral shear throughout the region. In the southern part, this shear is primarily accommodated by N-S right-lateral faults within the Sistan Suture Zone, while in the northern areas, it is absorbed by E-W left-lateral faults that exhibit clockwise rotation around vertical axes. The Giv and Nauzad thrusts, located at the eastern terminus of the Sistan right-lateral faults, are likely to undergo anticlockwise rotation (Bayasgalan et al., 1999 a and b). This rotational behavior enables a transition to the predominantly E-W thrust faulting near Birjand, which is thought to result from the clockwise vertical-axis rotation of crustal material around the Dasht-e Bayaz fault in the northern region (Modified from Walker and Khatib (2006)).

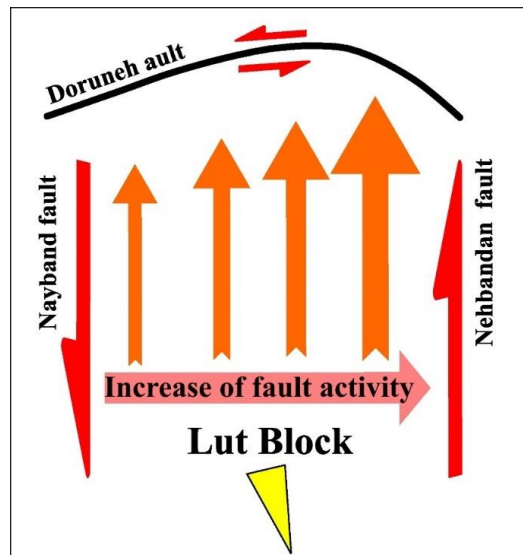


Figure 4. A symbolic model illustrating the role of cumulative north-south right-lateral shear in the structural bending of northern Lut. The gradual increase in applied stress from west to east significantly influences the structural bending of northern Lut and alters the trend of the Doruneh Fault in various sections. A green symbol within the Lut Block indicates counterclockwise rotation, supported by GPS measurements and paleomagnetic interpretations (Mattei et al., 2012; Walpersdorf et al., 2014). (modified from Yazdanpanah et al. (2015)).

detailed by Rojhani et al. (2020), proposes an oroclinal buckling model, where the Sistan Suture was initially an E-W trending Neo-Tethyan trench. Over time, regional tectonic forces caused a 180° buckling, resulting in its present N-S orientation. This interpretation aligns with paleomagnetic data indicating counterclockwise rotation of the Lut Block, as highlighted in studies by Bina et al. (1986), Davoudzadeh et al. (1981), and Soffel et al. (1996). The model suggests that the curvature of the suture zone reflects regional tectonic processes, similar to those observed in other orogenic systems. In contrast, the second hypothesis attributes the termination of the Sistan Suture Zone to transform faults, which facilitated the westward migration of the Helmand Block. This mechanism, associated with regional extrusion tectonics, posits that transform faults accommodated the westward escape of the Helmand Block

while simultaneously terminating the suture zone. This interpretation parallels the well-documented extrusion tectonics of the Tibetan Plateau, as noted by Li et al. (2017).

Figure 5 provides a comparative visual representation of these hypotheses. Figure 5a illustrates the oroclinal buckling model, emphasizing the curved geometry of the suture zone. In contrast, Figure 5b depicts the westward migration of the Helmand Block via transform faults. Key tectonic features, including the Central-East Iranian Microcontinent (CEIM), the Dorouneh Fault System, and the Herat Fault, are clearly labeled to provide additional context. These competing interpretations underscore the complexity of the tectonic processes that shaped the Sistan Suture Zone. Together, they offer valuable insights into the evolution of this tectonic system and its broader implications for regional geodynamics.

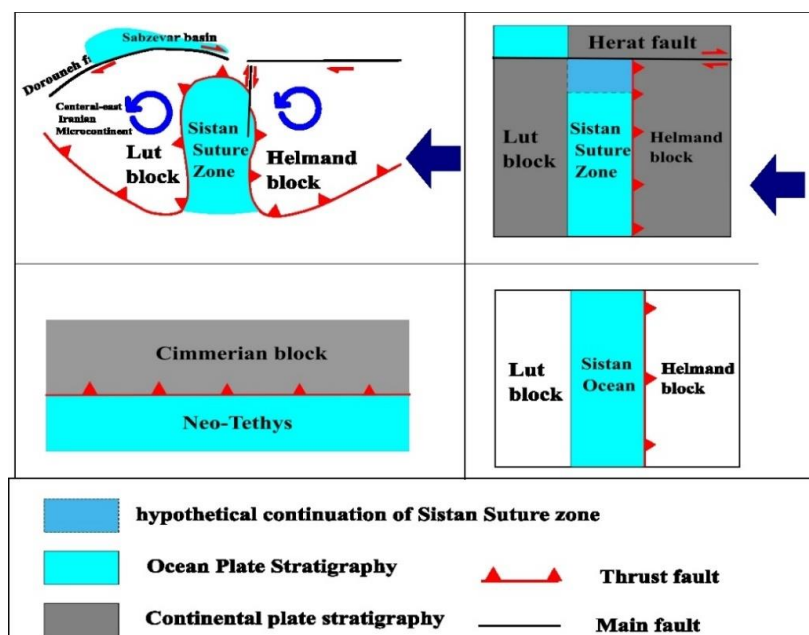


Figure 5. Conceptual illustrations depicting two contrasting hypotheses for the northern termination of the Sistan Suture Zone: (a) the oroclinal buckling model and (b) westward migration facilitated by transform faults. b-Value Analysis and Stress Tensor Inversion in the Sistan Suture Zone (modified from Rojhani et al. (2020))

6. b-Value Analysis and Stress Tensor Inversion in the Makran Zone

Sabahi et al. (2024) conducted a comprehensive investigation into the spatial and temporal variations of b-values, fractal dimensions, and stress tensor inversions within the Sistan Suture Zone, offering significant insights into its seismicity and tectonic evolution. Their findings reveal notable spatial contrasts in b-values, with the central segment displaying higher values than the northern and southern parts. This spatial distribution, as depicted in Figure 6 (a), highlights the heterogeneous seismic behavior across the zone and provides valuable context for understanding the region's tectonic activity. Analyzing the orientation of maximum horizontal stress (SHmax) is critical for studying stress sources, regional tectonics, and lithospheric deformation. The stress tensor inversion results presented in this study illustrate the faulting styles within the Sistan zone. The SHmax orientations are represented by striking bars that indicate the slip direction (Figure 6 (b)) and are color-coded to correspond to fault types: NF (normal), NS (normal-transcurrent oblique), SS (strike-slip), TS (reverse-transcurrent oblique), and TF (reverse fault). As shown in Figure 6 (b), the Sistan Suture Zone is predominantly characterized by strike-slip and reverse faulting, depicted by green and blue-colored striking bars, respectively. The NE-SW orientation of maximum horizontal stress reflects the tectonic forces shaping the region. Recent deformation within the Sistan Suture Zone is primarily associated with N-S to NNW-SSE right-

lateral strike-slip faults, alongside NW-SE reverse faults and E-W left-lateral strike-slip faults. This deformation is closely linked to the indentation of the Arabian shield into Iran. Notably, the transition from right-lateral strike-slip faults to thrust faults marks a significant shift from non-rotational to rotational deformation within the Sistan Suture Zone. Walker and Khatib (2006) highlighted this transformation, emphasizing its influence on the fault dynamics and structural evolution of the region.

7. Discussion and Conclusion

This schematic provides an integrated analysis of stress distribution and tectonic processes in the Sistan Suture Zone (SSZ) and adjacent regions, offering significant insights into the geodynamic behavior of eastern Iran. The SSZ is defined by N-S trending right-lateral faults, which lack rotational deformation and serve as a critical tectonic boundary. This zone facilitates relative motion between the Central-East Iranian Microcontinent (CEIM) and the Helmand Block, underscoring its importance in accommodating regional tectonic forces. In contrast, the Dorouneh Fault System (DFS) to the north demonstrates left-lateral motion with clockwise rotation, highlighting the tectonic complexity within the CEIM. The Qasr-e Qand Fault serves as a pivotal boundary in the southern SSZ, marking the transition to the Makran Subduction Zone. This fault separates the elevated, faulted, and folded terrains in the north from compressional structures such as folds in the south, while aligning with a

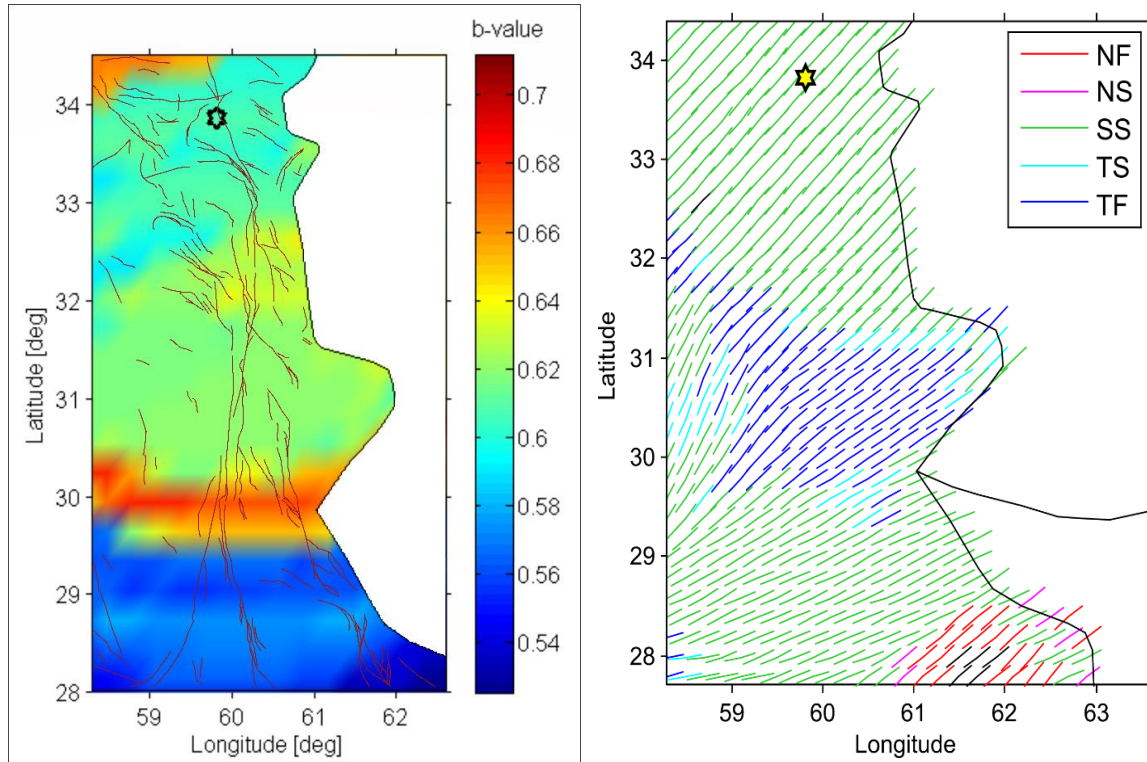


Figure 6. (a) Spatial variation in the b-value for the Sistan zone. the star symbol indicates the 7.3 Ms earthquake in Zirkuh in 1997. (b) Stress tensor inversion results for Sistan The yellow stars in panels (a) and (b) indicate the 1997 Zirkuh earthquake with magnitude of 7.3 Ms. The colours correspond to the fault types: NF, normal; NS, normal-transcurrent oblique; SS, transcurrent (strike-slip); TF, inverse; TS, Transpressional (modified from Sabahi et al. (2024)).

significant increase in the dip angle of the subducting lithosphere. This steepening underscores its contribution to the broader dynamics of the Makran Subduction Zone, where compressional forces dominate, forming an extensive accretionary wedge, as seen in features like the Jaz Murian Depression. The centrally located Lut Block undergoes a counterclockwise rotation under regional stress, absorbing strain and influencing the dynamics of adjacent fault systems. Similarly, the Nauzad and Giv thrusts exhibit anticlockwise rotations, indicative of localized compressional forces and the distributed nature of deformation in the region. This comprehensive synthesis of stress dynamics and fault interactions

provides valuable insights into the evolution of the SSZ and its role in the geodynamic framework of eastern Iran. The findings highlight the critical role of the Qasr-e Qand Fault in linking surface deformation to deeper subduction mechanisms, while emphasizing the intricate tectonic interactions shaping the SSZ. These insights contribute to a better understanding of the regional stress regime, fault kinematics, and deformation patterns, with broader implications for seismic hazard assessment and the tectonic evolution of the Makran Subduction Zone.

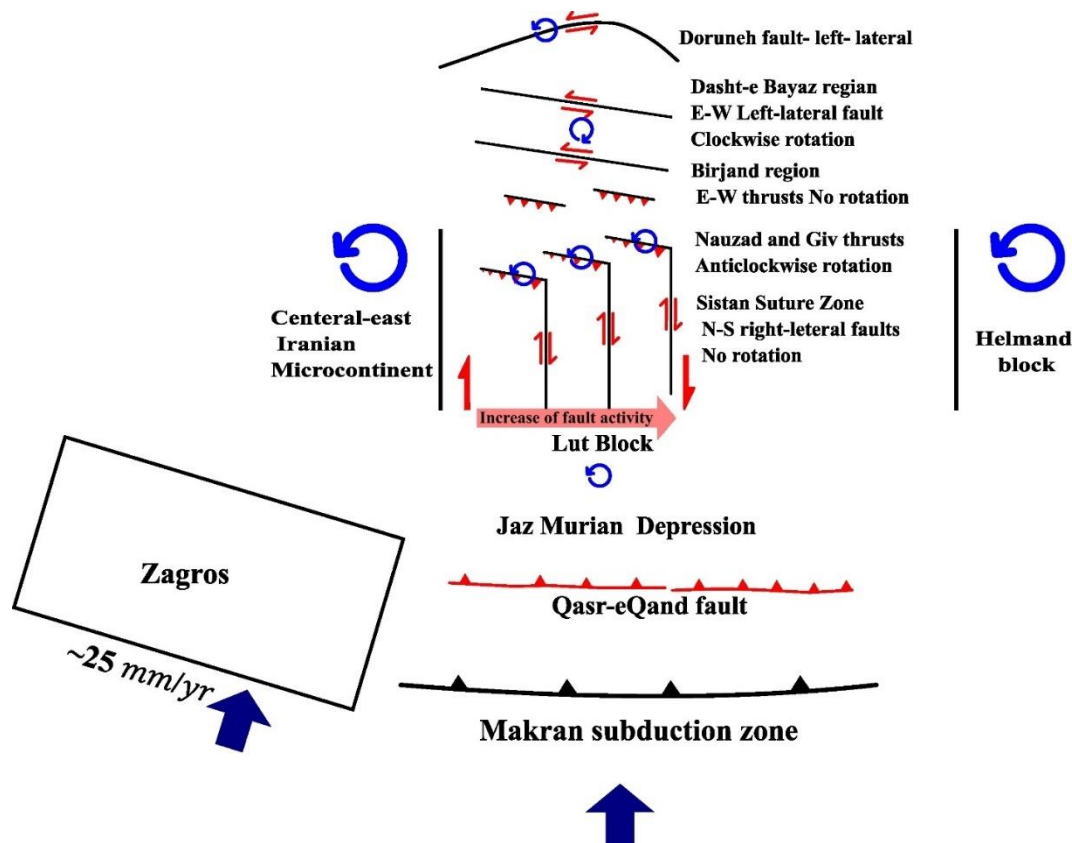


Figure 7. This schematic illustrates the tectonic framework of the Sistan Suture Zone and its surrounding areas, focusing on fault dynamics, block rotations, and stress distribution. The Dorounh Fault System (DFS) and Dasht-e Bayaz region exhibit clockwise rotation, while the Nauzad and Giv thrusts show anticlockwise rotation. The Sistan Suture Zone, dominated by N-S right-lateral faults with no rotation, serves as a key tectonic boundary. The Qasr-e Qand Fault marks the transition to the Makran Subduction Zone, where compressional forces dominate. The Lut Block experiences counterclockwise rotation and increased fault activity under regional stress.

References

- Afaghi, A. & Salek, M.M., 1977. Geological map of Iran: Tehran; Sheet no. 6, scale 1:1,000,000. Tehran, Iran: National Iranian Oil Company.
- Agard, P., Yamato, P., Jolivet, L. and Burov, E., 2009. Exhumation of oceanic blueschists and eclogites in subduction zones: timing and mechanisms. *Earth-Science Reviews*, 92(1-2), 53-79.
- Angiboust, S., Agard, P., De Hoog, J.C.M., Omrani, J. and Plunder, A., 2013. Insights on deep, accretionary subduction processes from the Sistan ophiolitic “mélange” (Eastern Iran). *Lithos*, 156, 139-158.
- Argus, D.F., Gordon, R.G., Heflin, M.B., Ma, C., Eanes, R.J., Willis, P., Peltier, W.R. and Owen, S.E., 2010. The angular velocities of the plates and the velocity of Earth's centre from space geodesy. *Geophysical Journal International*, 180(3), 913-960.
- Arjmandzadeh, R., Karimpour, M. H., Mazaheri, S. A., Santos, J. F., Medina, J. M., & Homam, S. M., 2011. Two-sided asymmetric subduction; implications for tectonomagmatic and metallogenic

- evolution of the Lut Block, eastern Iran. *Journal of Asian Earth Sciences*, 41, 93-93.
- Babazadeh, S.A. and De Wever, P., 2004. Radiolarian Cretaceous age of Soulabest radiolarites in ophiolite suite of eastern Iran. *Bulletin de la Société géologique de France*, 175(2), 121-129.
- Bagheri, S. and Gol, S.D., 2020. The eastern Iranian orocline. *Earth-Science Reviews*, 210, 103322.
- Bai, Y., Yang, J. and Qiu, Y., 2007, April. FD/I-based personalized recommendation in context-aware application. In: *2007 International Conference on Multimedia and Ubiquitous Engineering (MUE'07)*, 692-697. IEEE.
- Bayasgalan, A., Jackson, J., Ritz, J.F. and Carretier, S., 1999. Field examples of strike-slip fault terminations in Mongolia and their tectonic significance. *Tectonics*, 18(3), 394-411.
- Bayasgalan, A., Jackson, J., Ritz, J.F. and Carretier, S., 1999. Forebergs, flower structures, and the development of large intra-continental strike-slip faults: the Gurvan Bogd fault system in Mongolia. *Journal of Structural Geology*, 21(10), 1285-1302.
- Beydokhti, R.M., Karimpour, M.H., Mazaheri, S.A., Santos, J.F. and Klötzli, U., 2015. U-Pb zircon geochronology, Sr-Nd geochemistry, petrogenesis and tectonic setting of Mahoor granitoid rocks (Lut Block, Eastern Iran). *Journal of Asian Earth Sciences*, 111, 192-205.
- Bina, M.M., Bucur, I., Prevot, M., Meyerfeld, Y., Daly, L., Cantagrel, J.M. and Mergoil, J., 1986. Palaeomagnetism, petrology and geochronology of tertiary magmatic and sedimentary units from Iran. *Tectonophysics*, 121(2-4), 303-329.
- Bröcker, M., Rad, G.F., Burgess, R., Theunissen, S., Paderin, I., Rodionov, N. and Salimi, Z., 2013. New age constraints for the geodynamic evolution of the Sistan Suture Zone, eastern Iran. *Lithos*, 170, 17-34.
- Camp, V.E. and Griffis, R.J., 1982. Character, genesis and tectonic setting of igneous rocks in the Sistan Suture Zone, eastern Iran. *Lithos*, 15(3), 221-239.
- Davoudzadeh, M. and Schmidt, K., 1981. Contribution to the paleogeography and stratigraphy of the Upper Triassic to Middle Jurassic of Iran. *Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen*, 162(2), 137-163.
- Davoudzadeh, M., Soffel, H. and Schmidt, K., 1981. On the rotation of the Central-East Iran microplate. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte*, 3, 180-192.
- Dykstra, J.D. and Birnie, R.W., 1979. Segmentation of the Quaternary subduction zone under the Baluchistan region of Pakistan and Iran. *Geodynamics of Pakistan*, 319-323.
- Esmaily, D., Nedelec, A., Valizadeh, M.V., Moore, F. and Cotten, J., 2005. Petrology of the Jurassic Shah-Kuh granite (eastern Iran), with reference to tin mineralization. *Journal of Asian Earth Sciences*, 25(6), 961-980.
- Karimpour, M., Stern, C., Farmer, L. and Saadat, S., 2011. Review of age, Rb-Sr



- geochemistry and petrogenesis of Jurassic to Quaternary igneous rocks in Lut Block, Eastern Iran. *Geopersia*, 1(1), 19-54.
- Li, S., Advokaat, E.L., van Hinsbergen, D.J., Koymans, M., Deng, C. and Zhu, R., 2017. Paleomagnetic constraints on the Mesozoic-Cenozoic paleolatitudinal and rotational history of Indochina and South China: Review and updated kinematic reconstruction. *Earth-Science Reviews*, 171, 58-77.
- Mattei, M., Cifelli, F., Muttoni, G., Zanchi, A., Berra, F., Mossavvari, F. and Eshraghi, S.A., 2012. Neogene block rotation in central Iran: Evidence from paleomagnetic data. *Bulletin*, 124(5-6), 943-956.
- McCall, G.J.H., 1997. The geotectonic history of the Makran and adjacent areas of southern Iran. *Journal of Asian Earth Sciences*, 15(6), 517-531.
- Nabiei, E. and Bagheri, S., 2013. Tectonic Evolution of East Margin of Lut Block in Nosratabad area, SE Iran. *Bulletin of Environmental Pharmacology and Life Sciences*, 2(11), 78-86.
- Pang, K., Chung, S., Zarrinkoub, M.H., Khatib, M.M., Mohammadi, S.S., Lee, H., Chu, C. and Lin, I., 2011, December. Eocene-Oligocene calcalkaline magmatism in the Lut-Sistan region, eastern Iran: petrogenesis and tectonic implications. In: *AGU Fall Meeting Abstracts*, Vol. 2011, V43C-2598.
- Pang, K.N., Chung, S.L., Zarrinkoub, M.H., Khatib, M.M., Mohammadi, S.S., Chiu, H.Y., Chu, C.H., Lee, H.Y. and Lo, C.H., 2013. Eocene-Oligocene post-collisional magmatism in the Lut-Sistan region, eastern Iran: Magma genesis and tectonic implications. *Lithos*, 180, 234-251.
- Rad, G.F., Droop, G.T., Amini, S. and Moazzen, M., 2005. Eclogites and blueschists of the Sistan Suture Zone, eastern Iran: a comparison of P-T histories from a subduction mélange. *Lithos*, 84(1-2), 1-24.
- Rad, G.F., Droop, G.T.R. and Burgess, R., 2009. Early Cretaceous exhumation of high-pressure metamorphic rocks of the Sistan Suture Zone, eastern Iran. *Geological Journal*, 44(1), 104-116.
- Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S.M. and Neugebauer, J., 1989. Extension in compressional orogenic belts: the eastern Alps. *Geology*, 17(5), 404-407.
- Ratschbacher, L., Merle, O., Davy, P. and Cobbold, P., 1991. Lateral extrusion in the Eastern Alps, part 1: boundary conditions and experiments scaled for gravity. *Tectonics*, 10(2), 245-256.
- Richter, B. and Fuller, M., 1996. Palaeomagnetism of the Sibumasu and Indochina blocks: Implications for the extrusion tectonic model. *Geological Society, London, Special Publications*, 106(1), 203-224.
- Rojhani, E., Bagheri, S., Li, S., Lom, N. and van Hinsbergen, D., Tectonic Evolution of the Abrupt Northern Termination of the Sistan Suture Zone (Eastern Iran). Sasan and Li, Shihu and Lom, Nalan and van Hinsbergen, Douwe, Tectonic Evolution of the Abrupt Northern Termination of the Sistan Suture Zone (Eastern Iran).

- Rossetti, F., Nasrabad, M., Vignaroli, G., Theye, T., Gerdes, A., Razavi, M.H. and Vaziri, H.M., 2010. Early Cretaceous migmatitic mafic granulites from the Sabzevar range (NE Iran): implications for the closure of the Mesozoic peri-Tethyan oceans in central Iran. *Terra Nova*, 22(1), 26-34.
- Sabahi, M., Khatib, M.M. and Djamour, Y., 2024. Spatial and temporal changes of b-value, fractal analysis and stress tensor inversion in the Sistan and Makran zones, Eastern and Southeastern Iran. *Journal of Asian Earth Sciences*, 264, 106038.
- Saccani, E., Delavari, M., Beccaluva, L. and Amini, S., 2010. Petrological and geochemical constraints on the origin of the Nehbandan ophiolitic complex (eastern Iran): Implication for the evolution of the Sistan Ocean. *Lithos*, 117(1-4), 209-228.
- Samani, B. and Ashtari, S., 1992. Metallogenic evolution and its relevance to the geotectonic development of the Sistan-Baluchestan province, South Eastern Iran. *Geosciences. Sci. Q.*, 2(5), 3.
- Snead, R.J., 2002. Uplifted marine terraces along the Makran coast of Pakistan and Iran. In: *Himalaya to the Sea*, 225-246. Routledge.
- Soffel, H.C., Schmidt, S., Davoudzadeh, M. and Rolf, C., 1996. New palaeomagnetic data from Central Iran and a Triassic palaeoreconstruction. *Geologische Rundschau*, 85, 293-302.
- Stöcklin, J., 1968. Structural history and tectonics of Iran: a review. *AAPG Bulletin*, 52(7), 1229-1258.
- Stöcklin, J., Eftekhari-Nezhad, J. and Hushmand-Zadeh, A., 1972. Geological Reconnaissance Map of Central Lut. Geological Survey of Iran, Tehran (Vol. 22).
- Tapponnier, P., Mattauer, M., Proust, F. and Cassaigneau, C., 1981. Mesozoic ophiolites, sutures, and large-scale tectonic movements in Afghanistan. *Earth and Planetary Science Letters*, 52(2), 355-371.
- Tapponnier, P., Peltzer, G.L.D.A.Y., Le Dain, A.Y., Armijo, R. and Cobbold, P., 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology*, 10(12), 611-616.
- Tapponnier, P., Mattauer, M., Proust, F. and Cassaigneau, C., 1981. Mesozoic ophiolites, sutures, and large-scale tectonic movements in Afghanistan. *Earth and Planetary Science Letters*, 52(2), 355-371.
- Tapponnier, P., Peltzer, G.L.D.A.Y., Le Dain, A.Y., Armijo, R. and Cobbold, P., 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology*, 10(12), 611-616.
- Tirrul, R., Bell, I.R., Griffis, R.J. and Camp, V.E., 1983. The Sistan suture zone of eastern Iran. *Geological Society of America Bulletin*, 94(1), 134-150.
- Vernant, P., Nilforoushan, F., Hatzfeld, D., Abbassi, M.R., Vigny, C., Masson, F., Nankali, H., Martinod, J., Ashtiani, A., Bayer, R. and Tavakoli, F., 2004. Present-day crustal deformation and plate kinematics in the Middle East constrained by GPS measurements in Iran and northern



- Oman. *Geophysical Journal International*, 157(1), 381-398.
- Walker, R.T. and Khatib, M.M., 2006. Active faulting in the Birjand region of NE Iran. *Tectonics*, 25, TC4016.
- Walker, R.T., Gans, P., Allen, M.B., Jackson, J., Khatib, M., Marsh, N. and Zarrinkoub, M., 2009. Late Cenozoic volcanism and rates of active faulting in eastern Iran. *Geophysical Journal International*, 177(2), 783-805.
- Walpersdorf, A., Manighetti, I., Mousavi, Z., Tavakoli, F., Vergnolle, M., Jadidi, A., Hatzfeld, D., Aghamohammadi, A., Bigot, A., Djamour, Y. and Nankali, H., 2014. Present-day kinematics and fault slip rates in eastern Iran, derived from 11 years of GPS data. *Journal of Geophysical Research: Solid Earth*, 119(2), 1359-1383.
- White, R.S., 1984. Active and passive plate boundaries around the Gulf of Oman, north-west Indian Ocean. *Deep Sea Research Part A. Oceanographic Research Papers*, 31(6-8), 731-745.
- Yazdanpanah, H., Khatib, M.M., Nazari, H. and Gholami, E., 2015. Analysis of preliminary paleoseismic results and seismotectonic data in Qaleh-Sorkh fault; East of Iran. *Journal of Tectonics*, 1(3), 15-25.
- Zarifi, Z., 2007. Unusual subduction zones: Case studies in Colombia and Iran. Ph.D. Thesis, University of Bergen, Norway, 78 pp.
- Zarrinkoub, M.H., Pang, K.N., Chung, S.L., Khatib, M.M., Mohammadi, S.S., Chiu, H.Y. and Lee, H.Y., 2012. Zircon U–Pb age and geochemical constraints on the origin of the Birjand ophiolite, Sistan suture zone, eastern Iran. *Lithos*, 154, 392-405.