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Unraveling the role of dextral faults in the formation of pull-apart basin structures and their implications on the genesis of ophiolites and pluto-volcanics

Ali MohammadiNia[1], Ahmad Rashidi[2]*, Shahram Shafieibafti[3], Seyed Morteza Mousavi[1], Majid Nemati[2,3], Hossein Kianimehr[4], Maryam Ezati[5] and Reza Derakhshani[3,6]*

[1]Department of Geology, University of Birjand, Birjand, Iran, [2]Department of Earthquake Research, Shahid Bahonar University of Kerman, Kerman, Iran, [3]Department of Geology, Shahid Bahonar University of Kerman, Kerman, Iran, [4]Iranian Seismological Center, Institute of Geophysics, University of Tehran, Tehran, Iran, [5]Department of Civil Enginering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran, [6]Department of Earth Sciences, Utrecht University, Utrecht, Netherlands

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EDITED BY
Fabio Luca Bonali,
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REVIEWED BY
Hu Li,
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University of Insubria, Italy

*CORRESPONDENCE
Ahmad Rashidi,
✉ rashidi@uk.ac.ir
Reza Derakhshani,
✉ r.derakhshani@uu.nl

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Rhombic structures have been observed in the Qom-Zefreh-Nayin-Dehsheir-Baft region, specifically along the direction of the dextral faults, which have caused significant changes in strike length. This study investigates the geological features and fault interactions in the region through the examination of aerial images, fault-lithology correlations, petrology, crustal thickness, and seismic studies. The analysis of aerial photos and geological correlations revealed the presence of ophiolites and pluto-volcanics associated with faults and rhombic structures. By conducting field geology and combining various geological studies, a pull-apart basin was identified in the area, contributing to the formation of three rhombic structures. This basin played a crucial role in the genesis of the region's ophiolites and pluto-volcanics. The research suggests that the initial tensional stress leading to the pull-apart basin was caused by the right step of a dextral fault within the Urumieh-Dokhtar magmatic arc. This fault formation occurred due to the oblique Arabian subduction towards the Iranian plateau. During the Zagros orogeny, the stretched area persisted, leading to the formation of oceanic crust in this location. The subduction angle changes from subduction to super-subduction, resulting in the classification of the region into two types: C and E genes. Different types of magma, including alkaline, subalkaline, shoshonite, calcalkaline, and adakitic, were identified in this region. The study highlights the significance of tholeiitic arcs, abyssal features, crust thickness, and seismicity in understanding oblique diagonal subduction models and tensional pull-apart basins, which are crucial in the transition from subduction to super-subduction. This research offers valuable insights into the geological complexities of the region and opens up opportunities for further exploration of similar models.

KEYWORDS

geological interactions, fault kinematics, tectonic processes, magmatic arc, geodynamic evolution

1 Introduction

The Urmia-Dakhtar region, a focal point of significant geological interest, has been extensively studied due to its complex tectonic settings and unique magmatic history. Previous research in this area has primarily focused on the dynamics of subduction processes and the resulting magmatic activities (Agard et al., 2011; Moghadam et al., 2022). Notably, studies have highlighted the region's role in the convergence of the Arabian and Eurasian plates, which has shaped its geological structure through intense orogenic activities (Agard et al., 2011). The presence of ophiolites and volcanic arcs in this region provides critical evidence for the subduction and subsequent collisional processes, offering insights into the deeper mantle dynamics and crustal evolution (Moghadam and Stern, 2011; Moghadam et al., 2022). These geological features not only highlight the region's crucial role in tectonic research but also provide essential insights into continental growth and crustal dynamics. This understanding is enhanced by seismic profiles that have been extensively employed to explore the upper crustal structure of the Iranian plateau (Mohammadi et al., 2014; Irandoust et al., 2022). These seismic investigations are vital for unraveling the complex interactions between tectonic activities and crustal structures, thereby deepening our comprehension of the region's geodynamic behavior and its broader geological implications. Furthermore, the investigation of seismic activities and their correlation with structural geology in this area has helped delineate fault zones and assess seismic hazards, making it an invaluable site for studying earthquake genesis and mitigation (Jackson, 1992; Derakhshani and Eslami, 2011; Rashidi et al., 2023a).

The study of fault interactions and tectonic processes often involves the examination of analog models to better understand geological phenomena. A simple test involving the pinching of a cylindrical part between scissors provides valuable insights into the behaviour of geological structures subjected to oblique shortening (Figure 1). In Iran, the Alborz and Zagros mountain ranges represent two distinct pincer segments (Ghanbarian et al., 2021; Mehrabi et al., 2021; Ghanbarian and Derakhshani, 2022; Rashidi and Derakhshani, 2022; Kamali et al., 2023; Mohammadi Nia et al., 2023), while the central continental crust can be considered analogous to the center column. In central Iran, intriguing fault processes resembling horst and graben systems are observed, where abandoned regions exhibit similar behaviours to the Lut block, undergoing predominantly east-west processes (Rashidi et al., 2019; Rashidi et al., 2021).

Further investigations reveal the presence of extraterrestrial blocks, such as Shotory and Tabas, along with Posht-Badam, Dasht Bayyaz-Bardsir, and Yazd blocks (Ezati et al., 2022a; 2022b; Rashidi et al., 2023b). These blocks demonstrate an east-west stretching pattern influenced by diagonal stresses in the south-north direction (Figure 1). Moreover, the scissors-cylinder test indicates that closing the scissors at an angle of 135° induces rotation of the cylinder. Drawing a parallel, the continental crust of Central Iran exhibits similar behaviour, possibly forming coloured melange due to intercontinental rifts associated with strike-slip faults and pull-apart systems around the region.

To gain a comprehensive understanding of these geological phenomena, the current study focuses on the Urumieh-Dokhtar pluto-volcanics and ophiolites located within the Qom-Zefreh and Nayin-Baft fault regions. Detailed investigations of petrogenetic and structural geology are conducted to develop new models on the formation and evolution of these features.

The integration of these findings provides valuable insights into the complex tectonic processes and fault interactions occurring in the Qom-Zefreh-Nayin-Dehsheir-Baft region. Understanding the genesis of ophiolites and pluto-volcanics within the context of pull-apart basin structures and dextral fault stairs can significantly contribute to our broader knowledge of geological evolution in Central Iran.

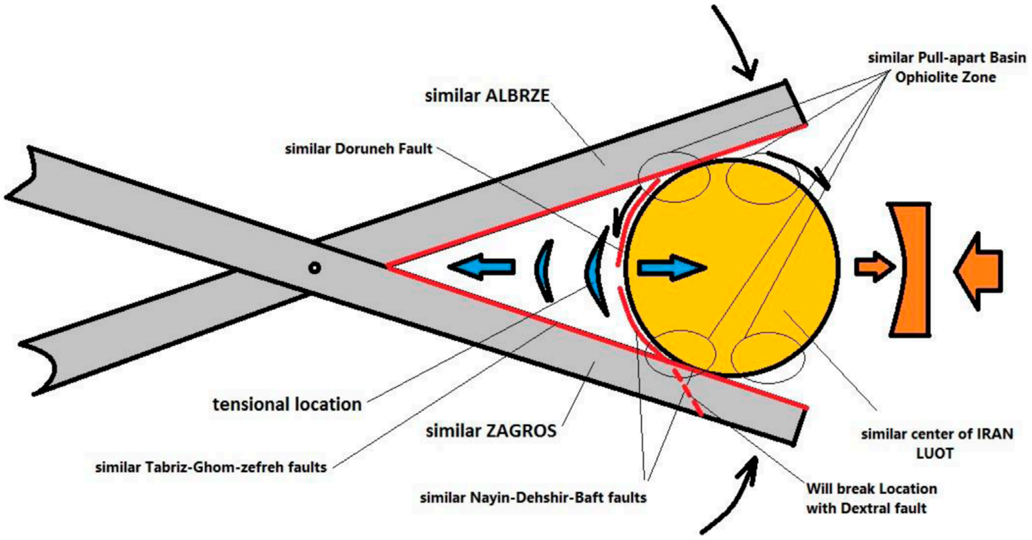

FIGURE 1
The schematic scissor model.

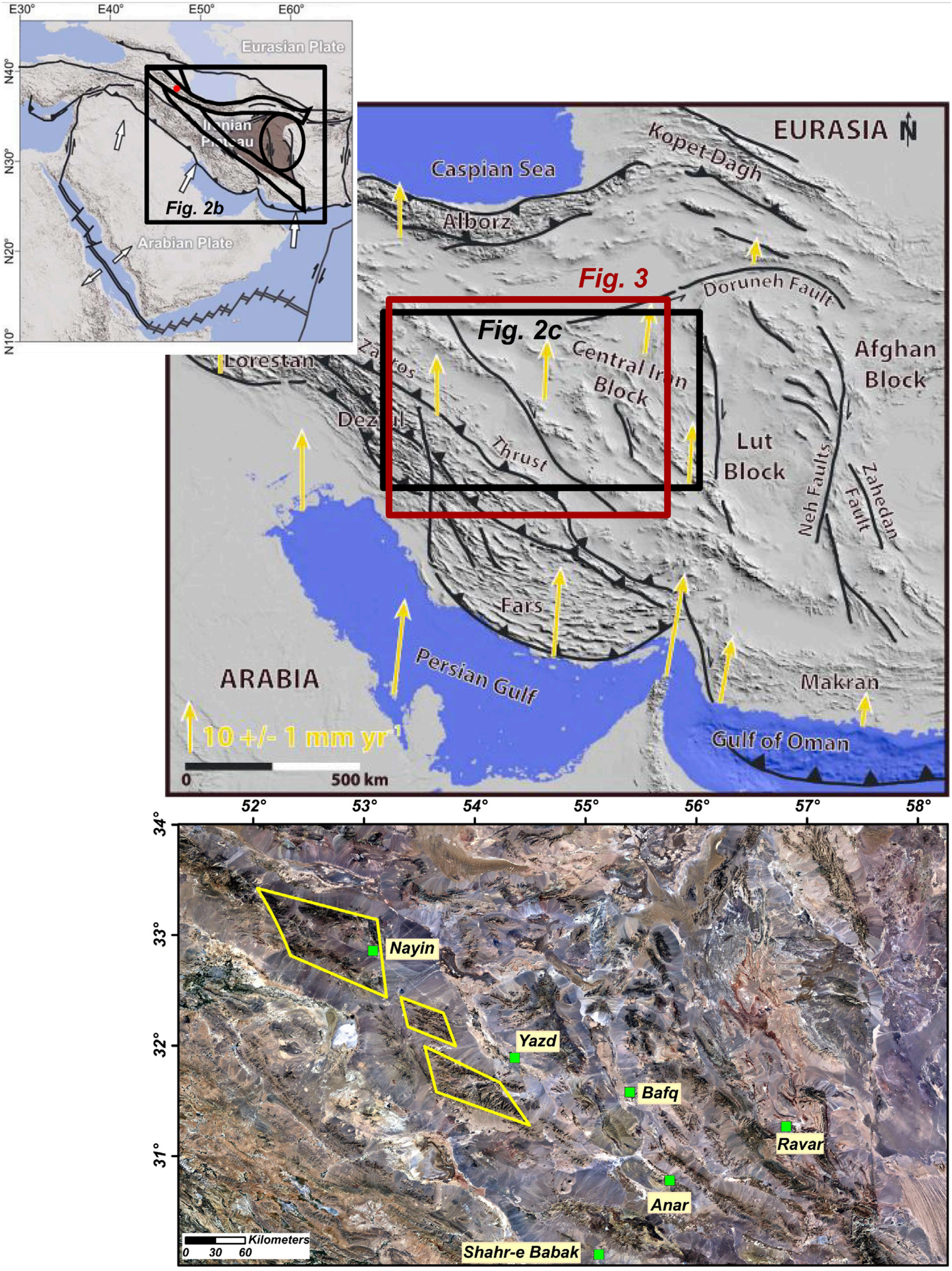

FIGURE 2
Aerial view of rhombic structures formed by shear zone activities: this image showcases the broken block patterns that have emerged as a direct consequence of geological movements within shear zones.

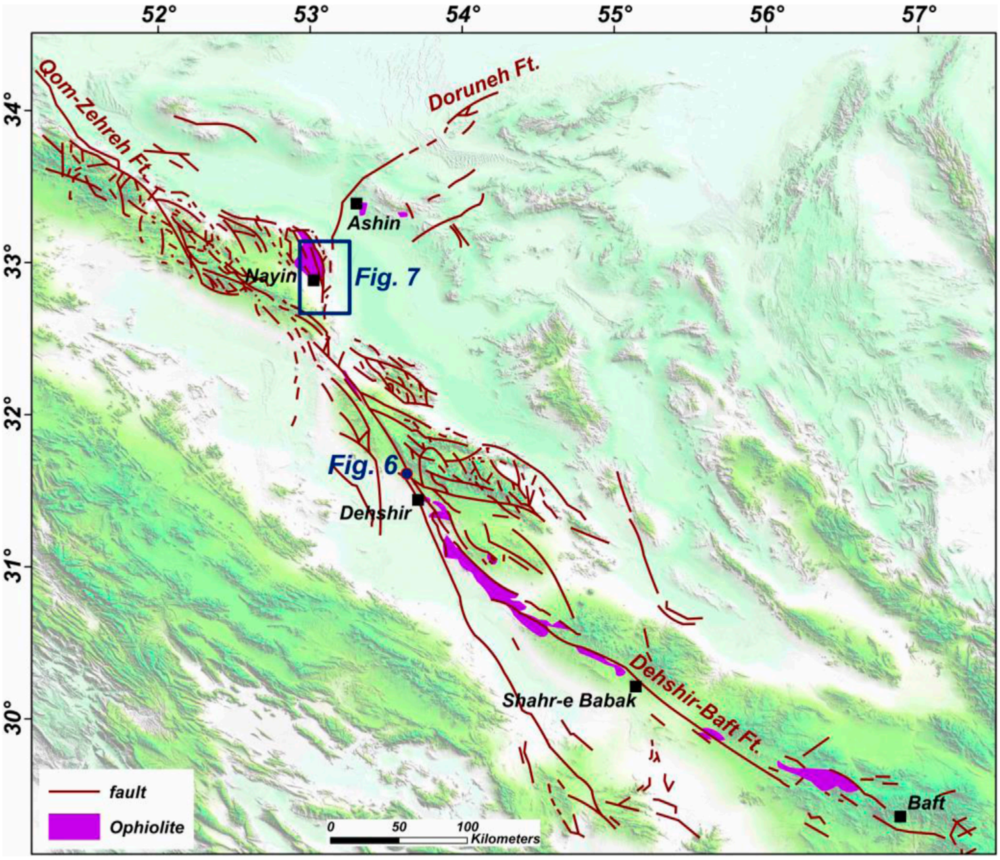

FIGURE 3
The map shows the distribution of Nayin-Dehshir-Baft faults and ophiolite locations.

2 Materials and methods

2.1 Methodology

In our study, we employed a multi-disciplinary methodology to analyze the Urmia-Dakhtar region's geological features comprehensively. We began with extensive fieldwork, collecting rock samples across various geological formations known for their complex tectonic structures and magmatic history. These samples underwent detailed petrological analysis using X-ray fluorescence (XRF) and electron microprobe analysis (EMPA) to determine their chemical compositions and textural properties. Geospatial analysis was conducted using satellite imagery and aerial photography to identify and map ophiolite sequences and volcanic arcs. This comprehensive approach, combining field observations with laboratory data and remote sensing, allowed us to develop a robust understanding of the region's geological framework and its dynamic processes.

Aerial photographs taken in the Nayin, Dehshir, and Baft areas reveal the presence of distinct rhombic structures in several regions. These structures are observed along the southwestern end of the Doruneh fault, southwest of the Qom-Zefreh fault, and along the Dehshir-Baft fault (Figure 2).

The comprehensive study and analysis of faults in this region reveal a significant correlation between faults and the occurrence of rhombic structures, underscoring the systematic influence of faults on their formation. It becomes evident that the appearance of these rhombic structures can be attributed to fault activities and the subsequent development of prominent right-stepping features.

Moreover, the intriguing presence of ophiolites in regions featuring these rhombic structures further suggests the crucial role played by the right-stepping dextral faults in the genesis of ophiolites within those areas. It appears that the pull-apart basins resulting from the right-stepping fault activity have contributed to the formation of ophiolites in these regions. Additionally, the occurrence of intercontinental rifts indicates the direction of oceanic crust formation in these areas (Figure 3).

The comprehensive understanding of the relationships between faults, rhombic structures, and ophiolites in this region will provide valuable insights into the geodynamic processes and tectonic evolution of the Qom-Zefreh-Nayin-Dehsheir-Baft region. These findings contribute to our broader knowledge of fault-related geological phenomena and the implications they have on the formation of significant geological features. Studying fault-related geological phenomena has

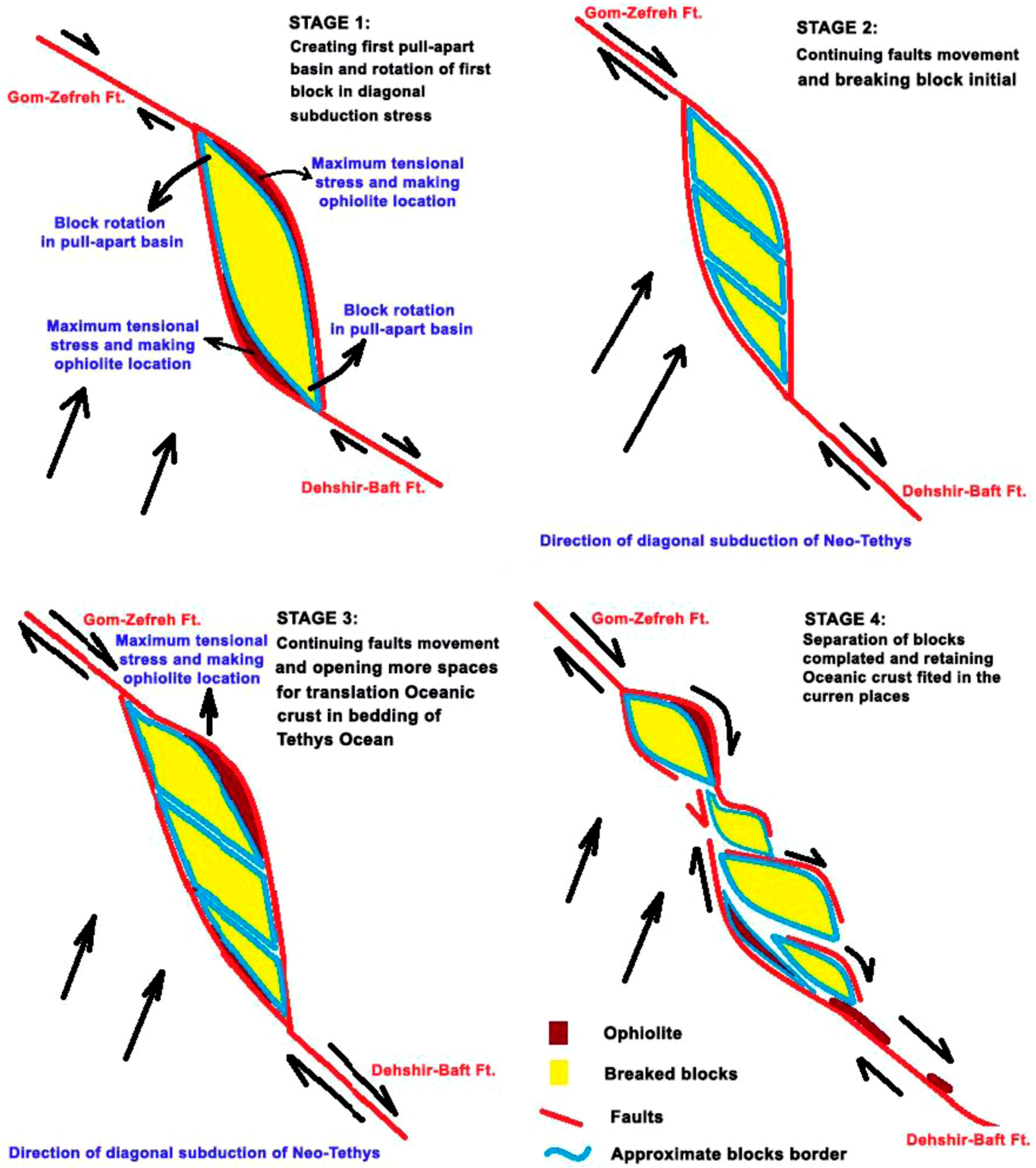

FIGURE 4
Structural domain model with a four-step shape.

been done in different parts of the world, such as the Himalayan fold-thrust belt (Bhattacharyya et al., 2015); western Ordos fold-thrust belt, China (Shi et al., 2019); Northern Eastern Ghats Province, India (Bose et al., 2020); Central Apennines, Italy (Smeraglia et al., 2022); Nanjieshan, western China (Yang et al., 2022); South China (Su, 2023); Northeast Asia (Wang et al., 2023), Southern Italy (Agostinetti, 2024); Idaho (McFadden et al., 2023); Ivrea-Verbano Zone, Southern Alps (Simonetti et al., 2023); eastern Mediterranean (Elitez and Yaltırak, 2023).

2.2 Role of faults in the formation of right-stepping faults and pull-apart basins

The studied area exhibits a network of faults originating from the Doruneh, Qom-Zefreh, and Dehshir-Baft intruder faults. Notably, the activity of the Dehshir fault has significantly influenced the overall trend of the magmatic arc in the Urumieh-Dokhtar region. Furthermore, variations in sediment thickness are evident, with the west side of the Nayin fault displaying thicker sediments compared to the east side, as observed through fault treatment in these areas.

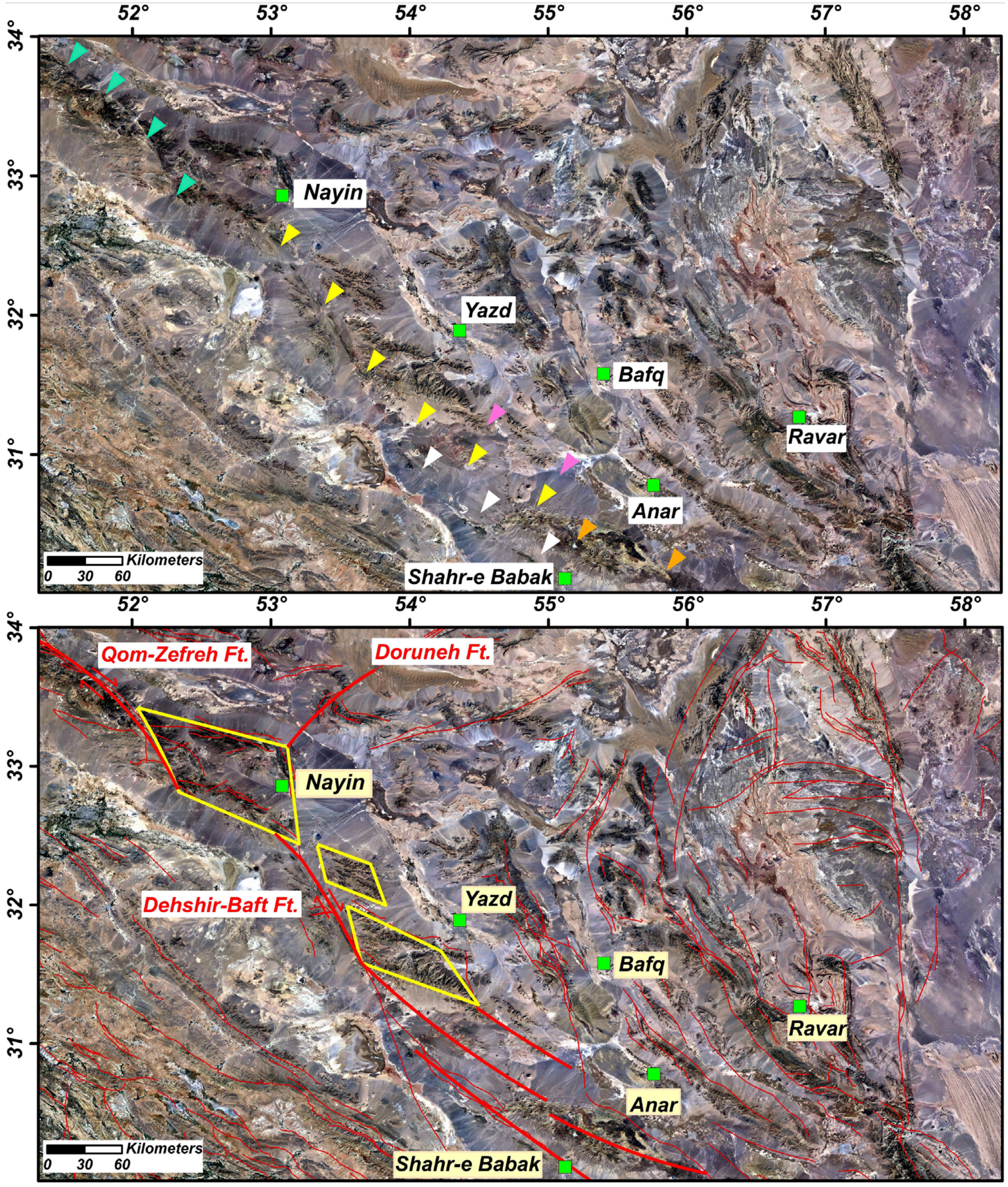

FIGURE 5
A model illustrating fault geodynamics and their impact on stress and gyration of ophiolites in relation to fault locations, enabling the construction of structures in the study area; the arrows in the upper part of the figure indicates the fault traces.

Interestingly, the distribution of ophiolites in the study area aligns consistently with the proposed pull-apart basin location model. Specifically, the northern Nayin ophiolites are situated east of the Nayin fault, while the Dehshir-Baft ophiolite is found west of the Dehshir-Baft fault. This spatial arrangement corresponds to the current fault map (Figure 3), where the most significant fault displacement and relocation can be attributed to the Nayin-Dehshir-Baft faults, thus confirming the model presented in Figure 4. By utilizing aerial images, we have successfully developed a four-level model that accurately represents the overall structure of the region (Figure 5).

2.3 Petrological insights into the ophiolite genesis

The rock formation of the Nayin magmatic ophiolite is of the type of tholeitic arc islands. This is evidenced by the composition of the Nain, Dehshir, Shahr-e-Babak, and Baft massifs, which are composed of associated slices of harzburgites, small bodies of gabbros, and dike swarm complexes, accompanied by various extrusives from basaltic-andesitic lava flows and breccias to dacites and rhyolites (Moghadam et al., 2009). The Dehshir ophiolite type is tholeiitic, and it contains dike sheets in the ophiolite sequence. This is characterized by the Late Cretaceous Dehshir ophiolite

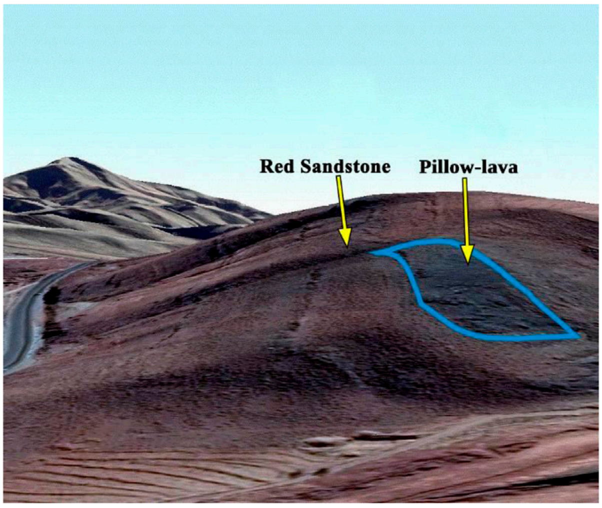

FIGURE 6
Pillow-lava placement interlayer between red Cretaceous sandstones in north of Dehshir.

being an important element within the Inner Zagros (Nain-Baft) ophiolite belt and containing all components of a complete "Penrose ophiolite," including tectonized harzburgites, gabbros, sheeted dike complexes, pillowed basalts, and rare ultramafic-mafic cumulates (Moghadam et al., 2010). The Nayin-Baft ophiolites are expected to exhibit the same structural and lithological stratigraphy along the entire length of the path to survive subduction with the oceanic crust, in comparison to the ophiolites of the Oman-Zagros axis associated with the Zagros-Geosutures (Derakhshani and Farhoudi, 2005). The Oman-Zagros axis ophiolites, including the Upper Cretaceous Zagros ophiolites, define the northern limit of the evolving suture between Arabia and Eurasia and comprise two parallel belts: the Outer Zagros Ophiolitic Belt (OB) and the Inner Zagros Ophiolitic Belt (IB) (Moghadam and Stern, 2011; Moghadam et al., 2022).

Therefore, there are differences in both the structure and age of ophiolite rock structures between the Zagros and Central Iran axis (Stocklin, 1968), which were formed from the late Jurassic to the Cretaceous. Since there is an age difference of about 10 million years between the ophiolites of the Zagros and those of Central Iran, the age of ophiolites in Central Iran is approximately 65 million years, while the age of those in the Zagros axis is 75 million years (Agard et al., 2011).

There might have been a continental rift around the Central Iran block initiated in the early Cretaceous after the neo-Tethys began to close. Deposition of the ridge in this semilunar narrow-headed plate, which separates Central and Eastern Iran from other continental plates, continued until the late Cretaceous. Sedimentary fossils indicate that they are accompanied by radiolarites and ophiolites from Zagros-Oman. Their age is Paleozoic, possibly Mesozoic, but never younger than the Turonian (Early Cretaceous). On the other hand, the colored melange mixtures around Central Iran exclusively belong to the late Cretaceous, from the Senonian to Maastrichtian index.

The Nayin-Dehshir-Baft region in Central Iran exhibits intriguing characteristics regarding the formation of ophiolites and tectonic evolution. The absence of wildflysch facies during the time of ophiolite deposition suggests a significant role of the magma arc in inducing these late Cretaceous ophiolites. It is evident that without the presence of the magma arc, these ophiolites would not have been deposited. The extent of subduction in the region remains uncertain. Formation mechanisms of ophiolites in this area can be attributed to the action of strike-slip faults and pull-apart basins, resulting in small rifts.

During the late Cretaceous, the Arabian plate exerted considerable influence on the Iranian plate, leading to significant pressure in the central part of Iran. Ongoing tensions in regions surrounding Central Iran can be attributed to the elasticity created by this pressure, driven by the force of Neo-Tethys subduction at an oblique angle beneath the Iranian plateau. It is believed that after the closure of the Paleo-Tethys during the Triassic, Central Iran and the Sanandaj-Sirjan zone consolidated and integrated in response to the pressure from the Neo-Tethys.

The impact of oblique subduction stress and tectonic scissors resulted in the splitting of the Iranian plate into various regions (Figure 1), forming local rifts, some of which led to the development of the oceanic crust. The first continental rift was seen in the early Cretaceous basement from sampling the red sandstones in the north of Dehshir with pillow-lava interlayer in the red sandstone location (Figure 6).

Within the study region, at least seven articles from 2005 to 2013 have been published, contributing to a deeper understanding of the geological complexities and tectonic processes in the Nayin-Dehshir-Baft such as (Eslamizadeh and Samanirad, 2014). This kind of methodology has been used in several researches such as (Wakabayashi, 2012; Jeřábek et al., 2016; Arai and Chigira, 2019; Lin et al., 2020; Rowan et al., 2022; Hu et al., 2023; Lei et al., 2023; Mameri et al., 2023; Li et al., 2024; Martin, 2024).

2.4 Petrology perspectives

In the southwest of Kashan and west of the Qom-Zefreh fault to the Gavkhony embayment and the south of Nayin in the Molla_ Ahmad province, to the west of Dehshir-Baft fault in the northwest and southwest directions, there is a mountain range known as the Andes magmatic arc. This mountain range is the result of the subduction of the oceanic Neo-Tethys crust beneath Central Iran since the collision of the Arabian plate and Iran occurred at the end of the late Cretaceous. This geological process is exemplified by the preservation in the early form of the Magma Island in the north of Nayin, as depicted in Figure 7. However, volcanic activities continued in the Urumieh-Dokhtar area, from the Oligo-Miocene to sometimes the Pliocene-Quaternary.

The results of various petrology studies have reviewed the thickness of the crust in the Nayin area of Dehshir and the warp, indicating a thickness of about 125–175 km for the axis of the Urumieh-Dokhtar. Four strong anomalies have been introduced in Anar, Dehshir, Kuhpayeh, and Maymeh (Figure 6). Moreover, adakite stones originated from these areas. Also, based on studies in eight areas of Ghom-Salfachegan, Josheghan, and Ghohrud, Kahang, Kajan, Dehshir, Arnan, Anar-Baft, collected geochemical data

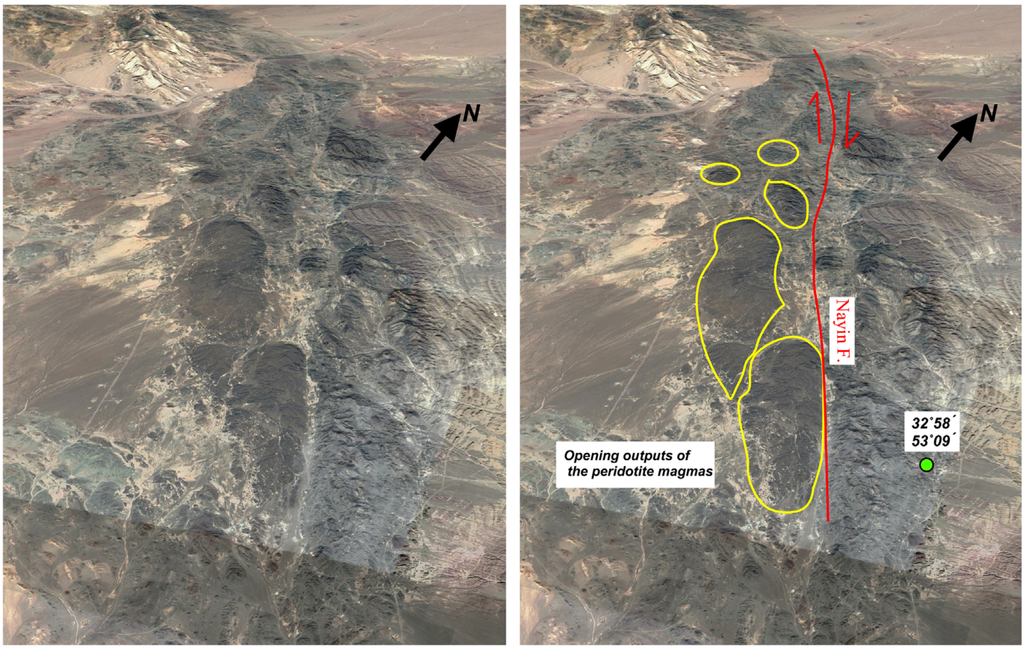

FIGURE 7
Early Preservation of Magma Island Located North of Nayin: This image captures the initial geological state of the Magma Island, highlighting its features and conditions during the early stages of formation.

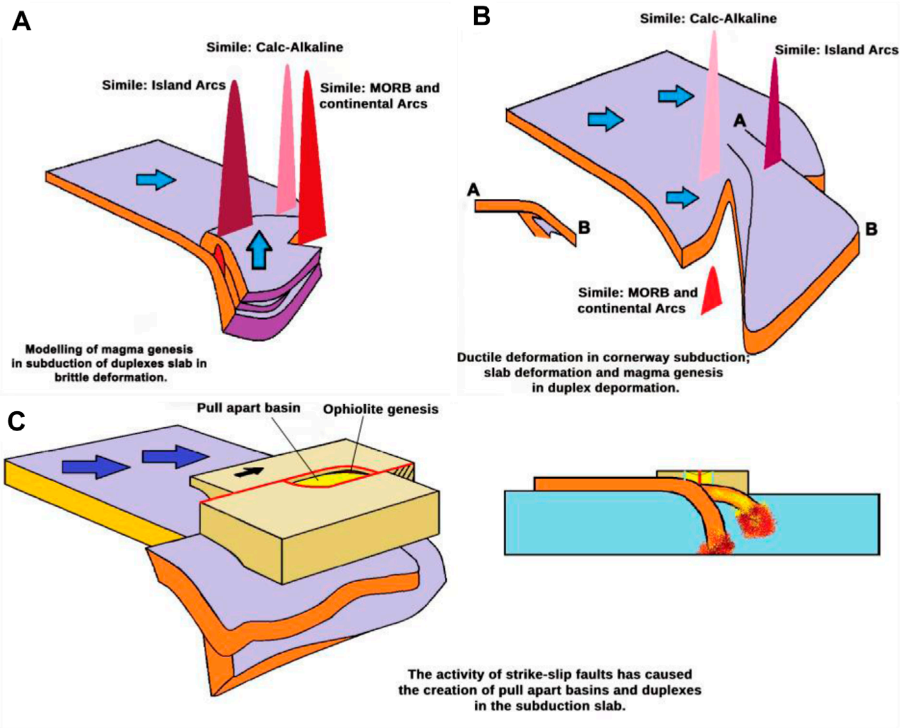

FIGURE 8
Three-Dimensional Model of Duplex Formation in a Subduction Fracture Zone and Integration with Continental Crustal Stubs: This set of models demonstrates the stages of duplex formation in subduction environments. **(A)** Shows the genesis of oceanic crust duplex in a brittle state during subduction. **(B)** Illustrates the oceanic crust duplex in a ductile state under subduction and genesis. **(C)** Depicts oblique subduction, the formation of a dextral strike-slip fault in the continental crust, the development of a Pull-apart basin, and the transition from subduction to super subduction.

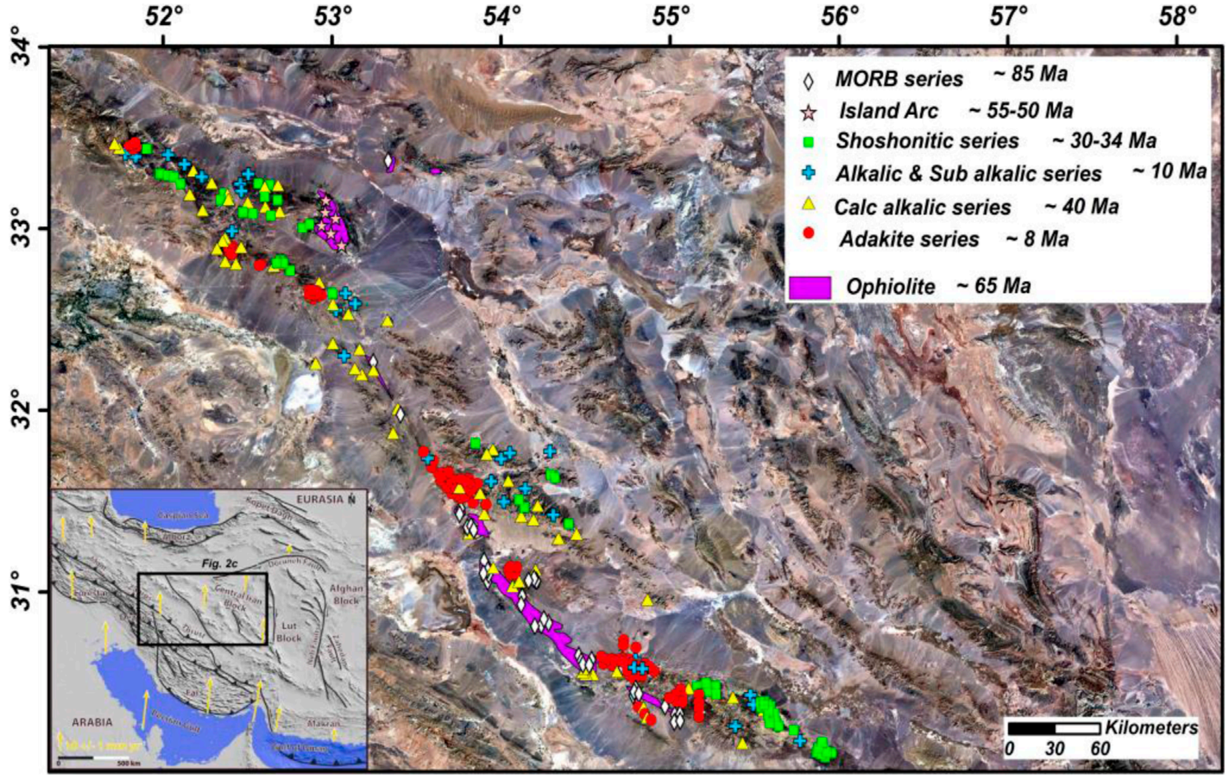

FIGURE 9
Diversity of magma geneses spanning the cretaceous to pliocene periods: This illustration highlights the range of magma formations occurring from the Cretaceous era to the Pliocene epoch, specifically in a region situated above the duplex structure of the oceanic crust.

show all the features of the adakitic magma. Additionally, various shoshonitic magmas have been observed in the Josheghan and Ghohrud groups. All the work by these researchers is summarized in three models for forming duplexes from the oceanic crust and forming all kinds of magma genesis in this region, intricately illustrated in the three-dimensional model of duplex formation in a subduction fracture zone as presented in Figure 8.

As has been observed, the Urumieh-Dokhtar Pluto volcanoes formed within the magmatic arcs, with their genes along those arcs resulting in tensile regions of alignment arc-directional where the magma is obtained from the calc-alkaline. The petro-genesis is not complete, and the alkaline magmas due to the dextral strike-slip fault stretch regions affect its nature and lead to a calc-alkaline leading to alkalinity (Figure 9).

3 Discussion

The presence of strike-slip faults and adjacent rhomboidal structures, along with volcanic activities aligned with these strike-slip faults, indicates a shear-tension tectonic system. This system facilitates the ascent of magma tongues from deeper parts by creating pull-aparts in the crust. On the other hand, the observation of ophiolitic rocks alongside rhomboid structures, the formation of a complete ophiolite sequence in the Dehshir regions, and the presence of pillow lava magma near the Dehshir-Baft fault and south of Nayin suggest active traction in these areas. Therefore, the tensile activities in a shear system, starting from the late Cretaceous during the convergence of the Arabian and Central Iranian plates, should be considered.

Such behaviors during the convergence of the plates and the creation of tension zones can be explained and justified by diagonal convergence and, subsequently, diagonal subduction. Moreover, due to this diagonal subduction, the subducting pillar, under diagonal stress, fractures and subducts under itself, forming a duplex of the oceanic slab. This process later leads to magmatism, such as the Tholuieta Arctic Islands type, in this location. Also, the emplacement of magma in the Oligo-Miocene occurred in the same fault areas and along the Urumieh-Dokhtar belt with oblique subduction as a result of the fracture and dextral strike-slip displacement along the edge of the Iranian plate corresponding to the magmatic belt's zone resulting from subduction.

Therefore, the fracture of the subduction edge since the late Cretaceous, while a large part of the Central Iranian plate was still deep in the sea, and the metamorphism of Cretaceous units near ancient diabase dykes and pillow lavas, can be considered a reflection of the onset of rifting in the Upper Cretaceous and the metamorphism of skarn formation and strip meta-cherts. This has led to the creation of deeper basins in sea areas and, consequently, the formation of pull-aparts and the presence of pillow lava magma in these areas. In the current location of the Urumieh-Dokhtar magmatism belt, which was the site of an ancient

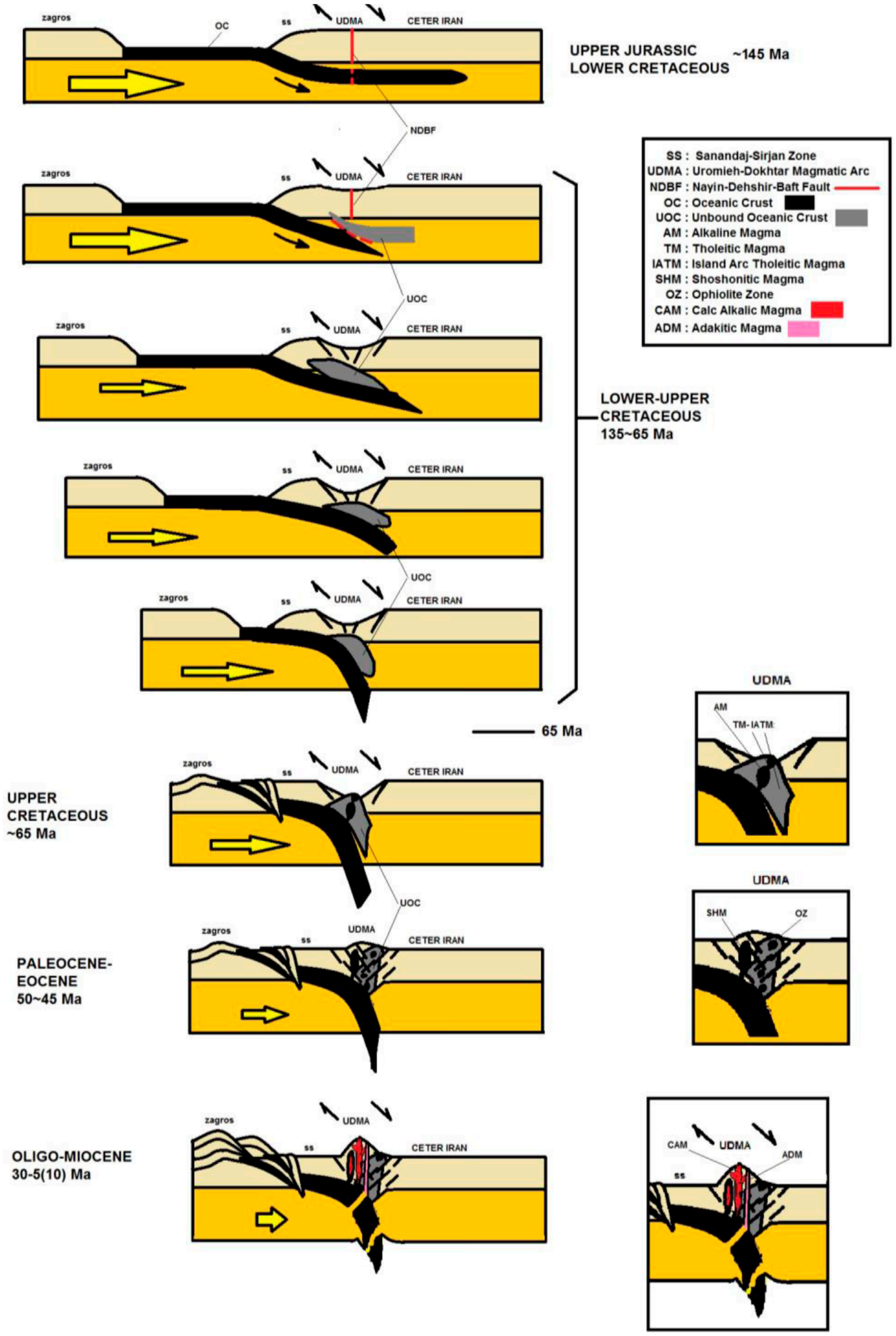

FIGURE 10
Schematic representation of subduction outcomes: A synthesis of geological processes.

fracture on the edge of the Central Iran plate during subduction, the increasing convergence of the plates due to diagonal subduction caused further displacements in this fractured edge. As a result, the extensional basin deepened, the sediments of the ophiolitic sequence became complete and mature, and this process of convergence continued until the pressure reduced the amount of displacement, breaking the corresponding tension basin and creating smaller basins with fault-formed sides. These faults were created due to the fracturing of the larger tensile basin and the creation of a smaller basin.

Finally, with the continued convergence of the plates and diagonal subduction, magmatism resulting from the subduction began to rise from the same ancient fracture of the plate edge and through the resulting fractures, creating the Urumieh-Dokhtar magmatism belt. Given the presence of various types of alkaline and calc-alkaline magmatism, it can be stated that the intrusion of magmatism resulting from subduction and traction occurred simultaneously. Additionally, considering the obliqueness of the subduction, the presence of adakitic magmatism originating from deeper depths can be attributed to the fracture of the subducting column or shrinkage in the slab. As a result, the presence of two types of magmatic rocks and an ophiolitic sequence in the vicinity, demarcated by faults and the transformation of ophiolites, indicates that the ophiolitic sequence predated the magmatism in the extensional basins, which later evolved due to the placement of magma within the fractures and its diagonal pressure and preceding faults. In fact, the presence of ophiolites and subsequent magma tongues resulting from subduction can be attributed to the creation of a pull-apart in the ocean floor and the formation of an oceanic rift, which, following the retreat of the sea, transformed the former rift into a stretching basin for magma emergence. The result of subduction is shown schematically in Figure 10.

4 Conclusion

In this study, we investigated the presence of magma types in an area in the vicinity of ophiolites of oblique and Iceland arc types, along with the presence of adakite and its consequences in the Urmia-Dakhtar region. Our findings highlight the deep melting depth required to form adakite magmas, originating from the melting point of the oceanic crust of the mantle wedge. As a result, the ascent of magma leads to contamination of the mantle. It is worth noting that we observed that the ophiolitic fabric in the Kashan Nain Dashir region is intricately linked with the volcanic arc.

The model developed by revealed a diverse range of magma types, including Tolutia, Toluieta Arctic Islands, Sub-Alkaline, Alkaline, and Calc-Alkaline, spanning from the late Cretaceous to the Tertiary period. These magmas exhibited distances varying from hundreds of meters to 20 km, indicating the complex tectonic regime in the region, far more intricate than a simplistic model suggests.

We propose a shear-tectonic system as a suitable model to explain the local dislocations caused by slip movements and the deformation of tensile stones in conjunction with subduction. The influence of subduction and pressure systems resulting from the collision between the Arabian plate and Iran induces a rightward movement in the Urumieh-Dokhtar axis, featuring a set of faults extending from the southeast to the northwest, spanning from Tabriz to Minab.

Our investigation further suggests an ancient transformation fracture located beneath the continental crust, which underwent its own displacement and gave rise to multiple magmas due to stretching motions and the creation of tensile stacks over various periods. Subsequent to the collision, volcanic activities ensued, leading to the formation of plavo-alkanic rocks during the Eocene to Oligocene period.

Notably, colored compounds observed in the east of the northern part and the western part of the southern part of the high-rise stack indicate that this arrangement occurred during the formation of a stretch stack in the Upper Cretaceous.

Furthermore, the crustal structure underwent deformation under tensile stretch and eventually formed the present-day duplex of oceanic plates. This duplex structure serves as a source of tholeiite magma for Arctic islands and necessitates the supply of calc-alkaline magma following the continental collision.

In conclusion, our comprehensive investigation presents an innovative understanding of the Urumieh-Dokhtar region's geological complexities, shedding light on the formation of Adakit magma, the interplay of tectonic forces, and the volcanic processes shaping the area's geological history. These findings provide valuable insights into the complex geological processes and contribute to a deeper understanding of the region's dynamic tectonic evolution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AM: Data curation, Methodology, Software, Writing–original draft. AR: Conceptualization, Formal Analysis, Investigation, Project administration, Validation, Writing–review and editing. SS: Investigation, Methodology, Visualization, Writing–review and editing. SM: Conceptualization, Data curation, Formal Analysis, Supervision, Validation, Visualization, Writing–review and editing. MN: Validation, Writing–review and editing. HK: Validation, Writing–original draft. ME: Software, Writing–original draft. RD: Conceptualization, Funding acquisition, Investigation, Resources, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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