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# Geochemistry and Tectonic Environment of Volcanic Rocks in North and Northeast of Kelardasht (Central Alborz zone)

***elham shahosinie*، sareh farahi، farzaneh farahi***
[1]Phd in petrology, Tehran, Iran.
[2]Department of Geology, North Tehran Branch, Islamic Azad University, Tehran, Iran.
[3]Department of Geology, Islamic Azad University, Lahijan, Iran

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*Corresponding Author's Email Address:
*elham_shahosinie@yahoo.com*

## Abstract

The study area structurally belongs to the Central Alborz tectonic range and is located 25 km south of Chalous City. The volcanic rocks in the region, composed of basalt, andesite, trachyandesite, and dolerite, have been formed by fractional crystallization and, in some cases, contamination processes. The major minerals in the rocks include clinopyroxene, olivine and plagioclase. Porphyritic to mega-porphyritic textures with chlorite, glomeroporphyritic, and amygdaloidal matrices are observed in the rocks. Plagioclase, hornblende, and pyroxene can be considered as the main mineral phases of this range of rocks. In general, the rocks of the region are rich in LIL and LREE elements and devoid of HFS elements. Investigation of trace element and rare earth element ratios shows that basalts in the study area can be formed by partial melting of a peridotite garnet at depths and high pressures. Negative Ce anomaly, Nb positive anomaly, Pb/Ce ratio similar to sources OIB, and variation in Ce / Pb ratio emphasize the role of continental and mantle lithospheres in the alignment of magmatic sources of volcanic rock elements in the study area. The two phenomena of delamination & detachment of the lithosphere and its immersion in the mantle (due to density difference) and transfer of dense lithosphere to the bottom (lower mantle) are related to the contamination of the magmatic source with the lithosphere for early magma rocks. The area's volcanism is known to be within the sheet.

## Introduction

Alborz has long been extensively studied by researchers because of being the collision zone of Gondwana to Eurasia (Stöcklin, 1974; Berberian & Berberian, 1981; Stampfli, 2000; Guest et al., 2006 a, b). Along the Alpine-Himalayan belt, the western Alborz extends the Molasses Oligocene Basin to the Quaternary in the Kora Basin in the northwest (Zanchi et al., 2006). It also reaches the Caucasus Molasses Basin in northeastern Turkey and the eastern part of the North Caucasus Molasses Basin (Ershov et al., 2003). Therefore, several phases have been identified and studied including orogeny, magmatic activity, and sedimentation from the Early Paleozoic to the present. In this zone, the Cenozoic magmatic activity significantly expands with a basic to acidic (less) composition. In terms of stratigraphic divisions, the Alborz Cenozoic magmatic activity, mostly with the Paleogene age, is considered equivalent to the Karaj Formation (Annells et al., 1975; Stöcklin, 1968). According to some researchers, the rocks of the Karaj Formation have been formed intercontinental dependent on subduction in the northern direction along Zagros (Zanchi, 2006; Asiabanha et al., 1989). The age of corresponding units in western Qazvin has been assumed equivalent to the Oligocene (Asiabanha, 2001). Following the submarine eruptions in Alborz, large volumes of intermediate to basaltic lavas have been ejected through surface fissures (Mobashergarmi, 2013). The origin of these volcanic lavas is a subduction-dependent zone with a small share of asthenosphere melt (Shafaii Moghadam & Shahbazi Shiran, 2010).

## Method

During field operations and systematic sampling, 50 samples were taken and thin sections were prepared and studied. Fifteen samples were selected and analyzed through induced coupled plasma mass spectrometry (ICP-MS) in MS Analytical Canada to investigate and determine the amount of major, minor, and trace elements present in the samples.

## Geology of the region

Central Alborz includes the southern convexity of the Caspian Sea and extends from Semnan to Qazvin. The study area 25 km northeast of Kelardasht, is located at 51° 13´ to 51° 25´E and 36° 32´ to 36° 36′N. The geomorphology of this area, like most other areas, is affected by the facies of rock units, the trend of folds, and the type of fault mechanism. In general, this region is resultant of an anticline with an axis along the west-northwest, and east-southeast, with an axial inclination toward the east and southeast. This volcanic unit is composed of Cretaceous and southeastern carbonate units with a normal boundary with Lower Cretaceous carbonate units. Therefore, this volcanic unit has a clear boundary with Middle-Upper Cretaceous carbonate rocks. Lower Cretaceous sediments in Central Alborz are characterized by nonconformity and progressively located on the sediments of the gypsum-melaphyre facies (locally) the Lar Formation (Upper Jurassic) or older sediments. This indicates the orogenic function of the Late Cimmerian (Darvishzadeh, 2002). Since these sediments are known as the Tizkooh Formation (Barremian-Aptian), there are no Neocomian sediments in Central Alborz. The main diversity of volcanic rocks in the area belongs to the Lower-Middle Cretaceous in the range of olivine alkane basalt, alkali basalt, basaltic andesite, andesitic basalt, pyrite, basaltic tuffs, agglomerate, autoclastic shearing, plastic such as volcanic sandstone with carbonated cement and conglomerates with coarse rounded to volcanic elliptical fragments. Moreover, plastics are also found in the area in layer form and occasionally in the structure of pillow lava.

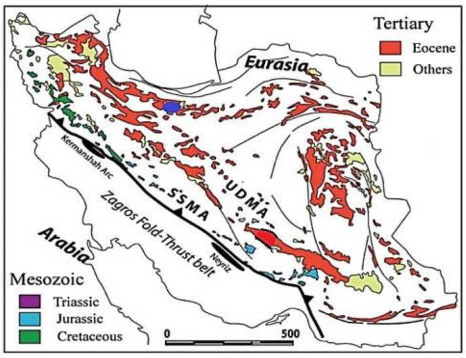

**Fig. 1.** The study area in the map of structural zones of Iran (Agard et al., 2011)

**Basalts group**

Plagioclase is more abundant in the group of basaltic olivine rocks in the area. Plagioclase phenocrysts are of the calcium type (Labradorite to Bitonite). Also, plagioclase crystals are observed in some specimens as microphenocrysts. The presence of plagioclase microlites and their relative orientation has led to the flow texture in the rocks of the region. Pyroxene is also one of the main minerals in the rock. These crystals are probably of the Augite type. Another phenocryst in these rocks is olivine (Fig. 2a and 2b). Olivine crystals are found as euhedral to subhedral crystals with a direct extinction. They are often round or embayed, crushed, iddingsite, and serpentine crystals. Iddingsite is also observed inside the cracks, in addition to the margin and crystal lattice. In the glass paste, olivine iddingsite microlites appear along with plagioclase microlites, alkaline feldspar, pyroxene, and opaque grains. The glasses are oxidized and blackened. Iron oxide is observed as euhedral. The amount of glass is very low in the matrix. Some cavities have been filled with calcite.

Plagioclase is the most abundant phenocryst in the group of trachybasalts. This mineral is observed as elongated microlites with glass in between. Plagioclase crystals show a sieve texture in the core. Considering their optical properties, these plagioclases vary from albite to oligoclase type. The presence of plagioclase microlites and their relative orientation has led to the flow texture in the trachybasalts of the region. Olivine is found as the euhedral phenocryst along with the olivine iddingsite microphenocryst. Pyroxene is observed as both a phenocryst and a microphenocryst. Regarding their optical properties, the type of these amphiboles is hornblende. These minerals are often replaced by chlorite and opaque minerals.

Dolerite: The texture of this group is porphyric with the microcytic matrix. Plagioclase is found as euhedral to amorphous with an average size of 450 mµ along with albite-Carlsbad and albite-pericline twins. These minerals are dispersed in the matrix in both monocrystalline and accumulation forms. Based on the optical properties, these plagioclases are oligoclase to andesine type. Alteration products of this plagioclase include clay, chlorite, calcite, and sericite minerals. Olivines are observed in subhedral to amorphous monocrystals and aggregate with relatively low frequency. These olivines have the characteristics of substitution by chlorite, opaque, and iddingsite minerals. Pyroxene is found subhedral to amorphous with an average size of 750 µm and occasionally with a double twin in the rock texture. These pyroxenes are in the Augite type based on their optical properties. Among the alteration products of these pyroxenes are chlorite, calcite, and opaque minerals. The matrix is composed of plagioclase, pyroxene, olivine, and opaque microcrystalline minerals. Minor minerals include euhedral to amorphous opaque monocrystalline minerals that are scattered throughout the texture (Op).

**Intermediate rocks**

In the group of intermediate rocks (trachyandesite and andesite), plagioclase is the most abundant phenocryst. The plagioclase crystals have mainly oscillating zoning based on the extinction angle within the range of andesine to labradorite (Figs. 2e and 2f), within which apatite infiltration is also observed. Corrosion of crystal margins and poikiloblastic texture is also seen in plagioclase representing physical and chemical imbalances during crystallization. In some samples, calcium plagioclase is observed as megaphenocrysts with oscillating zoning along with amphibole grains corroded and altered to sericite and carbonate. Possibly, very mild cooling may have caused plagioclase megaphenocrysts in some samples. The amphibole crystals found within plagioclase have been crystallized before plagioclase. The presence of plagioclase microlites and their relative orientation has resulted in microlithic texture in the rocks. Pyroxene is an augite microphenocryst in the studied samples, which is accompanied by magnetite and is mainly found as intact crystals. Accumulation of pyroxene, plagioclase, hornblende, and iron oxide crystals has originated glomeroporphyritic texture in these rocks.

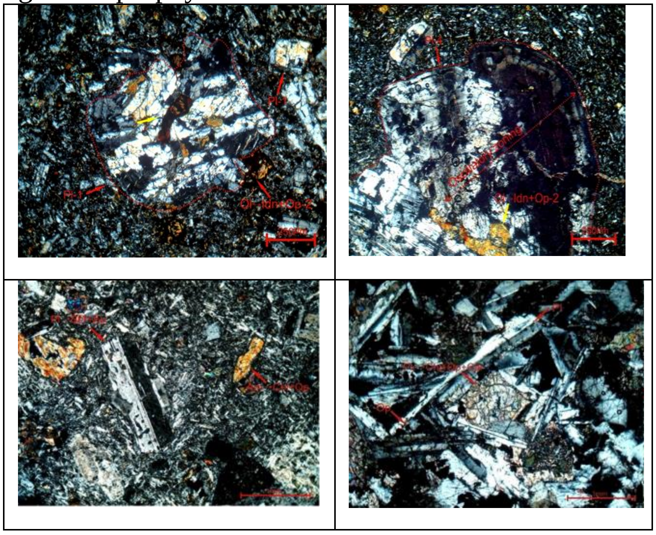

**Fig. 2. a)** Another view of the first type single crystal and accumulated plagioclase phenocryst (red dotted line) with the insertion of iddingsite olivine in olivine basalt; **b)** The plagioclase with poikiloblastic texture in the center in olivine basalt; **c)** The type 2 single-crystal plagioclase phenocryst with poikiloblastic texture and microlithic plagioclase; **d)** The type 3 single-crystal plagioclase phenocryst with dissolved margins (red dotted line) caused by the imbalance with the content of amorphous diopside-type pyroxene; **e)** The plagioclase, amorphous and amphibole pyroxene in trachyandesite; and **f)** The plagioclase, pyroxene, olivine iddingsite, and calcite + opaque mineral in dolerite.

## Geochemical studies of volcanic rocks in the area

Examining the main elements of the rocks in the region indicates that these rocks are a range of plutonic basic rocks. SiO2 levels in these rocks are 43 to 65% and the studied rocks are within the range of basalt and trachybasalts, trachyandesite, and dacite (Fig. 3.a and b). Moreover, based on the classification boundary of the semi-alkaline and alkaline series (Irvine & Baragar, 1971), the studied rocks are in the alkaline range (Fig. 3.c and d). Generally, the oxides of Fe2O3, TiO2, MgO, CaO, P2O5, Cao, MnO, and Al2O3 decrease with increasing silica, while the oxides of K2O and Na2O have an upward trend. An increase or decrease in any oxide or element can represent its presence or absence in the minerals constituting the plutonic rocks. In general, the changes of the main elements against SiO2 in the studied samples reveal a reproductive relationship in most of the different plutonic rocks in the area (Fig. 4).

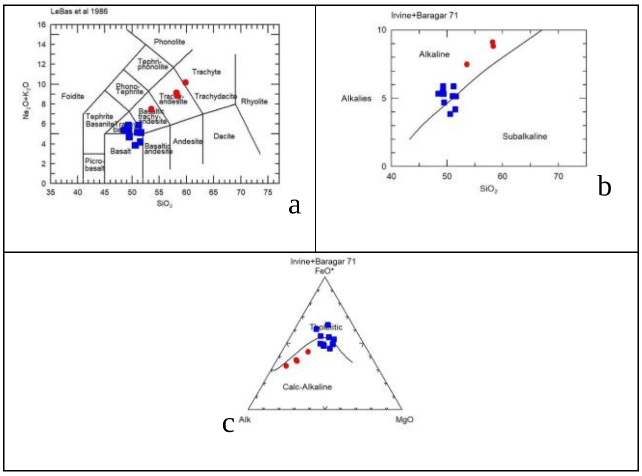

**Fig. 3**. **a)**. The diagram of $Na_2O + K_2O$ vs. $SiO_2$ (LeBas et al., 1979); **b)** The diagram of total alkaline versus $SiO_2$ (Irvine & Baragar, 1971); **c)** The AFM diagram (Irvine & Baragar, 1971).

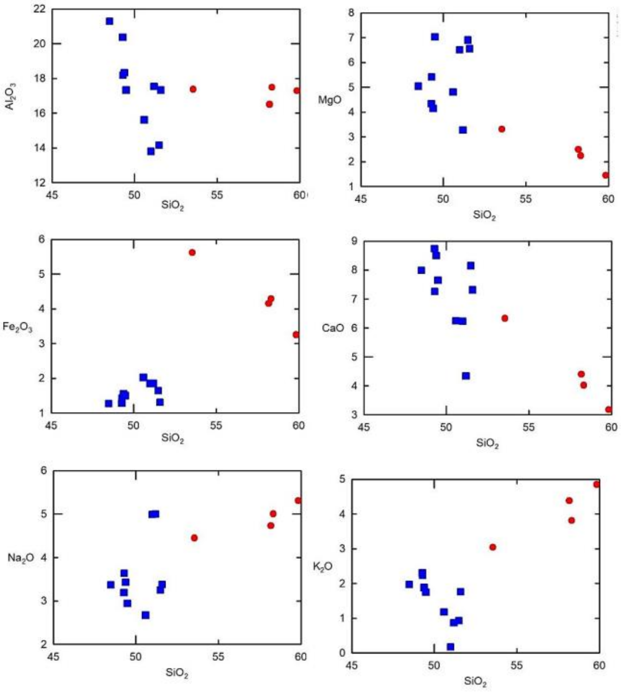

**Fig. 4.** The changes in key elements in Harker diagrams (Harker, 1909)

The diagrams in Fig. 5 represent the average pattern of normalized trace and rare earth elements relative to the values of chondrite, crust average, primary mantle, and OIB for the rocks of the study area. In all these diagrams, similar distribution patterns of elements in the rocks of the region are well demonstrated. Some positive and negative anomalies are found in the values of Sr, Rb, Nb, Pb, and Ba in the normalized diagram based on the values of the initial mantle (Fig. 4.a and b). Since Ti and P elements are in the group of elements with high stability field strength (HFS) and do not represent mobility during secondary processes, the observed anomalies can be interpreted based on petrological reasons. The existence of negative anomalies in Nb also indicates the role of magmatic contamination with the continental crust in the evolution of the rocks in the region. Severe positive anomalies of Pb and Ba denote the continental crustal contamination and a positive Sr anomaly represents the existence of plagioclase phenocrysts in the rock. The positive anomaly is related to Th, the increase of which indicates crustal contamination. The descending trend in the normalized multivariate diagram against the initial mantle composition, as well as the lack of negative anomalies of the elements Nb, Ti, and P, represent the obvious features of continental alkaline magmatism and lack of continental crustal magma contamination.

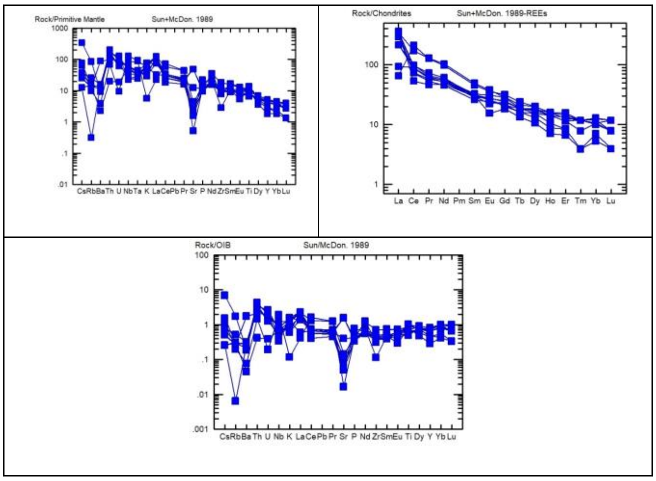

**Fig. 5.** **a**) The normalized diagram of samples relative to chondrite (Nakamura, 1974); **b)** The normalized diagrams of samples relative to the primary mantle (Sun and McDonough, 1989); and **c)** normalized diagrams of samples to OIB (Sun and McDonough, 1989).

According to Cabanis and Lecolle (1989), and Wood et al. (1980), the specimens are placed within the continental range (Fig.7.a and b). In the diagram of Peacer (1982), the specimens are placed within the in-sheet basalt position (Figure 7-d), and in the diagram of Muller et al. (1992) the samples are placed in the WIP range.

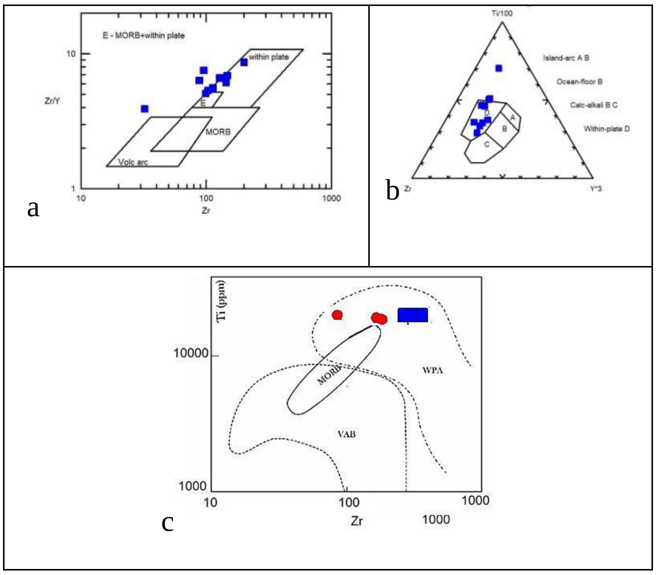

**Fig. 6. a)** The position of the studied samples in the diagram (Pearce and Cann, 1973); b) The diagram for determining the tectonic environment (Pearce and Norry, 1979); c) The diagram of Pearce (1982)

The degree of partial melting of mantle origin is assessed based on the abundance ratios of different trace elements (Zhou et al., 2008). The two elements La and Sm have no movement caused by the changes in the mineralogy of the origin, such as garnet or spinel, and represent the general composition of the mafic rock's origin. On the other hand, the compatibility of Yb in garnet against Sm in the origin is used to comprehend the mineralogy of the origin (Shaw, 1970). In terms of the abundance of La and Sm elements, all the studied samples have a similar composition to the melt derived from the enriched mantle and are placed on a trend consistent with about 5% partial melting of garnet-containing garnet. The origin of spinel Lherzolite is also confirmed in the diagram of LaN/ SmN versus TbN/ YbN. Based on the location of the studied rocks, the mantle often has Lherzolite spinel composition originating from a depth of 60-70 km equivalent to a pressure of 18 to 20 kb, which is the stability range of spinel (Fig.8.a). In the diagram of Th/ Yb versus Ta/ Yb, the specimens of the region are within the OIB range denoting the enriched origin of the OIB type for the progeny in the area. According to Fitton (2007), alkaline and continental transition basalts with the same composition as real OIB basalts have an ambiguous origin compared to real OIBs. In general, in intercontinental zones, the alkaline formation of basalts is similar to the formation of OIB basalts associated with mantle plume processes or the melting of upwelled asthenospheric materials (McKenzie and O'Nions, 1991). Fitton et al. (1977) presented the following criterion to identify the origin of plum and non-plum alkaline basalts.

$\Delta Nb = \{1.47+\log(Nb/Y)-1.92\log(Zr/Y)$

If $\Delta Nb > 0$, the origin is a plume, however, by $\Delta Nb < 0$ the rocks have a non-plume origin. For the rocks in the region, $\Delta Nb$ is about 0.35 to 1.44. Therefore, these rocks are located in the plume-associated alkaline range. The alkaline nature of the basaltic magma is a result by two mechanisms the lower partial melting rate of lherzolite garnet and the partial melting of the metasomatized mantle (Best, 2003).

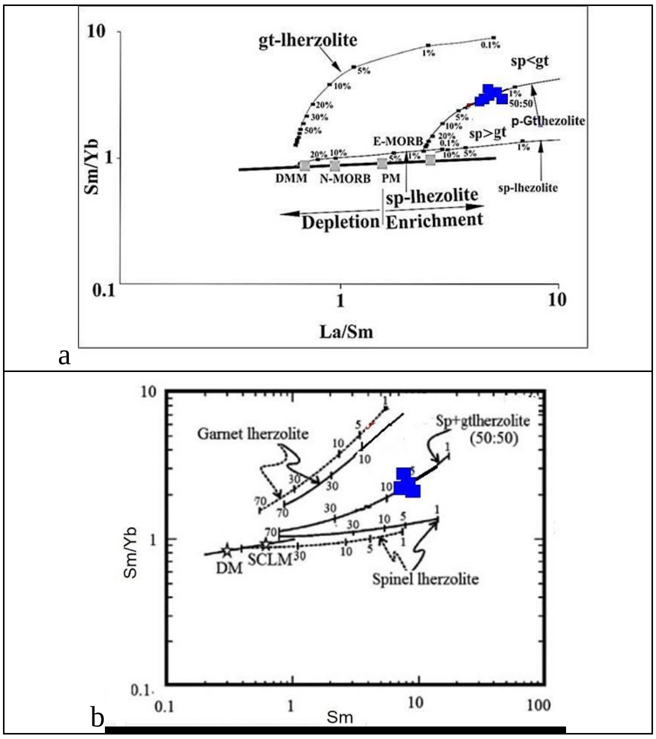

**Fig. 7a)** Sm / Yb versus La / Sm diagram where the melting curves were calculated based on the lherzolitic spinel mantle and the lherzolitic garnet mantle (Shaw, 1970); **b)** The diagram of Li & Chen (2014).

## A geodynamic model for the formation of igneous rocks in the study area

Three main regions are characterized in Iran within the Paleozoic-Triassic, including northern Iran, central Iran, and Sanandaj-Sirjan. Northern Iran includes the Alborz Belt with borders with central Iran in the south of the Alborz Mountains. The sequences of late Precambrian-Triassic rock in the Alborz area are very similar to the rock sequences of other parts of Iran. Moreover, there is a Gondwana proximity at least in a large Paleozoic part (Stocklin, 1974; Berberian & King, 1981: Angiolini et al., 2007; Wendt et al., 2005).

Several studies have been performed regarding the time of opening, the beginning of the subduction, and the ultimate closure of the Paleo-Tethys Ocean. The beginning of Paleo-Tethys rift formation in northern Alborz has been considered as the end of the Ordovician Period (Stampfli, 1978; Chateautieuf & Stampfli, 1979; Stampfli et al., 1991; Ghasemi and Khanalizadeh, 2012). However, Lasemi (2000) considered the former Ordovician as the onset of traction associated with Paleo-Tethys rift formation (known as Turan rift). He also considered the formations of Shirgasht, Lashkark, Gholi, and Neivar and their equivalents generating the large progressive sequences as the facies simultaneous with the formation of this rift. He argued that the oceanic crust of Paleo-Tethys has expanded since the Devonian era. Furthermore, Lasemi (2000) considered the emergence of an incomplete rift basin in Tabas (Central Iran) during the Early Ordovician related to the Paleo-Tethys margin located in northern Iran. Considering several geological features (such as ocean fragments and remnants in northern Iran (Mashhad, Fariman, and Dareh-e-Anjir) and central Iran (Jandagh and Anarak), accompanied by a thick magmatic sequence of the Sultan Maidan Formations, it is indicated that Iran continental lithosphere was fractured and separated by the rifting process during the Lower Paleozoic. Then, oceanic zones appeared in parts of the Iranian plateau (such as Mashhad ophiolites, Talesh in the north, and Bayaze and Jandagh ophiolites in central Iran).

These oceanic fragments and remnants outcropped in the northern zones of Iran, especially Mashhad, Fariman, and Darreh-e-Anjir) and Central Iran (Jandagh and Anarak) originated the Paleo-Tethys oceanic lithosphere (Shafaii Moghadam et al., 2015). The main and most important stage of Paleo-Tethys ophiolite formation in the Lower to Middle Paleozoic occurred after the rift formation phenomenon and upward separation of the continental parts of Gondwana’s northern margin (Shafaii Moghadam et al., 2015).

Various geological features reveal that this crustal tension phase started followed by the synergy of the Precambrian blocks and the formation of the Gondwana supercontinent, followed by the formation of the magmatic arc and the opening of the back-arc. The Gondwana supercontinent has been formed by the collision and combination of 7 to 8 Neoproterozoic continents (Cadomini Blocks) as large as Australia through two stages (the first period: 650 to 600 million years ago and the second period: 570 to 520 million years ago) (Ustaömer et al., 2009; Collins and Pisarevsky, 2005; Shafaii Moghadamet et al., 2013).

## Conclusion

According to studies, the rock units of the region are plutonic. Based on petrographic studies, they include dolerites, olivine dolerites, and trachyandesite basalts representing porphyric texture with microlithic and trachyte structures. According to the geochemical studies, the magma constituting these rocks was formed by partial melting of 5 to 10% of an upwelling peridotite garnet mantle magma at a depth of 100 to 105 km. The obvious role of separation crystallization is revealed as the main process in the formation of the magma generating these rocks. Based on the tectonic charts and geostructural studies, the rocks of the study region have been formed in an intercontinental tensile (rift) environment.

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