

Some characteristics of mafic dykes in Gondwanan land from South of Gorgan, Northeastern Iran: Implication to Petrogenesis and Paleotectonic

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Abstract

The igneous dykes are a small mafic rock unit exposed in the South Gorgan of Eastern Alborz, North Iran. These mafic dykes are intruded in the Middle–Upper Paleozoic sedimentary and metamorphic rocks units representing a part of the north Gondwana province. The studied samples were collected from various locations along the exposed bodies. Thin sections of these rocks show medium to coarse grained sizes and the texture varies from ophitic to intergranular under polarized microscope. The mineralogical composition of mafic dykes is dominated by large crystals of clinopyroxene, orthopyroxene, plagioclase and hornblende. These rocks can be classified as gabbroic rock. Geochemical studies show that these rocks have low to medium K₂O contents. The trace element data shows low La/Nb ratios (1.2–3.2) and LREE enrichment (La/Yb 10–21.4). The high LREE/HREE ratios and low Y content corresponding high Ti/Y ratios of the gabbros suggest that they could be derived from melt fractions of a garnet stable source. According to present data, it could be suggested that these rocks have been formed in a rift setting from partial melting of an asthenospheric mantle. This tectonic setting could be explained by the initiation of the opening of the Paleothetys in the northern part of Gondwana during the Late Ordovician.

Keywords: Gondwana, Mafic dykes, Gorgan, Eastern Alborz, Iran.

1–Introduction

The studied area is located in the Eastern Alborz (Fig. 1), which was the northern margin of the Gondwana (Fig. 2) during Palaeozoic (e.g. Stocklin, 1974; Salehie Rad, 1979; Berberian and King, 1981, Davoudzadeh *et al.*, 1986; Davoudzadeh and Weber–Diefenbach, 1987; Sengor, 1990; Alavi, 1991, 1996; Stampfli and Borel, 2002; Allen, *et al.*, 2003; Horton *et al.*, 2008; Sinha, 2012, 2013). Mid Paleozoic mafic intrusions, sills, dykes, volcanic tuffs and lava flows are widespread in Iran (e.g. Jenny, 1977a; Delaloye *et al.*, 1981; Alavi, 1996; Wendt *et al.*, 2005). The most prominent volcanic activity is expressed by the up to 600 m– thick andesitic lavas and tuffs in the Soltan Maidan Formation in the eastern Alborz, which are ascribed to the breakup of the northern margin of Gondwana (Jenny, 1977b; Alavi, 1996). The Soltan Maidan

volcanics are unconformably overlain by conglomerate and sandstones of Lower Devonian age (Wendt *et al.*, 2005). However, in some places Lower to Middle Ordovician age deposits (Lashkarak Formation) underlie these volcanic rocks. Thus, the Soltan Maidan volcanic rocks are generally considered as Silurian in age (e.g. Sharabi, 1990; Zamani Pedram and Hossieni, 2003; Rahimi–Chakdel, 2007; Raghimi, 2010).

Jenny (1977a) has reported a 398 Ma age for the mafic dykes using K/Ar methods. The precise age of these sub–volcanic rocks is not known because K/Ar dating has yielded contradictory results ranging from 398 to 175 Ma. Nonetheless, the most recent ones are certainly rejuvenated (Delaloye *et al.*, 1981). The early Devonian age (398 Ma) is consistent with field observation, as some dykes intrude Devonian deposits. Horton *et al.* (2008) have measured U–

Pb of detrital zircon grains from Paleozoic sandstones of the Alborz Mountains. They have indicated detrital zircon ages in Late Devonian–Early Permian and Cambrian–Ordovician zircon

crystallization. These ages could reflect magmatic activity related to subduction of Paleotethys or related oceanic lithosphere.

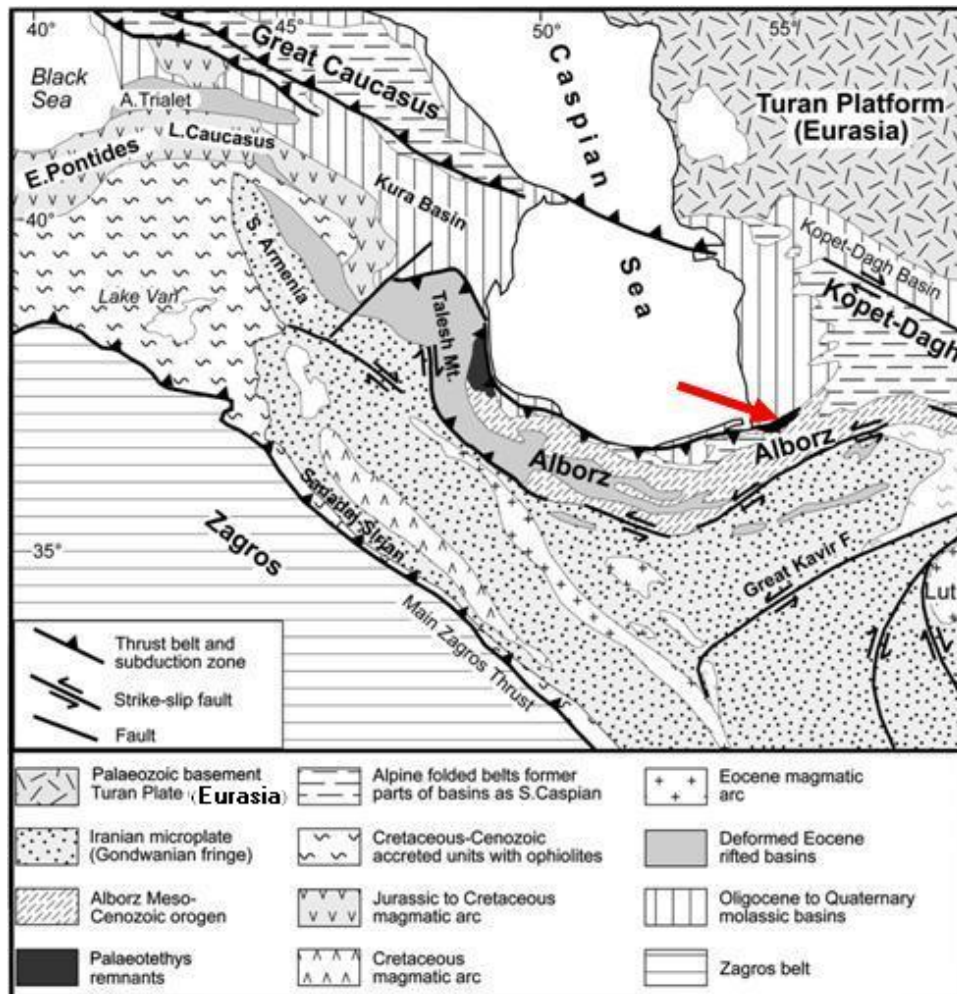


Figure 1) General tectonic map of North Iran and of the South Caspian region with slightly modified from Brunet (2003). The arrow shows the studied area.

Alternatively, these zircons may be the product of rift-related magmatism during opening of Paleotethys (Horton *et al.*, 2008). These zircon data suggest that Iran was affiliated with Gondwana magmatic arcs or that rift-related magmatic activity during opening of Paleotethys. The poorly dated igneous rocks may include a record of Paleozoic zircon crystallization in the eastern Alborz. This could be consistent with Paleozoic paleobotanical evidence and basement ages including a Gondwanian affinity for the Alborz (Horton *et al.*, 2008). Although poorly understood, middle to late Paleozoic magmatism may be the product of intra-arc or back-arc spreading related to opening of Paleotethys (Stampfli *et al.*, 1991).

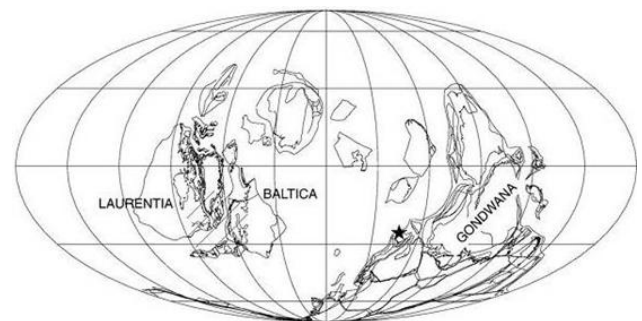


Figure 2) Palaeogeographical model of continental mass distributions during Late Ordovician (Hirnantian) times based on BugPlates Software (courtesy of Center for Geodynamics, Geological Survey of Norway). Star indicates the palaeoposition of the study area, assigned to the North Gondwanan Province.

Petrogenetic studies can provide important information for understanding the mantle source of the magmas and the tectonic evolution of the orogenic belt and adjacent regions (Gorring *et al.*, 2001, 2003). In this paper, we report major and trace element geochemistry of mafic dykes from the southern Gorgan in northeastern of Iran in order to: (1) document the geochemical characteristics of these rocks; (2) investigate their mantle sources and petrogenesis; and (3) evaluate the paleotectonic implications for the southern Gorgan during the Paleozoic.

2–Geological Setting

The Iranian plateau is divided into nine geological–structural zones (Stocklin, 1968). Based on this division, the Alborz zone lies with EW–trending in the north of Iran. This zone is sub–divided into three parts: east, central and west. The study area is located in the eastern part of the Alborz zone and belongs to the east Alborz subdivision (Fig. 1). The study area is situated approximately 5 Km south of the Gorgan city, in northeastern Iran. In this area, Paleozoic rock units comprise Upper Ordovician, Silurian and Upper Carboniferous deposits (Fig. 3). The main outcrops consist of the Gorgan metamorphic greenschists (Allen *et al.*, 2003) intruded by Paleozoic mafic dykes (Gansser and Huber, 1962; Stöcklin, 1974). The Gorgan schists are known to the south, preventing a direct correlation with the Paleozoic units of the Iranian margin (Zanchi *et al.*, 2009). The Gorgan schist has been suggested to be time equivalent of the Ghelli Formation, which is late Ordovician (late Katian–Hirnantian) in age, based on stratigraphic relationship (Ghavidel–Syooki *et al.*, 2011). The field observations show no contact metamorphism at the boundary of mafic dyke and schists (Fig. 4). Then, it could be suggested that mafic dyke have been intruded in this area before Gorgan schist.

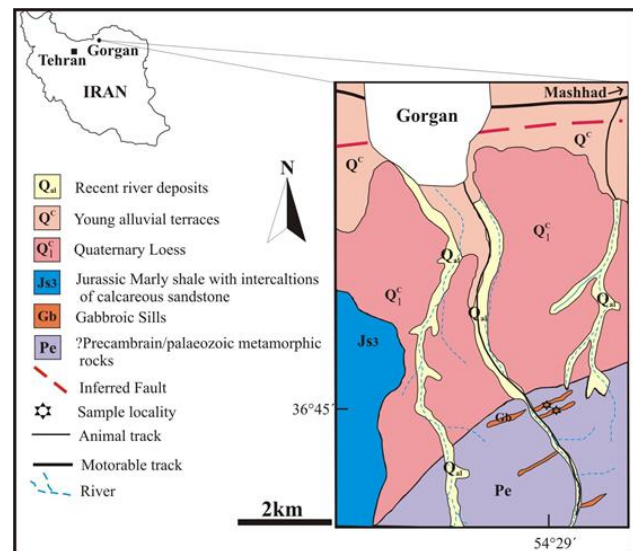


Figure 3) Geological map of the studied area (after Sharabi, 1990, and Zamani Pedram and Hossieni 2003).

3–Petrography

The mafic dykes are 1 to 5 meter in width and several hundred meters in length. They are surrounded by greenschists and show weak metamorphism (Fig. 4). The samples have mesocratic to melanocratic color index (Fig. 4).

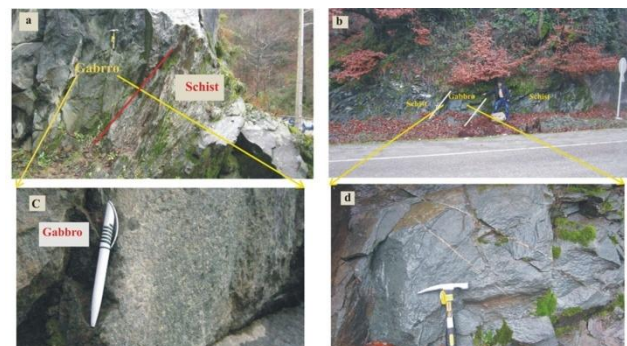


Figure 4) Field photographs of samples in southern Gorgan (Rahimi-Chakdel 2007). a) Boundary of gabbro and foliated Schist are clearly visible with red and yellow lines (b). Close up photos show mesocratic (c) and melanocratic (d) colors. White mineral is plagioclase in c photo.

They have a basaltic composition, with medium to large–grained size. They show ophitic to intergranular textures under polarized microscope (Fig. 5). These rocks show some mineralogy variation, but are typically plagioclase–clinopyroxene–phyric with a groundmass of plagioclase microphenocrysts and Fe–Ti oxides.

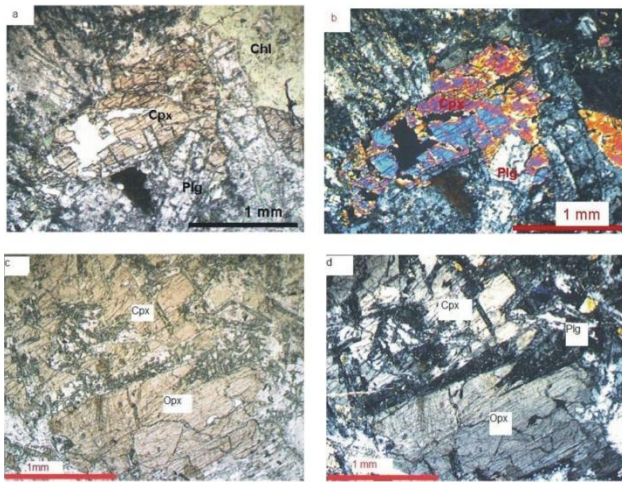


Figure 5) Images are showing intergranular, b) and ophitic, d) textures of gabbroic rocks in Southern Gorgan under PPL(a, c) and XPL(b, d). Cpx= Clinopyroxene, Opx= Orthopyroxene, Chl= Chlorite and Plg= Plagioclase (after Kretz, 1983).

The main minerals are plagioclase (40–45%), clinopyroxene (40–47%), hornblende (~5%), K-feldspar (~3%), orthopyroxene (~2%), and minor olivine, quartz and biotite. Accessory minerals include sphene, zircon, apatite,

ilmenite and magnetite. The detailed mineralogy of all samples is listed in Table 1.

Clinopyroxene is the main phenocryst phase and often is up to 3–4 mm in diameter. It occurs in all samples, but it is rarely fresh being typically replaced along cracks by brown or blue chlorite and green hornblende. The plagioclase phenocrysts have euhedral shape. They are occasionally optically enclosed by pyroxene. Plagioclase laths are a major groundmass phase. They are typically sericitized. Olivine is also present as a phenocryst phase. Olivine is typically <0.5 mm in diameter.

The smaller olivine grains tend to be more altered and are often enclosed by clinopyroxene.

After the petrographic examination, the 7 freshest samples were selected from a total of 12 samples taken from the southern Gorgan (Table 2).

Table 1) Petrography and mineral assemblages of the South Gorgan mafic dykes, North Iran.

Sample No	Latitude, Longitude	Texture	Mineral assemblage
06GAR001	N36°45'00", E54°29'00"	Medium-grained, Intergranular texture	Cpx+ Plg+ Kf+Ol+ Fe-Ti+ Ap+Sph
06GAR002	N36°45'00", E54°29'00"	Fine- to medium-grained Intergranular- texture	Cpx+ Plg+ Kf+ Fe-Ti+ Hbl+Ap+Zr+ Qtz
06GAR003	N36°45'00", E54°29'00"	Medium-grained, Ophitic texture	Cpx+ Plg+ Kf+ Fe-Ti+ Hbl+Ap+ Sph +Zr
06GAR004	N36°45'00", E54°29'00"	Medium-grained, Intergranular	Cpx+ Plg+ Kf+ Fe- Ti+Ap+Zr+ Sph+ Qtz
06GAR005	N36°45'00", E54°29'00"	Medium-grained, Ophitic texture	Cpx+ Plg+ Kf+Ol+ Fe- Ti+Ap+Zr+ Sph+ Qtz
06GAR006	N36°45'00", E54°29'00"	Medium-grained, Granular texture	Cpx+ Plg+ Kf+ Fe-Ti+ Ap+Zr+ Chl+ Sph+ Qtz
06GAR007	N36°45'00", E54°29'00"	Medium-grained, Ophitic texture	Cpx+ Plg+ Kf+ Fe- Ti+Ap+Zr+ Sph +Qtz

Ap, apatite; Cpx, clinopyroxene; Fe-Ti, Fe-Ti oxides; Kf, K-feldspar; Ol, olivine; Plg, plagioclase; Qtz, quartz; Hbl, hornblende; Zr, zircon; Sph, sphene (Kretz, 1969)

4-Geochemistry

The selected samples were crushed and powdered in an agate mill for geochemical analysis. Major elements were determined by

X-ray fluorescence (XRF). Selected trace elements (Sc, Rb, Cs, Sr, Y, Zr, Hf, Nb, Ba) were determined by WD-XRF on pressed powder pellets. Other trace elements, including rare earth elements (REE), were analyzed by

inductively coupled plasma mass spectrometry. All chemical analyses were performed in the laboratories of the Geological Survey of Iran.

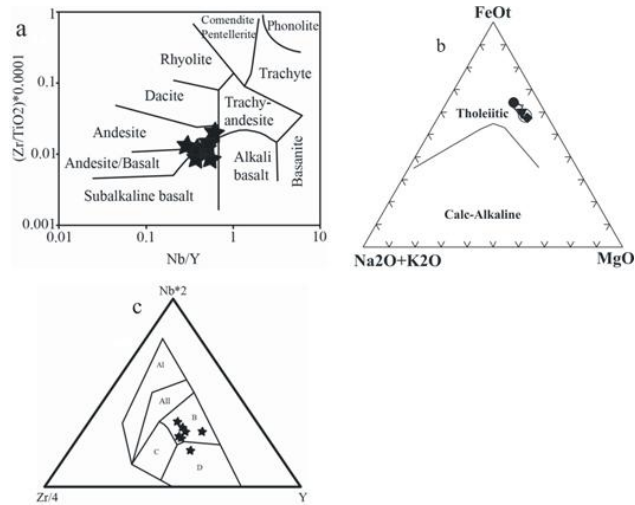


Figure 6a) Zr/TiO₂–Nb/Y diagram after Winchester and Floyd (1977) b) AFM diagram showing geochemical variations. The tholeiitic and calc-alkaline trend are after Wilson (1989), c) Nb*2–Zr/4–Y variation diagram (Meschede 1986) for the mafic dykes of Southern Gorgan, North Iran. AI, within-plate alkali basalts; All, within-plate alkali basalts and within-plate tholeiites; B, E-type MORB; C, within-plate tholeiites and volcanic-arc basalts; D, N-MORB and volcanic-arc basalts.

Full major and trace element analyses of the mafic dykes are presented in Table 2. The samples exhibit no significant variations in major and trace element. The mafic dykes are basaltic (Fig. 6a) in composition (SiO₂ 49.75–51.67 wt %) and in the tholeiitic field on standard AFM plot (Fig. 6b). All the gabbro samples show typical E-type MORB Basalt affinity (Fig. 6c). They have high abundances of total Fe₂O₃ (15.13–16.97 wt %), CaO (7.11–9.51 wt %) and relatively low concentrations of Al₂O₃ (11.27–12.65 wt %), MgO (6.66–8.48 wt %) and K₂O (0.95–1.24 wt %).

The trace elements Sc, Rb, Ce, Sr, Y, Zr, Hf, Nb, Ba show little absolute variation, ranging from 24 to 29 ppm, 32 to 43 ppm, 1.1 to 1.9 ppm, 301 to 371 ppm, 31 to 41 ppm, 157 to 241 ppm, 7.4 to 9.2 ppm, 12 to 21 ppm, 309 to 439 ppm, respectively. All sample REEs are normalized to Chondrite (Sun and McDonough,

1989). All the samples are enriched in light REE (LREE) relative to heavy REE (HREE) and show in Chondrite normalized REE pattern (Fig. 7).

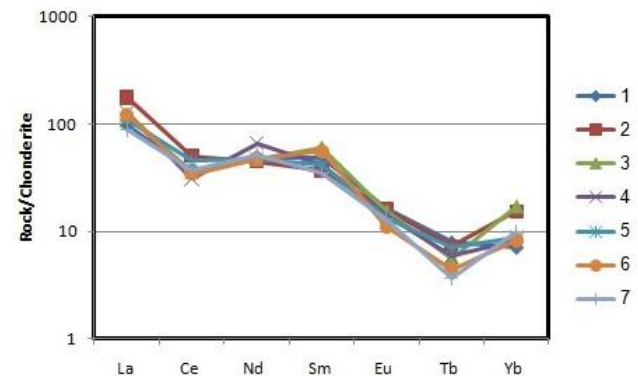


Figure 7) Chondrite-normalized REE patterns after Sun and McDonough (1989) of mafic dykes, South Gorgan, North Iran.

5–Discussion

All mafic dykes show a decrease in total Fe₂O₃, K₂O, P₂O₅ and TiO₂ concentrations with increasing MgO abundances (Fig. 8) whereas an increase Al₂O₃ and CaO concentration with decreasing MgO. It may be the result of accumulation of Fe–Ti oxides. Therefore, the parent magmas of dykes should have low SiO₂ abundances and high total Fe₂O₃, TiO₂ and CaO contents (Table 1). All these characteristics preclude a simple, common evolution by closed–system fractionation process. They can be suggested the operation of combined processes of partial melting of enriched, refractory lithospheric mantle that experienced some fractional crystallization (e.g. Yang *et al.*, 2007a, b). All samples have little variable SiO₂ (49.75–51.67 wt %), MgO (6.46–8.48 wt %), Al₂O₃ (11.27–12.65 wt %) values. These dyke samples represent low to medium K (Fig. 9) tholeiitic type, with high TiO₂, total Fe₂O₃, low MgO (>6.0 wt %) and SiO₂ (49.75–51.67 wt %) abundances.

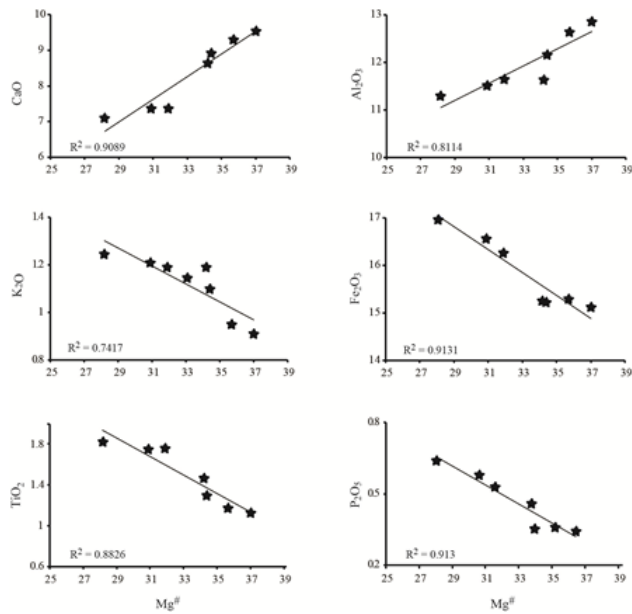


Figure 8) Major and trace elements vs Mg# for mafic dykes, South Gorgan, North Iran.

La/Yb ratios are high (10–21.4) in all samples (Table 2). The low La/Yb ratios reflect a melting regime dominated by relatively large melt fractions and/or spinel as the predominant residual phase (e.g. Yanget *et al.*, 2007b; Riley *et al.*, 2005; Falloon *et al.*, 1988) whereas high La/Yb ratios are indicative of smaller melt fractions and/or garnet control. The high LREE/HREE ratios and low Y content corresponding high Ti/Y ratios of the gabbros suggest that they could be derived from small melt fractions of a garnet stable source. Zr and Y do not fractionate significantly during partial melting (e.g. Yanget *et al.*, 2007a).

Table 2) Major (wt%) and trace element (ppm) data of mafic dykes from Gorgan, NE Iran.

Location:	N36°45'00", E54°29'00"						
Sample:	1	2	3	4	5	6	7
wt%							
SiO ₂	50.34	51.59	49.75	51.67	50.81	51.23	51.09
Al ₂ O ₃	12.65	11.51	12.87	11.27	12.17	11.64	11.63
Fe ₂ O ₃ ^t	15.27	16.57	15.13	16.97	15.23	16.24	15.25
MgO	8.48	7.41	8.89	6.66	7.98	7.61	7.93
CaO	9.31	7.37	9.51	7.11	8.91	7.38	8.65
Na ₂ O	1.23	1.28	1.15	1.35	1.18	1.34	1.16
K ₂ O	0.95	1.21	0.91	1.24	1.1	1.19	1.19
MnO	0.21	0.16	0.31	0.12	0.21	0.19	0.22
TiO ₂	1.17	1.74	1.12	1.81	1.29	1.75	1.46
P ₂ O ₅	0.36	0.58	0.34	0.64	0.35	0.53	0.46
Total	99.97	99.42	99.98	98.84	99.23	99.1	99.04
Mg#	35.7	30.9	37.01	28.18	34.4	31.9	34.2
ppm							
Rb	33	33	32	43	33	42	34
Sr	334	301	307	368	346	371	345
Y	31	34	33	38	35	41	37
Zr	241	157	164	167	185	233	176
Hf	9.2	7.4	7.6	7.7	8.2	8.7	7.9
Nb	19	13	17	21	17	12	14
Ba	439	377	366	318	354	309	324
La	23	42	29	30	26	29	21
Ce	23	31	22	19	28	21	23
Nd	23	21	22	31	22	22	24
Sm	7.5	5.6	9.3	6.3	6.3	8.5	5.4
Tb	0.69	0.63	0.49	0.51	0.61	0.38	0.32
Yb	1.2	2.6	2.9	1.4	1.5	1.4	1.7
Ta	1.4	1.3	1.2	1.4	1.3	1.2	1.4
Eu	0.94	0.93	0.89	0.83	0.78	0.64	0.76
Sc	25	28	24	29	25	27	26

However, the dykes display low Rb/Sr (<0.1) and high Ba/Rb (>10). All of the dykes are enriched in LILE and LREE and depleted in Nb and Ta anomalies which are suggesting that metasomatism of source were triggered by subduction-related fluids or melts. Thus, the geochemical data indicate that all of the dykes may have formed by relatively low-percentage melting of an amphibole-bearing (e.g. Dai *et al.*, 2011), refractory lithospheric mantle source in the garnet stability field. It may be metasomatized by recycled crustal materials prior to generation.

6–Paleotectonic implications

The major part of the study area belongs to the stable northern margin of Gondwana at least until mid Paleozoic (e.g. Allen *et al.*, 2003). During the Paleozoic, the Iran and Arabian plates formed a coherent terrain and were separated from the Turan Plate by the Paleo – Tethys (e.g. Stampfli, 1996). As a consequence of the Late Ordovician glaciations and a lowstand of sea level, large areas of northern Gondwana including Azerbaijan, the western and central Alborz, parts of the Sanandaj–Sirjan Belt, the Zagros Mountains and eastern Iran were emergent since the Late Cambrian/Early Ordovician (Wendt *et al.* 2005). Stampfli, (1996), and Stampfli and Pillevuit (1993) have presented evidence from Alborz and elsewhere that the PaleoTethys opened in Silurian time.

A palaeogeographic reconstruction of Iran during the Silurian/Lower Devonian was presented by Davoudzadeh *et al.* (1986). In the Late Paleozoic, or Early Triassic, the Iranian Plate drifted away from the Arabian Plate by the opening of the Neo–Tethys. At this time, the Iranian Plate collided with the Turan Plate. Stampfli *et al.* (1991) suggested that the Alborz block separated from Gondwanaland in Ordovician–Silurian times (Fig. 6c). It collided with Eurasia in the late Triassic with subduction of Paleotethys (Şengor *et al.*, 1988).

In Iran, Turkey, and Greece the closure of PaleoTethys did not take place before Carnian, late Triassic, 231 m.y. ago, (Davoudzadeh and Schmidt 1984; Stampfli, 1996). By the late Carnian, about 225 m.y. ago, there was no Paleotethys left on an Iranian transect. Then, subduction of PaleoTethys oceanic crust under Turan plate started in Late Devonian and continued into Triassic and led to the formation of a volcanic arc (Baud and Stampfli, 1989). The obducted remnants of the PaleoTethys Ocean were included in several rock assemblages including ophiolite complexes, meta–flysch and some submarine pyroclastics in the Binaloud range, northeastern Iran (Alavi, 1992). Clark *et al.* (1975) have noted Upper Devonian equivalents might be present in the schists and phyllites in the mountain ranges of the Talesh Range from the western Alborz. Such metamorphic rocks are preserved in the studied area as Gorgan schists of the eastern Alborz.

Based on the above explanations, the Gorgan schists of the studied area could be remnants of the PaleoTethyan collision occurring as discontinuous outcrops along the northern Gondwana margin of the present range. However, the Gorgan schists have surrounded the mafic intrusions which are rift-related magmatic activity during opening of Paleotethys (Figs. 2, 6c). Some diabase sills erupted in other parts of Iran such as Mighan, Khoshyeilagh and Shirooyeh of eastern Alborz during Early Devonian (Wendt *et al.* 2005).

As mentioned above, it can be ascribed that the emplacement of the mafic gabbroic dykes was a part of the north Gondwana at late Ordovician–Silurian by Middle–Late Devonian time.

7–Summary and Conclusions

A suite of mafic gabbro dykes are intruded in the Middle–Upper Paleozoic rock units representing a part of the north Gondwana province. These rocks are characterized by

altered olivine, plagioclase and pyroxenes under optical microscopy. Pyroxenes are typically replaced along cracks by brown or blue chlorite and green hornblende during later regional metamorphism. These rocks are basaltic, andesite and andesite/basalt rocks in composition. Based on present geochemical data, mafic dykes are originated from partial melting of an ancient, refractory lithospheric mantle source at depth of garnet stability. The tectonic environment of mafic dyke can be assigned to the initiation of the opening of Paleotethys in northern part of Gondwana province in late Ordovician time.

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