Geochemistry and petrogenesis of Biabanak-Bafq mafic magmatism: Implication for the evolution of central Iranian terrane

MONIREH POSHTKOOHI^{1,2,*}, TALAT AHMAD^{1,3} and ASHWINI KUMAR CHOUDHARY⁴

¹Department of Geology, Centre for Advanced Studies, University of Delhi, New Delhi 110 021, India.

²Department of Petrology, Geological Survey of Iran, Tehran, Iran.

³Currently Vice Chancellor of University of Jamia Millia Islamia, New Delhi 110 025, India.

⁴Institute Instrumentation Centre, Indian Institute of Technology, Roorkee 247 667, India.

*Corresponding author. e-mail: m_poshtkoochi@yahoo.com

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Precambrian magmatism in the Biabanak-Bafq district represents an extensive sequence of mafic magmatic rocks. Major, trace and rare earth elements reveal that the low-Ti basement mafic rocks are magnesium tholeiite and low-Ti cover a mafic rock belongs to Fe-tholeiite, whereas, the high-Ti alkaline mafic rocks, as well as dolerites, show much more Fe–Ti enrichment. Primitive mantle normalized trace element patterns show a relative enrichment of LREE and LILE and depletion of HFSE, but have an equally distinct continental signature reflected by marked negative Nb, Sr, P, and Ti anomalies. The composition of the intrusive rocks is consistent with fractional crystallization of olivine $\pm$ clinopyroxene $\pm$ plagioclase, whereas variations in the Sr and Nd isotope compositions suggest heterogeneous sources and crustal contamination. Low-Ti group samples contain a crustal signature in the form of high La/Yb, Zr/Nb, and negative ϵ Nd values. In contrast, high-Ti mafic magmatic rocks display an increase in La/Yb with a decrease in Proterozoic alkaline rocks recognized across the central Iran. The presence of diverse mafic magmatic rocks probably reflects heterogeneous nature of sub-continental lithospheric mantle (SCLM) source. The mafic magmatism largely represents magmatic arc or rift tectonic setting. It is suggested that the SCLM sources were enriched by subduction processes and asthenospheric upwelling.

Keywords. Proterozoic; mafic magmatism; sub-continental lithosphere; asthenosphere; crust; rift; arc.

1. Introduction

The cratonization of Arabian–Nubian Shield (ANS) occurred transitionally from African towards Iranian plate as evidenced from the age of the Precambrian basements (Ghorbani 2013). The ANS represents juvenile crust that evolved during the Pan-African orogenic event ($\sim$ 950–540 Ma) (Kröner 1985). Part of the ANS is represented by the basement rocks of central Iran in Saghand

region, which has been studied by many authors (Stöcklin 1968, 1974; Nabavi 1976; Berberian and King 1981). The central Iranian terrane (CIT) is one of the continental fragments that got welded to the oceanic crust along shear zones. As one of the largest Late Proterozoic orogenic belt in the Iran, the central Iran orogenic belt is of great interest due to its long-term evolutionary history and complex tectonic magmatism. The Proterozoic geological history of the Biabanak-Bafq district

was fundamentally related to the amalgamation and dissociation of the supercontinent Rodinia (Ghorbani 2013). Although, the general tectonic framework, the timing, and geometry of rifting, along this area are not well constrained.

The end of the Proterozoic was a period of a widespread continental breakup, before Paleozoic reassembly of the fragments in the Gondwanaland and Pangaea (Hoffman 1991). The Proterozoic rock assemblages from Chapedony, Boneh-Shurow and Posht-e-Badam complexes of central Iran consist of granitoidic gneiss, amphibolite, meta-gabbro, meta-diorite, meta-andesite, hornblendite, pyroxenite, serpentinite, which are considered to belong to island arc tectonic setting (Stöcklin *et al.* 1972; Haghipour 1974, 1977; Berberian and King 1981). After the establishment of the Arabian–Iranian platform at the end of Pan-African orogeny, an extension was accompanied by bimodal magmatic activity. The Late Neoproterozoic alkali-enriched Zarigan and Narigan granites in Biabak-Bafq district are equivalents of Doran granites of western Iran, which are considered equivalent to the ~600 Ma granites of Arabian Peninsula (Stöcklin *et al.* 1964; Schmidt *et al.* 1978; Sillitoe 1979). The Doran granite cuts the Proterozoic low-grade metamorphic rocks of the Kahar Formation and is covered by Early Cambrian sediments (Stöcklin 1968). The extensive ‘post-orogenic’ volcanic to volcanoclastic rocks including basalt, andesite and tuff, which overlie the basement rocks and are in turn overlain by Late Neoproterozoic–Early Cambrian sediments. Following Late Neoproterozoic (Pan-African) orogeny and consolidation of the basement, the Precambrian cratons of Iran, Pakistan, central Afghanistan, south-eastern Turkey and Arabia became a relatively stable continental platform with epicontinental shelf deposits. According to White and McKenzie (1989), the origin of basic volcanic magmas in the continental settings is often believed to be by decompression and partial melting of an upwelling asthenospheric mantle close to the base of the sub-continental lithospheric mantle (SCLM). Small volumes of alkaline mafic magmas can also originate within the SCLM through direct partial melting of the metasomatised lithospheric mantle as a consequence of thermal perturbations (White and McKenzie 1989). Hassanzadeh *et al.* (2008) and Alirezaei and Hassanzadeh (2012) determined U–Pb crystallization ages of the granites and orthogneisses and suggested that they were Late Neoproterozoic–Early Cambrian (533 ± 8 to 547 ± 3 Ma), which

matches with the evolution of juvenile ANS and Peri-Gondwanan terranes. Zircon U–Pb data indicate that the Boneh-Shurow metamorphic complex is the oldest rock unit yielding $^{207}\text{Pb}/^{206}\text{Pb}$ age of 543 ± 36 Ma; while some grains yielded older ages indicative of an inherited component typical for non-juvenile granitic melts or detrital inheritance (Ramezani and Tucker 2003; Verdel *et al.* 2007). Boneh-Shurow complex is intruded by quartz-dioritic body, for which concordant analyses were obtained with the $^{207}\text{Pb}/^{206}\text{Pb}$ age of 547 ± 3 Ma. For the well-known Zarigan-type leucogranites and granodiorites, a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 533 ± 8 Ma was obtained with an older inherited component (Ramezani and Tucker 2003).

By integrating stratigraphic, geochronological, geochemical, and structural data of the key units, our understanding of the crustal evolution of basement and cover rocks connecting to Rodinia can be refined. The present study aims to discuss the geochemical characterization, petrogenesis and tectonic setting of the investigated orogenic and post-orogenic mafic igneous rocks. We shall use geochemical data to put constraints on the source characteristics, magma evolution, partial melting and fractional crystallization processes that govern the investigated mafic rocks from Biabanak-Bafq district in central Iran. These are of great importance to understand the evolutionary history of the central Iranian basement rocks during the Pan-African Orogeny.

2. Regional geological setting

The Iranian plateau consists of several continental fragments welded together along old oceanic suture zones. The continental crust of the CIT is one of these fragments, which was metamorphosed, folded and intruded by granites during the Pan-African Orogeny (Ramezani and Tucker 2003; Nadimi 2007). In the Biabanak-Bafq district of CIT, three roughly NE trending litho-tectonic domains, from east to west, are Posht-e-Badam, Chatak, and Chapedony with faulted contacts with each other (figure 1). The basement complexes are cropped out in the Saghand region and extensively overprinted by the Pan-African orogeny and younger igneous events. Early Cambrian orogeny of the Biabank-Bafq district marks one of the fundamental lithospheric boundaries within Gondwana. This boundary belongs to Late Neoproterozoic–Early Paleozoic orogenic system that was active along

Figure 1. (a) Location of central Iran. (b) Accessible road map. (c) Simplified structural map of central Iran and constituent crustal blocks (compiled from Jackson and McKenzie 1984; Alavi 1991; Ramezani and Tucker 2003). (d) Geological map of the Precambrian basement of Saghand region (modified after Haghpor 1977). (e) Geological map of Late Neoproterozoic–Early Cambrian.

Figure 2. Geological map of Late Neoproterozoic–Early Cambrian of southeastern part of Posht-e-Badam Block, Biabanak-Bafq district, central Iran (modified after Haghipour 1977).

the Proto-Tethyan margin of the Gondwanaland, extending from Arabian margin to the Himalayan margin of the Indian sub-continent. The Biabanak-Bafq district comprises continental basement with volcano-sedimentary cover including most important iron ore resources of Iran, which is located between Bafq city in the south and Posht-e-Badam village in the north. The Posht-e-Badam Block, located in Biabanak-Bafq district, is a narrow

N–S trending rift zone, constituting metallogenic province of Precambrian–Cambrian age, which is a part of Central Iranian Structural Zone (Stöcklin 1968) (figure 2). All metamorphic, plutonic and volcanic rocks in the study area are cut by post-orogenic mafic-felsic dykes. The Late Neoproterozoic–Early Cambrian volcanism has a predominantly felsic character (rhyolitic to rhyodacitic) with subordinate andesite-andesitic basalt,

spilitic basalts, mafic intrusive bodies and late doleritic dyke swarms with alkaline character (figure 2). Metavolcanic rocks in this area are intercalated with quartzite and slate with marble lenses. The Late Neoproterozoic–Early Cambrian magmatism is related to an arc setting, as proposed by Ramezani and Tucker (2003) that is consistent with low-Ti samples of basement amphibolites and cover mafic rocks. The high-Ti cover mafic sequences indicate alkaline nature, considered as an extensional regime during shortly after arc tectonic settings (Samani 1988; Daliran 2002; Daliran *et al.* 2009, 2010).

3. Petrography

The samples have been collected from the basement amphibolites and cover mafic rocks from the study area. In this study, we have used the term ‘amphibolites’ for all varieties of basement metamorphosed mafic rocks. The cover mafic rocks are termed as gabbros, gabbro-diorites, doleritic dykes, basalts and basaltic andesites, based on their texture and mineralogy. The amphibolites are dark green to black and massive. Xenoliths of amphibolite take place within the basement gneisses, which indicate that amphibolites are probably the oldest units in this area. The composition of fresh phenocrysts of plagioclase is mostly andesine-labradorite but albitization is also observed in some samples where plagioclases have calcic cores and albitic rims. These rocks are schistose and banded with amphibole and feldspar rich layers. Brownish hornblende is the chief mafic mineral in hornblende or mala gabbros of the study area. In these rocks, hornblende makes up two-thirds of the volume, anorthite a quarter, and the rest is composed of pyroxene (which is converted to amphibole) and iron oxide. Hornblende occurs as large ophitic or hetero-granular textures enclosing the other constituents (figure 3a). Majority of cover mafic rocks have preserved igneous textures and contain pyroxene, amphibole (hornblende), feldspar (plagioclase and K-feldspar), biotite, magnetite, titanite, rare quartz and apatite (figures 3b–f). Post-crystallization and deformation can be visualized by the presence of fractured phenocrysts of feldspar and plagioclase. Rounded corners of feldspar phenocrysts indicate an event of magmatic corrosion. Plagioclase crystals are saussuritized to some extent. Actinolite and biotite retrograde reaction rims are present around pyroxenes and amphiboles.

Clinopyroxene and hornblende minerals occur as euhedral to subhedral phenocrysts, but they are often partially replaced by actinolite, chlorite, and biotite. Some of the amphiboles (hornblende) may have formed due to the alteration of augite at the late magmatic stage as suggested by the parallelism of hornblende with augite and at some places the former makes a reaction rim around augite crystals. Ophitic to sub-ophitic relationships between plagioclase and clinopyroxene phenocrysts are common (figure 3f). The more mafic samples have small olivine phenocrysts, mostly pseudomorphosed by chlorite-serpentine. Other minors, accessory and secondary minerals are chlorite, serpentine, epidote, calcite, quartz, biotite, Fe–Ti oxides and titanite.

Basic volcanic rocks often show vesicles with quartz, calcite, epidote and zeolite amygdaloids. The fine-grained basic rocks show quenched texture in the form of variolitic laths of plagioclase feldspars (figure 3b). Joints and fractures are common and filled from quartz and epidote veins. Doleritic dykes show ophitic or sub-ophitic textures. Mineralogically, they resemble the volcanic rocks except for the presence of late crystallizing K-feldspar as an interstitial component. They have escaped the effects of albitization, and lucid phenocrysts of plagioclases are observed in the most of dyke samples. Alteration effects to some extent can be seen in the field and also through petrographic studies. The growth of secondary minerals like chlorite, epidote, biotite, and amphibole are used as parameters to understand the degree of alteration. Limited growth of these minerals at grain boundary may develop due to the interaction with late magmatic fluids and thus are considered isocheimal (Pollard *et al.* 1983; Taylor and Pollard 1988). Bands of quartz and feldspar grains are also present, but the bands are not continuous.

The mafic rocks reported here appear to have been affected by some extents by post magmatic alteration, metamorphism, and deformation. This alters the abundance of individual elements to some extent, particularly for samples with higher LOI (> 2 wt.%). The mafic intrusive rocks are fresh and massive with very little alteration compared to the volcanic rocks. Similarly, the dykes are less altered compared to contemporary lava volcanic rocks. In this study, mafic samples in the Biabanak-Bafq district with anomalously low CaO (<5 wt.%), high LOI (> 2 wt.%), or high Na₂O (2.95 wt.%) concentrations are interpreted to be

Figure 3. Photomicrographs under cross-polarized light of basement and cover basement rock samples: (a) amphibolite; (b) spilitic basalt; (c) doleritic dyke; (d) spilitic doleritic dyke; (e) hornblende; (f) micro-monzogabbro. Abbreviations of mineral names are after [White and McKenzie \(1989\)](#). Act-Tr = actinolite-tremulite; Hbl = hornblende; Cpx = clinopyroxene; Pl = plagioclase and Fsp = feldspar.

altered and were omitted from our compilation and for any further discussion.

4. Whole-rock geochemistry

4.1 Analytical procedures

4.1.1 Major, trace and rare elements data

A total of 94 samples were analyzed by X-ray fluorescence spectrometry (XRF) (Panalytical Model

Philips Magix Pro Model 2440) at University of Delhi, Delhi, for their major and a few trace elements composition, following [Longjam and Ahmad \(2012\)](#). Out of 94 samples, 42 samples were selected for the analyses of trace elements including rare earth elements (REE) using ICP-MS (Perkin Elmer, Sciex Elan DRC II) at Indian Institute of Technology (IIT), Roorkee as a part of our study for whole-rock trace elements, and rare earth elements (REEs) (table 1a–d). The precision of the ICP-MS data was $\pm 4.1\%$ RSD. The procedure for ICP-MS

Table 1(a). Representative major (wt.%) and trace (ppm) elemental abundances of low-Ti amphibolites from Biabanak-Bafq district, central Iran.

Sample	ES.13	Es.14-1	Es.16-1	Bo.20	Bo.21	Bo.22	Sa.17	Sa.21	Sa.22	Sa.25	Sa.26	Sa.48	Sa.53	Chp.38-1
SiO ₂	50.33	52.87	46.87	49.19	50.96	50.92	48.53	45.11	50.47	46.79	49.17	48.69	51.18	48.91
TiO ₂	1	1.35	1.13	0.68	0.9	1.07	0.78	0.85	0.95	1.04	0.82	0.64	1.1	0.4
Al ₂ O ₃	16.17	14.19	14.04	14.47	14.98	14.46	14.05	15.2	14.4	13.87	14.33	14.95	14.26	15.37
FeO ^T	9.6	9.58	10.04	11.72	10.25	10.29	9.19	11.06	9.75	10.15	8.93	10.82	9.62	9.53
MnO	0.23	0.19	0.19	0.22	0.2	0.22	0.19	0.2	0.22	0.17	0.22	0.2	0.19	0.25
MgO	9.41	7.59	9.12	7.03	6.26	7.79	10.08	8.37	9.54	8.55	9.9	9.76	6.71	8.73
CaO	10.13	10.11	10.01	12.14	10.92	10.79	11.9	10.39	10.97	12.28	12.04	12.36	9.24	11.38
Na ₂ O	2.13	1.24	1.15	1.63	1.92	1.89	1.36	1.05	1.66	1.23	1.25	1.31	2.51	1.55
K ₂ O	0.45	1.22	1.34	0.34	0.59	0.6	0.62	0.77	0.64	0.41	0.71	0.47	0.39	0.23
P ₂ O ₅	0.1	0.16	0.13	0.09	0.11	0.14	0.06	0.07	0.13	0.12	0.07	0.05	0.13	0.05
LOI	1.55	1.43	2.13	1.46	1.23	0.82	1.83	3.18	0.96	1.42	2.03	1.27	1.85	1.43
Total	101	100	96	99	98	99	98	96	100	97	98	100	96	97
Ba	49	216	198	95	136	138	60	142	195	94	116	196	189	32
Rb	11	55	56	14	20	21	18	26	18	14	26	20	20	16
Sr	204	197	192	308	205	207	167	162	181	220	180	229	209	313
Ga	15	21	21	19	20	21	19	22	13	18	19	15	21	20
Nb	1	5	3	3	5	5	3	4	2	3	1	1	7	3
Zr	81	140	77	66	65	73	57	52	76	75	51	51	108	58
Y	22	35	29	23	21	23	22	21	25	21	23	16	35	18
Th	3	6	6	1	1	2	1	2	1	1	2	4	2	1
U	1	2	2	1	1	1	1	1	1	1	1	1	1	1
Cr	567	476	531	281	224	429	605	317	718	548	471	281	279	206
Ni	158	80	126	23	14	111	151	65	164	123	115	25	45	58

Table 1(a). (Continued.)

Sample	ES.13	Es.14-1	Es.16-1	Bo.20	Bo.21	Bo.22	Sa.17	Sa.21	Sa.22	Sa.25	Sa.26	Sa.48	Sa.53	Chp.38-1
Co	210	199	259	513	299	304	141	389	336	129	110		205	194
Sc	47	126	134	162	174	139	176	143	38	233	155	71	187	209
V	240	247	238	201	232	227	195	209	231	221	183	315	209	nd
Cu	33	47	nd	8	20	72	80	17	225	79	nd	40	nd	nd
Pb	23	24	9	1	15	8	8	4	16	10	10	4	9	16
Zn	157	111	153	156	115	144	127	178	142	109	173	111	98	123
La	1.95	10.49	2.81	2.89	4.63	5.07	1.94	0.95	5.7	3.55	1.45	2.14	5.78	2.42
Ce	5.64	22.94	7.24	8.34	10.53	10.91	2.17	2.78	12.85	7.87	3.63	14.05	14.38	5.74
Dy	3.67	5.26	3.98	3.28	2.91	3.31	3.35	2.45	4.05	3.65	3.49	5.68	6.85	2.33
Nd	4.79	15.19	5.52	6.75	6.45	6.52	2.1	2.55	9.63	5.85	3.25	2.13	11.11	3.86
Pr	0.92	3.06	1.1	1.35	1.44	1.47	0.36	0.46	1.83	1.21	0.6	5.38	2.26	0.83
Eu	0.59	1.04	0.61	0.5	0.51	0.61	0.38	0.31	0.79	0.62	0.49	1.47	0.77	0.36
Ho	0.45	1	0.5	0.4	0.36	0.42	0.44	0.3	0.78	0.45	0.46	0.6	0.88	0.3
Lu	0.16	0.44	0.18	0.13	0.14	0.18	0.17	0.1	0.35	0.16	0.18	0.12	0.33	0.13
Tb	0.32	0.91	0.35	0.31	0.27	0.3	0.27	0.21	0.7	0.33	0.29	0.63	0.62	0.2
Hf	0.32	0.43	0.29	0.68	0.71	0.59	0.33	0.22	0.39	0.33	0.32	2.26	0.45	0.3
Sm	1.62	4.25	1.74	1.94	1.68	1.76	0.94	0.96	2.95	1.75	1.21	4.82	3.31	1.09
Yb	1.13	2.93	1.26	0.9	0.93	1.14	1.16	0.72	2.36	1.08	1.2	2.99	2.26	0.86
Gd	1.77	5.04	2	1.89	1.71	1.85	1.33	1.12	3.68	1.91	1.52	4.74	3.53	1.17

Table 1(b). Representative of major (wt.%) and trace (ppm) elemental abundances of low-Ti cover mafic rocks from Biabanak-Bafq district, central Iran.

Sample	Sa.29	Az.3	Es.109	Es.134	Zr.11	Az.12	Zr.96	Ch.7-1	Zr.15	Ch.10	Zr.55
SiO ₂	53.46	48.85	49.19	48.52	50.22	52.27	48.21	47.24	52	50.23	52.1
TiO ₂	0.58	1.34	1.84	1.84	1.73	1.81	1.93	1.84	1.89	1.65	1.93
Al ₂ O ₃	14.72	14.07	14.98	14.6	14.36	14.75	13.99	13.63	14	14.02	13.7
FeO ^T	8.25	11.86	10.53	17.17	10.3	12.69	12.52	14.02	10.17	12.72	12.66
Fe ₂ O ₃ ^T	9.17	13.17	18.36	19.07	13.45	12.99	13.91	15.58	13.3	14.13	14.07
MnO	0.17	0.13	0.11	0.04	0.13	0.13	0.14	0.23	0.21	0.29	0.15
MgO	6.71	6.37	8.99	8.91	8.03	8.54	8.76	7.29	7.54	8.37	8.14
CaO	10.2	9.77	8.91	8.59	8.42	8.01	9.49	9.65	9.47	9.73	7.38
Na ₂ O	2.04	2.63	2.87	2.7	2.27	2.35	2.69	2.8	3.98	2.8	3.44
K ₂ O	0.81	1.33	1.46	1.37	1.52	1.72	1.43	1.4	0.9	1.02	0.72
P ₂ O ₅	0.09	0.26	0.19	0.18	0.2	0.25	0.25	0.33	0.33	0.35	0.32
LOI	1.18	1.44	3.11	2.87	3.46	1.18	1.23	3.64	2.81	3.91	1.02
Total	98	99	101	100	96	100	98	99	98	101	100
Ba	142	278	274	455	282	336	422	469	349	353	418
Rb	27	36	33	39	21	19	40	11	26	7	16
Sr	200	199	123	193	211	261	339	121	132	85	202
Ga	20	19	21	24	21	21	24	23	24	26	26
Nb	6	5	8	7	6	8	7	10	10	9	10
Zr	65	148	130	167	173	174	119	131	180	155	134
Y	26	34	27	23	32	35	35	33	41	40	36
Th	3	4	3	4	2	1	4	1	2	1	1
U	1	1	1	1	1	1	1	1	1	1	1
Cr	236	228	277	302	278	235	294	197	222	216	239
Ni	22	41	32	50	68	22	81	8	16	11	20

Table 1(b). (Continued.)

Sample	Sa.29	Az.3	Es.109	Es.134	Zr.11	Az.12	Zr.96	Ch.7-1	Zr.15	Ch.10	Zr.55
Co	16	531	1217	1300	295	513	608	828	287	649	649
Sc	123	181	-88	-110	-31	18	17	14	15	24	35
V	166	331	336	398	343	336	335	499	413	434	438
Cu	24	181	272	nd	nd	13	9	nd	17	9	51
Pb	12	7	18	9	13	13	9	6	14	10	17
Zn	114	31	81	55	202	75	209	131	161	117	34
La	10.95	5.58	8.01	6.84	6.38	6.77	6.6	8.28	9.33	22.59	23.01
Ce	21.17	10.03	20.41	19.81	19.86	19.56	19.66	22.84	23.39	23.36	21.77
Dy	3.98	0.33	4.08	1.56	5.37	3.5	7.69	11.66	9.69	11.11	9.8
Nd	15.05	4.72	11.25	15.66	10.62	16.91	12.34	16.94	16.81	17.39	15.6
Eu	0.67	0.16	0.73	0.43	0.97	0.65	1.29	1.72	1.29	2.3	2.1
Pr	3.2	1.4	2.28	1.14	2.31	2.07	2.54	3.71	3.53	7.65	7.15
Ho	0.76	0.03	0.8	0.28	0.65	0.44	0.93	1.42	1.2	2.01	1.9
Lu	0.31	0.01	0.21	0.1	0.22	0.19	0.24	0.34	0.4	0.59	0.74
Tb	0.35	0.05	0.69	0.31	0.5	0.33	0.71	1.08	0.89	2.08	1.79
Hf	0.74	0.03	1.53	0.62	2.49	0.65	2.68	2.27	3.56	2.9	3.18
Sm	3.81	2.6	2.89	1.51	2.89	2.14	3.7	5.84	4.82	10.44	9.01
Yb	2.1	0.6	1.86	0.7	1.52	1.22	1.92	2.82	2.88	4.51	5.23
Gd	4.18	0.62	3.53	1.87	2.98	2.21	4.08	6.38	5.23	12.12	10.23

Table 1(c). Representative of major (wt.%) and trace (ppm) elemental abundances of high-Ti cover mafic rocks from Biabanak-Bafq district, central Iran.

Sample	Es.98	Zr.6	Es.91	Zr.94	Es.101	Es.111	Es.108	Es.125	Es.99	Es.119	Zr.99	Es.112
SiO ₂	43.23	50.07	42.71	49.49	44.82	49.79	49.3	45.94	42.84	52.16	47.18	50.71
TiO ₂	2.69	2.69	2.79	2.77	2.92	2.94	3.03	2.36	2.38	2.41	2.32	2.56
Al ₂ O ₃	16.98	15.83	16.77	16.71	16.23	15.52	15.02	16.39	16.3	16.97	16.39	15.16
FeO ^T	12.49	11.93	12.76	12.39	13.27	11.5	11.55	11.25	13.37	10.96	11.76	11.1
MnO	0.25	0.18	0.22	0.19	0.09	0.13	0.08	0.15	0.2	0.11	0.19	0.08
MgO	8	4.06	8.5	4.7	8.4	5.84	6.07	5.51	6.45	6.94	6.52	5.72
CaO	5.69	6.42	6.2	5.09	3.51	4.23	2.25	6.1	6.51	5	5.54	3.38
Na ₂ O	2.52	4.56	2.83	4.65	2.4	2.92	3.13	3.63	2.06	3.17	3.39	4.99
K ₂ O	2.86	2.27	3.42	1.81	3.66	3.85	3.13	1.77	2.95	3.39	2.7	2.95
P ₂ O ₅	0.41	0.68	0.42	0.69	0.42	0.99	0.48	1.1	0.61	0.32	0.56	0.55
LOI	2.89	4.61	1.67	2.81	4.69	6.38	3.79	3.62	2.87	3.44	4.68	2.48
Total	96	100	100	98	99	96	98	96	96	100	98	97
Ba	696	675	559	598	577	631	693	705	617	292	680	182
Rb	50	23	54	44	65	82	76	30	58	39	48	91
Sr	370	699	377	484	135	226	215	1222	571	277	753	474
Ga	19	27	20	22	21	28	25	19	24	24	24	25
Nb	39	56	31	58	43	60	38	35	52	27	46	50
Zr	231	303	223	308	249	339	246	269	310	250	268	273
Y	39	30	37	35	35	44	36	35	32	47	37	43
Th	6	1	6	5	8	11	10	3	7	4	5	5

Table 1(c). (Continued.)

Sample	Es.98	Zr.6	Es.91	Zr.94	Es.101	Es.111	Es.108	Es.125	Es.99	Es.119	Zr.99	Es.112
U	2	2	2	2	2	3	3	1	2	1	2	2
Cr	222	48	266	104	281	39	109	44	236	265	200	61
Ni	224	13	241	12	209	23	42	13	129	249	121	24
Co	466	412	644	606	743	390	497	438	646	405	371	360
Sc	90	60	127	0	0	0	85	43	16	3	13	8
V	259	193	259	162	291	170	269	207	289	173	219	258
Cu	0	157	15	0	0	7	3	4	7	nd	76	7
Pb	12	15	21	18	14	13	16	17	0	15	16	22
Zn	497	145	461	146	63	35	68	216	302	149	144	56
La	36.74	22.16	16.07	14.04	20.03	29.91	36.49	37.17	20.56	23.35	19.66	30.18
Ce	70.25	45.86	43.11	40.12	42.04	63.72	69.21	72.82	43.12	46.73	47.45	59.87
Dy	4.7	5.13	4.5	3.97	1.88	4.36	4.77	4.66	4.19	25.17	5	4.04
Nd	36.51	23.07	28.14	24.89	26.1	34.86	36.32	41.35	22.27	24.69	28.4	30.4
Eu	1.77	1.52	1.22	1.05	0.4	1.37	1.83	2.31	1.26	1.25	1.31	1.46
Pr	8.37	5.7	4.33	3.59	1.45	7.75	8.24	8.88	5.49	5.82	4.6	6.89
Ho	0.75	0.53	0.47	0.43	0.21	0.69	0.79	0.71	0.41	0.57	0.55	0.68
Lu	0.18	0.12	0.11	0.1	0.06	0.15	0.21	0.14	0.07	0.12	0.16	0.16
Tb	1.03	0.59	0.52	0.44	0.19	1.01	1.05	1064	0.52	0.78	0.55	0.87
Hf	3.85	3.76	3.59	2.96	3.19	1.72	1.31	2.52	3.83	2.42	3.29	2.54
Sm	7.17	4.8	4.04	3.3	6.35	7.02	7.04	8.04	4.52	5.14	3.93	5.91
Yb	1.44	0.93	0.78	0.76	1.44	1.16	1.58	1.17	0.6	0.92	1.12	1.29
Gd	7.45	4.55	3.89	3.25	1.31	7.1	7.25	8.01	4.21	5.46	4.1	6.01

Table 1(d). Representative of major (wt.%) and trace (ppm) elemental abundances of high-Ti doleritic dykes from Biabanak-Bafq district, central Iran.

Sample	Az.22-1	Zr.9	Es.105	Es.106	Es.115	Es.88	Es.104	Es.92	Es.89	Es.124	Es.90	Es.100	Es.117
SiO ₂	47.36	51.77	51.37	50.11	46.3	44.98	47.19	46.82	46.37	45.61	45.47	43.98	46.57
TiO ₂	2.95	2.73	2.97	3.09	3.1	3.45	3.47	3.59	3.53	3.71	3.41	3.48	3.24
Al ₂ O ₃	17.52	16.87	16.72	16.89	16.2	17.45	16.89	17.53	17.07	17.42	17.7	17.47	16.91
FeO ^T	12.21	12.84	11.71	11.71	16.99	14.71	13.35	12.43	14.38	12.63	15.59	12.18	12.98
MnO	0.2	0.12	0.08	0.07	0.03	0.08	0.07	0.15	0.08	0.1	0.08	0.2	0.16
MgO	5.56	6.23	7.02	6.62	6.45	6.03	6.61	5.32	8.43	9.37	8.24	6.38	6.14
CaO	5.43	5.8	2.46	3.65	3.62	3.29	2.44	4.15	3.44	3.42	3.52	5.43	4.79
Na ₂ O	3.06	3.25	4.21	5.15	3.08	2.37	2.69	3.26	1.63	2.88	0.97	2.6	3.17
K ₂ O	2.48	3.05	3.69	1.92	3.13	4.11	2.44	1.37	4.39	2.65	3.9	2.58	2.84
P ₂ O ₅	0.39	0.58	0.53	0.76	0.45	0.45	0.56	1.19	0.39	0.46	0.33	0.55	0.54
LOI	4.21	2.2	2.73	2.85	3.67	2.91	2.39	3.01	4.17	3.7	3.97	3.15	6.69
Total	96	99	96	98	97	99	99	98	100	97	100	97	95
Ba	491	742	582	532	440	683	867	645	632	633	593	627	489
Rb	40	58	96	60	92	103	122	33	116	60	94	31	61
Sr	458	694	334	215	209	105	180	1093	141	437	104	525	411
Ga	24	26	24	26	22	21	25	19	20	25	21	21	23
Nb	37	51	37	48	34	36	47	39	29	40	25	42	52
Zr	208	321	244	318	204	202	254	278	284	257	260	288	317
Y	40	39	37	41	35	44	56	27	37	31	32	37	34
Th	4	6	12	7	12	14	3	3	16	7	12	3	7
U	1	2	3	2	3	4	5	1	4	2	3	3	2
Cr	132	216	90	79	179	267	69	44	253	122	357	284	54
Ni	47	124	37	25	67	53	25	11	150	54	144	86	42

Table 1(d). (Continued.)

Sample	Az.22-1	Zr.9	Es.105	Es.106	Es.115	Es.88	Es.104	Es.92	Es.89	Es.124	Es.90	Es.100	Es.117
Co	437	385	423	376	642	954	749	549	908	648	1067	567	400
Sc	97	16	nd	nd	nd	nd	nd	76	10	14	10	101	12
V	201	176	223	244	311	309	249	214	328	361	315	344	223
Cu	56	19	nd	nd	nd	nd	9	2	49	36	nd	58	nd
Pb	9	11	20	nd	12	12	15	16	14	20	5	16	5
Zn	111	212	89	41	89	43	61	162	31	54	27	482	24
La	17.88	28.8	30.76	39.72	30.64	15.69	39.03	18.78	32.66	28.04	24.1	21.75	41.89
Ce	43.9	54.14	60.37	67.92	59.16	55.68	73.27	50.29	62	57.23	46.53	43.67	78.96
Dy	5.19	5.8	4	5.6	4.3	3.36	5.31	3.58	4.38	4.51	3.55	5.49	3.39
Nd	26.17	32.28	31.07	36.8	31.32	35.62	37.5	30.61	32.69	31.91	24.53	24.16	38.4
Eu	1.15	2.02	1.49	2.02	1.56	1.05	1.95	1.44	1.87	1.63	1.37	1.58	1.75
Pr	4.08	7.86	7.06	8.12	7.02	3.89	8.73	4.9	7.45	7.02	5.51	5.75	8.98
Ho	0.6	0.54	0.66	0.94	0.69	0.31	0.88	0.35	0.7	0.75	0.59	0.55	0.47
Lu	0.19	0.09	0.17	0.23	0.14	0.04	0.18	0.06	0.16	0.16	0.13	0.11	0.11
Tb	0.53	0.75	0.87	1.17	0.96	0.41	1.11	0.46	0.94	0.97	0.74	0.65	0.88
Hf	3.04	4.79	2.9	3.26	2.19	2.26	3.14	2.65	2.33	2.98	1.98	4.37	1.15
Sm	6.47	6.78	6.1	7.68	6.3	3.25	7.39	4.1	6.6	6.65	4.96	5.33	7.32
Yb	1.34	0.71	1.33	1.86	1.18	0.4	1.6	0.51	1.29	1.34	1.02	0.86	0.76
Gd	3.75	6.25	6.2	8.25	6.72	3.13	7.81	3.82	6.71	6.86	4.27	5.05	7.09

analysis is described in [Bhattacharya et al. \(2010, 2011\)](#).

4.1.2 Whole rock Sr and Nd isotopic data

$^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for samples were determined on the multi-collector Finnigan-MAT 262 mass spectrometer at Institute of Instrument Centre (IIC), Indian Institute of Technology (IIT), Roorkee by using a double-collector dynamic algorithm and normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ with a linear fractionation correction. $^{147}\text{Sm}/^{143}\text{Nd}$ ratios were determined by isotope dilution on separate aliquots ([Bickle 1986](#)). The Nd and Sr isotopic measurements were carried out following the procedure involving digestion of 0.1–0.3 g sample powders by standard acid mixture technique. The standard replicates showed a precision of 0.0035% (2σ) for Nd and 0.0045% (2σ) for Sr. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were analyzed using a triple collector dynamic algorithm and normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ with an exponential fractionation correction.

4.2 Geochemical characterization

Zirconium is one of the most immobile elements during low-grade alteration of basaltic rocks and is essentially incompatible in basaltic rocks ([Torney et al. 1979](#)). To illustrate this, we have plotted major and trace elements against Zr as an index of fractionation in Harker diagrams (figure 4b–l). MgO and FeO^t against Zr are given in figure 4(c and e) that show a sharply decreasing trend for MgO (16–2 wt.%) and FeO^t (20–2 wt.%). The low-Ti basement mafic rocks were observed to be rich in Mg and low- to high-Ti cover mafic rocks rich in Fe. In binary diagrams, TiO_2 vs. Zr (figure 4g), P_2O_5 vs. Zr (figure 4f), and Y vs. Zr (figure 4i) indicate both major and trace elements increased linearly with increasing Zr, which is supposed in the basaltic rocks. For the suite of samples used, the other major elements (Al, Ti) appear to define cohesive magmatic trends and the high field strength trace elements (Nb, Hf, Zr, Y), and the rare earth elements (REE) display smooth trends in chondrite-normalized diagrams indicating that they have been relatively immobile. To assess the mobility of individual elements during post crystallization processes, we have plotted a few known mobile elements such as Ba, Sr, and Na_2O , K_2O against Zr, these elements also show consistent trends, indicating that most of the major and trace

elements were not perturbed (figure 4i–l). Major element ratio plots, MgO/TiO_2 vs. CaO/TiO_2 , $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 vs. TiO_2 show tight magmatic trends ([Nesbitt et al. 1979](#)). Normalized REE and complimentary multi-element patterns are regular and consistent with magmatic processes, implying that the incompatible trace element abundance and their ratios appear to reflect near primary magma characteristics (figure 5a–f).

4.2.1 Classification and magma series

The mafic rocks of Biabanak-Bafq district have been classified on the basis of geochemical studies in three groups as (a) low-Ti basement amphibolites; (b) low-Ti cover mafic rocks and (c) high-Ti cover alkali mafic rocks and doleritic dykes. Besides, alkaline basalts generally have higher average TiO_2 than tholeiitic basalts and thus caution must be paid to distinguish ‘higher than average-Ti’ tholeiitic basalts from alkaline basalts because their origin is distinct (e.g., [Cummins et al. 1992](#)). High-Ti alkali mafic cover rocks, as well as doleritic dykes, depict similar geochemical characteristics and enriched sources. We suggest that the doleritic dykes could have acted as feeder dykes for the Ti-rich cover mafic volcanic and gabbroic bodies. Petrographic studies of the investigated mafic magmatic rocks indicate that some of the samples are slightly altered; samples with more than 2% LOI are discarded. Geochemical classification based on immobile trace elements is very useful in this case. One of the most useful discrimination diagrams for the altered or metamorphosed rocks is log-log Zr/Ti against Nb/Y diagram (figure 4a; [Pearce 1996](#)), which has been used for the classification of the Biabank-Bafq district samples. The majority of the low-Ti samples plot within the basalt and andesitic basalt fields, a majority of the high-Ti samples plot in the alkali basalt field, with a few samples plot in a basanite/nephelinite field. The low- to high-Ti cover mafic rocks occur as volcanic rocks and hypabyssal intrusive bodies and associated mafic dykes. Plotting on the Nb/Y-Zr/ P_2O_5 discrimination binary diagram ([Winchester and Floyd 1977](#)), low-Ti basement amphibolites along with low-Ti of the cover mafic rocks and high-Ti of the cover mafic rocks of Biabank-Bafq district distinctly indicate tholeiitic and alkaline nature, respectively. All these low- to high-Ti cover mafic rocks indicate Fe enriched nature. Observation of negative trends in major elements (e.g., MgO , CaO , Al_2O_3 ,

Figure 4. (a) $\log \text{Nb}/\text{Y}$ vs. $\log \text{Zr}/\text{TiO}_2$. These diagrams are proposed by Winchester and Floyd (1977) for classification of volcanic rocks using incompatible element ratios. (b–l) Harker major and trace variation diagram from Biabanak-Bafq district.

FeO^t vs. Zr) and positive trends of TiO_2 , P_2O_5 and $\text{Mg\#}$ (Mg number) vs. Zr plots (figure 4b–h), indicate fractionation of olivine, pyroxene, plagioclase, and titanomagnetite crystals. The classic AFM diagram (Irvine and Barager 1971)

confirmed a tholeiitic nature, as the investigated low-Ti basement and low- to high-Ti cover mafic rocks and the doleritic dykes are predominantly iron-rich (figure 6a). A diagram which is similar to AFM triangular plot, but is based on the

Figure 5. Chondrite, primitive mantle-normalized REE and trace patterns. Normalizing values from Sun and McDonough (1989).

elements Ti-Zr+Y-Cr (Davies *et al.* 1979) that are normally immobile during alteration, shows that the samples follow a clear tholeiitic trend, with two distinct lineages being evident in the dykes (figure 6b). A triangular plot of cations of Al-Fe+Ti-Mg (Jensen 1976) shows that majority of low-Ti samples fall in the komatiitic basalt, whereas high-Ti samples occupy in the high-Fe field tholeiitic basalt (figure 6c). The low-Ti basement amphibolites are more towards Mg and Fe tholeiite fields and low-Ti cover mafic samples are distinctly Fe-tholeiite, whereas the high-Ti cover mafic suite and dyke samples have Fe-enriched alkaline nature. Geochemical data thus reveal that the low-Ti basement amphibolites and cover mafic rocks is tholeiitic in nature, whereas the high-Ti cover mafic rocks as well as doleritic dykes are alkaline in nature and showing considerably more Fe enrichment than the low-Ti mafic samples.

4.2.2 Nd-Sr isotope geochemistry

The investigated mafic rocks have calculated Nd model age (T_{DM} ; table 2a and b), indicating average crustal residence time of 1.5 Ga. The

Nd model ages (T_{DM}) for basement amphibolites varies in the range of 1.22–2.93 Ga (figure 7a), with the corresponding ϵ_{Nd} at 1.5 Ga varying from -17.20 to $+3.92$ and demonstrating that the Saghand region might have experienced interaction of depleted mantle derived magmas with older crust (Nelson and Davidson 1993) (figure 7b). The negative epsilon values indicate long crustal residence for the basement samples. Nd model ages (T_{DM}) for low-Ti, high-Ti and dolerites from cover rocks varied in the range of 0.86–1.42, 1.19–1.91 and 1.01–1.69 Ga, respectively. The corresponding ϵ_{Nd} at 1.5 Ga varies from -4.71 to $+3.67$, $+0.85$ to $+3.33$, -3.53 to 2.19 and -1.02 to $+6.66$, respectively indicating that the Biabank-Bafq district might have experienced the interaction of depleted mantle derived magmas with older crust (Nelson and Davidson 1993) (figure 7b).

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ (1.5 Ga) *vs.* initial $^{143}\text{Nd}/^{144}\text{Nd}$ (1.5 Ga) indicates the derivation of low-Ti basement amphibolites, low- to high-Ti cover mafic rocks as well as doleritic dykes from enriched mantle similar to (EMI and EMII) sources (figure 8). In $^{143}\text{Nd}/^{144}\text{Nd}$ ratios *vs.* $^{87}\text{Sr}/^{86}\text{Sr}$

Figure 6. Triangular plots of (a) AFM (Irvine and Barager 1971); (b) (Zr+Y)–TiO₂*100–Cr (Davies *et al.* 1979); and (c) cation percent Al–(Fe+Ti)–Mg (Jensen 1976), all illustrating the tholeiite nature of the Posh-e-Badam block rocks.

evolution diagram (figure 8), the low-Ti amphibolites and low- to high-Ti cover mafic samples of Biabanak-Bafq district plot in the enriched mantle source between EMI (<0.5112) and EMII (0.5121) type source (Rollinson 1993). However, both of them follow the mixed mantle-crust source, but more likely towards enriched mantle source.

5. Discussion

5.1 Petrogenesis of mafic rocks

Low-Ti cover mafic rocks are distinctly enriched in incompatible elements such as large ion lithophile elements (LILE) and light REE (LREE) compared to primordial mantle abundances, but have an

equally distinct “continental” signature reflected in marked less Nb, Sr, P and Ti anomalies (Ahmad and Tarney 1991; Tarney 1992) in their mantle-normalized spidergrams (figure 5a–c). These geochemical features may have close similarities with Proterozoic continental flood basalt (CFB) signatures (Tarney 1992). These signatures were probably imposed upon the sub-continental lithosphere at the time of continental crustal evolution. The high-Ti mafic rocks and doleritic dykes show LREE and LILE enrichment and high field strength elements (HFSE) depletion (figure 5d–f). The whole-rock chemical composition of the low-Ti cover rocks (mafic dykes and gabbro) is consistent with fractional crystallization of an assemblage of olivine ± clinopyroxene ± plagioclase, probably derived from CFB-like magmas,

Table 2(a). *Sm-Nd (ppm), Sm/Nd and initial Nd isotope ratios and ϵ_{Nd} for low-Ti basement amphibolites, low- and high-Ti cover mafic rocks, high-Ti doleritic dykes.*

	Sample ID	Nd (ppm)	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	T (DM, Ga)	ϵ_{Nd} (t)			
						ϵ_{Nd} , today	ϵ_{Nd} , t = 0.5 Ga	ϵ_{Nd} , t = 1.0 Ga	ϵ_{Nd} , t = 1.5 Ga
Low-Ti basement amphibolites	Sa-46	3.68	0.74	0.12	2.93	-34.93	-29.05	-23.15	-17.20
	Sa-48	8.14	3.50	0.14	1.99	-19.21	-14.42	-9.60	-4.76
	Esk-13	6.42	1.38	0.13	1.27	-13.79	-8.40	-2.98	2.48
	Esk-16-1	5.84	1.20	0.12	1.30	-15.12	-9.32	-3.50	2.37
Low-Ti cover mafic rocks	Es.112	6.33	35.36	0.13	1.36	-21.53	-15.96	-10.35	-4.71
	Es.120	6.60	1.40	0.13	1.19	-13.23	-7.69	-2.12	3.49
	Zr.96	8.76	2.18	0.15	1.06	-8.72	-4.61	-0.48	3.67
	Es-96	6.17	1.32	0.13	1.62	-17.75	-12.30	-6.82	-1.30
	Az.22-1	5.66	1.50	0.16	1.19	-8.34	-4.85	-1.34	2.19
	Es.105	6.15	37.51	0.15	1.31	-11.68	-7.24	-2.76	1.73
	Es-101	8.33	4.01	0.12	1.44	-17.64	-11.54	-5.40	0.77
	Es-103	5.66	1.13	0.12	1.79	-21.70	-15.68	-9.63	-3.53
High-Ti cover mafic rocks	Zr.55	13.68	3.09	0.14	1.32	-13.23	-8.23	-3.20	1.86
	Es.91	17.79	3.58	0.12	1.19	-14.21	-8.25	-2.26	3.77
	Es.99	21.36	4.57	0.13	1.26	-13.86	-8.40	-2.91	2.62
	Ch-8	35.05	6.34	0.14	0.94	-14.41	-9.36	-4.27	0.85
	Az-6	45.39	9.65	0.13	0.90	-9.99	-4.47	1.08	6.66
High-Ti doleritic dykes	Chf-131	6.61	1.60	0.15	1.61	-14.28	-9.89	-5.47	-1.02
	Es.90	7.67	2.00	0.16	1.28	-9.35	-5.73	-2.08	1.58
	Es.92	15.92	3.60	0.14	1.15	-11.48	-6.49	-1.47	3.58

Table 2(b). Rb/Sr , $^{87}Sr/^{86}Sr$, and initial Sr isotope ratios; ϵSr for low-Ti basement amphibolites, low- and high-cover mafic rocks, high-Ti doleritic dykes.

Sample ID	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$			ϵSr , today	ϵSr (t)		
		T = 0 (today)	T = 0.5 Ga	T = 1 Ga		ϵSr , t = 0.5 Ga	ϵSr , t = 1.0 Ga	ϵSr , t = 1.5 Ga
Sa-46	1.82	0.708438	0.707149	0.705858	55.90	38.42	20.93	3.42
Sa-48	1.04	0.706943	0.706202	0.705461	34.68	24.99	15.29	5.58
Es-13	1.06	0.720041	0.719290	0.718539	220.60	210.78	200.96	191.13
Es-16-1	1.37	0.717268	0.716292	0.715316	181.23	168.22	155.20	142.17
Es-112	0.56	0.708007	0.707611	0.707215	49.8	44.98	40.19	35.38
Es-120	1.64	0.709942	0.708778	0.707612	77.2	61.55	45.83	30.10
Es-96	0.35	0.70542	0.705174	0.704927	13.1	10.39	7.72	5.04
Zrg-96	1.47	0.707859	0.706818	0.705776	47.7	33.72	19.76	5.78
Az-22-1	1.14	0.704496	0.703689	0.702881	-0.1	-10.69	-21.34	-32.00
Es-105	0.59	0.708353	0.707935	0.707517	54.7	49.59	44.48	39.37
Es-101	0.42	0.70753	0.707229	0.706929	43.0	39.57	36.13	32.68
Es-103	2.43	0.715844	0.714119	0.712393	161.0	137.37	113.70	90.01
Zr-55	1.47	0.707859	0.706818	0.705776	47.7	33.72	19.76	5.78
Es-91	0.87	0.704915	0.704298	0.703681	5.9	-2.04	-9.99	-17.93
Es-99	0.48	0.706099	0.705756	0.705413	22.7	18.66	14.61	10.56
Zrg-99	1.00	0.704903	0.704196	0.703488	5.7	-3.49	-12.72	-21.95
Az-6	0.34	0.709799	0.709554	0.709310	75.2	72.57	69.93	67.28
Chf-131	1.37	0.717268	0.716292	0.715316	181.2	168.22	155.20	142.17
Es-90	0.81	0.710593	0.710020	0.709447	86.5	79.18	71.87	64.55
Es-92	0.56	0.707398	0.707001	0.706604	41.1	36.32	31.51	26.69

Figure 7. (a) Evolution of ϵ_{Nd} growth curves for basement amphibolites. (b) Evolution of ϵ_{Nd} growth curves for cover mafic rocks. DM and CHUR lines are taken from Rollinson (1993) refereed.

Figure 8. Comparison of basement amphibolites with cover mafic rocks in evolution of initial $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ diagram. DM and CHUR lines are taken from Rollinson (1993).

it also suggests some contributions from crustal contamination. Low-Ti cover mafic samples contain a crustal component in the form of an increase in La/Yb with Zr/Nb ratios. In contrast, voluminous high-Ti mafic magmatic samples and doleritic dykes of this terrane display an increase in La/Yb with a decrease in Zr/Nb ratios, indicative of an alkaline mantle component. REE patterns indicate that low- to high-Ti cover rock samples can potentially be related to each other through varying degrees of partial melting of similar sources followed by gabbroic fractionation with plagioclase as an important phase. Low-Ti basement amphibolites depict large variation from low- to high-LREE patterns (figure 5d), which resemble island arc tholeiites (IAT), mid-ocean ridge basalts (MORB) and the high-Ti samples resemble ocean-island basalts (OIB) (after Sun and McDonough 1989; Greenough *et al.* 1990, 2007). Island arc tholeiites have flat to slightly enriched REE profiles, much less pronounced than OIB, whereas MORB show LREE depletion. These gently sloping profiles are consistent with the generation of magma in the shallow (spinel lherzolite) mantle. High-Ti cover mafic samples with highly enriched REE patterns ~ 50 to 120 times chondrite illustrate the derivation of these rocks from rather deeper (garnet lherzolite) and enriched mantle source(s) (figure 5f). OIB shows severely depleted HREE pattern indicating a presence of garnet in the source. The different REE patterns, which are observed in all the investigated rocks indicate the heterogeneous source(s). Therefore, it can be assumed that heterogeneous source and melting conditions also played a significant role in the generation of these rocks.

In the case of high-Ti mafic samples, low K_2O/P_2O_5 (0.02–11.82), high TiO_2/P_2O_5 (2.25–10.33), La/Nb (0.75–9.59), Nb/Th >1.71 and negative Rb anomaly probably reflects little contamination from the granitic continental crust. Geochemical compositions such as Al_2O_3/TiO_2 (3.87–10.83), mid-to-high TiO_2 (1.74–2.81 wt.%), positive Nb anomalies and LREE enrichment of the Biabanak-Bafq district samples attest to their OIB type signature, which probably got derived from enriched mantle source similar to EMI. Ba/Th (11.01–187), Ba/La (2.33–12.33) and Th/Nb (0.07–0.10) ratios suggest that the source enrichment process was marked by recycling of sediments into the mantle through subduction (Hergt *et al.* 1989). The ratios of Zr/Hf (28.57–56.11) and Zr/Ba (0.08–3.13) indicate the involvement of a deeper mantle source.

The Ce and Nd relationship is used to evaluate the crustal contamination. Horan *et al.* (1987) observed that in a Ce *vs.* Nd plot, the mantle derived melt that gets affected by progressive crustal contamination or assimilation fractional crystallization (AFC) lie along the lines intersecting the Nd axis and do not pass through the origin. In the Ce *vs.* Nd diagram (figure 9a), the low-Ti cover mafic intrusive rocks follow the trend passing through the origin and occupy the place between calculated 2 and 10% partial melting of primitive mantle (Sun and McDonough 1989), which indicates that the source of these rocks was enriched in light rare earth elements (LREE). The incompatible trace element ratios such as Zr/ TiO_2 , Zr/Y, La/Nb and Ce/Nb are not affected by processes of fractional crystallization and higher degrees of partial melting (Condie 1990a, b), thus the values of such ratios observed in the low-Ti mafic rocks appear to be source derived. Fractionation of plagioclase and olivine cannot alter the Zr/Y ratios, but fractionation of amphibole and clinopyroxene may raise the ratio with increasing Zr content (Ahmad and Tarney 1991; Floyd 1993; Ahmad *et al.* 1999; Kumar and Ahmad 2007). Thus, the positive correlation between Zr/Y and Zr shown by the dolerites and high-Ti mafic rocks indicate fractionation of clinopyroxene. However, the positive correlation between Zr/Y and Zr can also be produced by the decreasing degree of partial melting (figure 9b). Two calculated partial melting curves (Drury 1983) corresponding to two sets of source mineralogy (curve 1: olivine 60% $\pm$ orthopyroxene 20% $\pm$ clinopyroxene 10% $\pm$ plagioclase 10%; curve 2: olivine 60% $\pm$ orthopyroxene 20% $\pm$ clinopyroxene 10% $\pm$ garnet 10%) for Archean mantle source (Sun and Nesbitt 1977) are shown in the diagram. Most of the studied samples plot along curve ‘2’ indicating that the low-Ti group represent higher degrees of partial melting and the high-Ti group represent lower degrees of partial melting. Subsequent to their generation, most of these samples have experienced gabbroic fractionation involving olivine, clinopyroxene, and plagioclases as the dominant fractionating phase (figure 9b).

In the Zr *vs.* Ce and Y plots (figure 10a and b), the low-Ti basement amphibolites and a few of low-Ti cover mafic samples plot in the depleted field with respect to chondrite and primitive mantle lines, respectively. In the case of high-Ti cover mafic rocks and doleritic dykes, all the samples plot clearly in the enriched fields with respect to chondrite and primitive mantle lines. The high-Ti

Figure 9. (a) Nd vs. Ce plot for mafic volcanics. Dashed line shows calculated different extents of melting for garnet lherzolite source. Melting calculations were performed using the Batch melting equations. Garnet lherzolite mineralogy and melting proportions from Hanson (1980) and REE abundances are from Sun and McDonough (1989); (b) Binary plot of Zr/Y vs. Zr; melting curves (1 and 2) are after Drury (1983) and vectors for fractional crystallization are after Floyd (1993).

cover alkaline mafic rocks along with dolerites are characterized by severe enrichment of LILE-LREEs and HFSE (Nb, P, and Ti) (figure 5c). However, the majority of the low-Ti basement and cover mafic samples have enriched LREE-LILE, but depleted in HFSE (figure 5d and e). The enriched LREE-LILEs in low-Ti basement and cover mafic samples are an indication of their derivation from enriched

sources, the depletion of HFSE in the case of low-Ti group probably indicate crustal/lithospheric influence (Tarney 1992). The negative Eu anomaly in low-Ti basement and cover mafic samples indicate fractionation of plagioclase during the evolution of these rocks. Depletion of Nb, P, Ti and Y relative to LILEs in low-Ti cover mafic samples indicate typical continental rift setting with some influence

Figure 10. (a and b) Discrimination diagrams of Zr vs. Ce and Y and bivariate plot reflect the enriched and depleted source of the high- and low-Ti mafic samples.

of crustal material. Large variations in Nb/La and La/Sm ratios possibly reflect varying influence of the crustal material and also some LREE-LILE enrichment processes. Moreover, Nb/La and Nb/Ce ratios of the mafic rocks and dykes vary from 0.10 to 0.94 and from 0.08 to 0.50, respectively, which are lower compared to the respective primitive mantle values of 1.02 and 0.4, but not much different from the average crustal values of 0.69 and 0.33, respectively (Taylor and McLennan 1985). So, it becomes apparent that crustal contamination alone cannot produce lower ratios of Nb/La and Nb/Ce. The observed negative Sr and Eu anomalies and geochemical characteristics of the Biabanak-Bafq district mafic rocks and dykes reflect enriched source characteristics.

5.2 Tectonic settings of mafic rocks

On the $\text{MnO} \cdot 10\text{-TiO}_2\text{-P}_2\text{O}_5 \cdot 10$ (figure 11a) ternary tectono-magmatic diagram (after Mullen 1983), it becomes evident that the low-Ti base amphibolites, low- and high-Ti cover mafic rocks of Biabanak-Bafq district plot in distinct IAT, CAB, OIT and OIA fields, respectively. On the other hand, the majority of low-Ti basement amphibolites plot in the IAT and CAB field, the low-Ti cover mafic rocks fall in the IAT-OIT border and high-Ti alkaline mafic samples in the OIT and OIA fields. In the tectonic discrimination diagram Ti/1000 against V (ppm) (after Shervais 1982), the low-Ti basement samples plot in the arc-tholeiite basalts and low-Ti cover mafic rocks in the continental flood basalt (CFB), which occupy within the 10 to 20 Ti/V ratios (figure 11b).

Whereas the high-Ti cover mafic rocks as well as doleritic dykes plot in the oceanic island and alkali basalt field within the 50 to 100 Ti/V ratios. The high-Ti alkaline mafic samples show high ratios of Ti/V (>20) within the range of typical OIB and continental tholeiites.

As discussed earlier, the high-Ti mafic rocks are part of the extensional tectono-magmatic event, which had affected in Biabanak-Bafq district, these are consistent with the evolutionary history of the ANS (Stern *et al.* 1984; Stern and Voegeli 1987). The extensive Late Neoproterozoic low- to high-Ti cover mafic rocks of the Biabanak-Bafq district is comparable to the post-orogenic calc-alkaline (630–590 Ma) and alkaline (610–590 Ma) rocks of the north ANS. Both these magma types were emplaced between 610 and 590 Ma (Merritt 2003; Avigad and Gvirtzman 2009; Be'eri-Shlevin *et al.* 2009; Azer *et al.* 2010, 2012; Eyal *et al.* 2010; Azer 2013). It appears that these magmas might have formed during crustal thinning and extension (Be'eri-Shlevin *et al.* 2009; Be'eri-Shlevin *et al.* 2010; Eyal *et al.* 2010). The negative Nb, P, and Ti anomaly suggests the involvement of titanomagnetite/rutile fractionation and/or influence of sub-continental lithosphere on the mantle-derived rocks (Tarney 1992; Dasgupta *et al.* 2013). Considering that the Sm/Yb ratio is susceptible to the presence or absence of residual garnet in the source and also that La/Sm and Sm/Yb ratios are sensitive to the degree of partial melting (Neumann *et al.* 2014). The low-Ti basement amphibolites and low-Ti cover rocks reveal a generation of mafic magma from shallow garnet free source(s) (Huang *et al.* 2000). Also, a strong enrichment

Figure 11. (a) $\text{MnO} \cdot 10$ – TiO_2 – $\text{P}_2\text{O}_5 \cdot 10$ ternary tectono-magmatic diagram (after Mullen 1983), indicating of plotting the low-Ti basement amphibolites in the island arc tholeiite (IAT) and the majority of high-Ti cover alkali mafic rocks as well as dolerites in the oceanic island arc (OIA) fields. Interestingly, a few samples of high-Ti followed by low-Ti cover mafic rocks and plot within the IAT and OIT fields close to border lines. (b) $\text{Ti}/1000$ vs. V (ppm) binary tectonic discrimination diagram (after Shervais 1982).

of LILE (Ba and Sr) coupled with enrichment of the incompatible elements Zr and Ti relative to Y and Yb, leave little doubt that these high-Ti mafic rocks, as well as dolerite dykes, are the products of a smaller degree of partial melting. The post-collisional stage of tectono-magmatic evolution of the ANS commenced at ~ 620 Ma, the transition from convergence to extension occurred at ~ 600 Ma (Jarrar *et al.* 1993; Stern 1994; Genna *et al.* 2002; Be'eri-Shlevin *et al.* 2009) that finally gave way to a stable craton and platform setting (Be'eri-Shlevin *et al.* 2009). The cover volcanic rocks vary from acid to basic in composition and include rhyolite-rhyodacite, tuff

and keratophyre-spilitic lava that appear geochemically related. The mafic to ultramafic intrusive rocks, doleritic dykes indicate distinct Fe–Ti rich basalts.

The resemblance among the EMII, OIBs and some basaltic rocks from island-arc settings, where sediment subduction and contamination of upper mantle wedge is strongly implicated (e.g., Banda and Antilles arcs; Hart 1985, 1988), suggest that a subduction-modified SCLM may be another potential EMII-like mantle reservoir. We propose therefore that the EMII component recognized in the cover mafic rocks of Biabanak-Bafq district may have been derived from an SCLM modified by the

Figure 12. A hypothetical model for the magmatism of Proterozoic basement and cover rocks in the Biabanak-Bafq district.

addition of subduction-related metasomatic fluids during the Late Proterozoic. The partial melting for the high-Ti group probably occurred within the asthenosphere, with inputs from the SCLM in various proportions.

Studies of rift-related mafic dyke swarms associated with high-Ti mafic rocks are essential for the understanding generation of such extensive mafic magmatism and to identify asthenospheric upwelling (Ernst and Buchan 1997, 2001). There is general agreement that mafic magma experiences some degree of crustal contamination during ascent and/or residence in crustal magma chambers (Yu *et al.* 2015). Crustal contamination has been shown to be important in the petrogenesis of flood basalts (Devey and Cox 1987; Peng *et al.* 1994; Chesley and Ruiz 1998; Baker *et al.* 2000). On the other hand, a mantle source enriched in incompatible trace-elements, not influenced by a major crustal input, was postulated for some Proterozoic dyke swarms (Condie *et al.* 1987; Tarney and Weaver 1987; Boily and Ludden 1991) and other flood basalts (Molzahn *et al.* 1996). If a mantle derived geochemical signature can be demonstrated, it remains difficult to locate the mantle source, i.e., whether the magmas are predominantly derived from the sub-continental lithospheric mantle (SCLM) (e.g., Gallagher and Hawkesworth 1992; Turner *et al.* 1996), from an upwelling asthenospheric mantle (e.g., LeCheminant and Heaman 1989; Walker *et al.* 1997; Puchtel *et al.* 1999) or from a mixture of both (e.g., Ellam 1992; Gibson *et al.* 1995). Magmas of continental igneous provinces are generally large volumes of

tholeiitic flood basalts with several geochemical features similar to that of ocean island basalts (OIB) providing evidence for an enriched mantle source (Eby 1985). Thus, like OIB, magmas from many continental igneous provinces are believed to reflect mantle melts associated with a mantle upwelling. As discussed earlier, the low-Ti cover mafic series correspond quite well with the range of variation seen in the Posht-e-Badam sequence, and could be feeders; the other type high-Ti series, has more alkalic characteristics (high Nb/Zr) and could represent rift volcanic, or tectonically accreted fragments of ocean islands (Ahmad and Tarney 1994). According to Ahmad and Tarney (1991), even though such geochemical features are generally assumed to indicate contamination of the magmas with a continental crust constituent, the evidence is strongly in favour of the compositional characteristics being inherited from their mantle source. These geochemical characteristics are possibly imposed upon the sub-continental lithosphere at the time of continent formation, but in the case of younger CFB suites, this may have been modified to a lesser extent by following additions of asthenospheric mantle material. Generation of the Biabanak-Bafq district cover, mafic volcanic rocks could be induced by upwelling asthenospheric mantle responding to regional extension and/or stress release (Cloetingh and Wortel 1985, 1986).

In the proposed model (figure 12), it is possible that there was an initial rifting between the eastern and western central Iran or otherwise between basement complexes in the west and cover rocks

in the east, there may be extension/stretching of sub-continental lithosphere within the central Iran craton in turn produced highly attenuated crust/lithosphere. The sediments were deposited above this attenuated crust, followed by mafic intrusion before the stabilization of this craton. As the mafic magma ascent through thin/attenuated crust that was undergoing extension, they show lesser crustal contamination supporting the above observation. Therefore, the cover high-Ti alkali mafic-ultramafic magmatism formed within the intraplate continental rift tectonic environment setting. It is also possible that there was some activity undergoing during that time due to which crustal stretching initiated within the craton. It may be possible that there was a plume activity.

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References

- Ahmad T and Tarney J 1991 Geochemistry and petrogenesis of Garhwal volcanics: Implications for evolution of the N-Indian lithosphere; *Precamb. Res.* **50**(1–2) 69–88.
- Ahmad T and Tarney J 1994 Geochemistry and petrogenesis of late Archean Aravalli volcanics, basement enclaves and granitoids, Rajasthan; *Precamb. Res.* **65**(1–4) 1–23.
- Ahmad T, Mukherjee P K and Trivedi J R 1999 Geochemistry of Precambrian mafic magmatic rocks of the western Himalaya, India: Petrogenetic and tectonic implications; *Chem. Geol.* **160**(1–2) 103–119.
- Alavi M 1991 Tectonic map of the Middle East: Tehran; Geological Survey of Iran, scale 1:5,000,000.
- Alirezaei S and Hassanzadeh J 2012 Geochemistry and zircon geochronology of the Permian A-type Hasanrobat granite, Sanandaj–Sirjan belt: A new record of the Gondwana break-up in Iran; *Lithos* **151** 122–134.
- Avigad D and Gvirtzman Z 2009 Late Neoproterozoic rise and fall of the northern Arabian–Nubian Shield: The role of the lithospheric mantle denudation and subsequent thermal subsidence; *Tectonophysics* **477** 217–228.
- Azer M K, Stern R J and Kimura J I 2010 Origin of a Late Neoproterozoic (605 ± 13 Ma) intrusive carbonate-albitite complex in southern Sinai, Egypt; *Int. J. Earth Sci.* **99**(2) 245–267.
- Azer M K, Abu El-Ela F F and Ren M 2012 The petrogenesis of late Neoproterozoic mafic dyke like intrusion in south Sinai, Egypt; *J. Asian Earth Sci.* **54** 91–109.
- Azer M K 2013 Late Edicaran (605–580 Ma) post-collisional alkaline magmatism in the Arabian–Nubian Shield: A case study of Serbal ring-shaped intrusion, southern Sinai, Egypt; *J. Asian Earth Sci.* **77** 203–223.
- Baker J, MacPherson C G, Menzies M A, Thirwall M F, Al-Kadal M and Matthey D P 2000 Resolving crustal and mantle contributions to continental flood volcanism, Yemen: Constraints from mineral oxygen isotope data; *J. Petrol.* **41**(12) 1805–1820.
- Be’eri-Shlevin Y, Katzir Y and Whitehouse M 2009 Post-collisional tectonomagmatic evolution in the northern Arabian–Nubian Shield: Time constraints from ion-probe U–Pb dating of zircon; *J. Geol. Soc.* **166** 71–85.
- Beeri-Shlevi Y, Katzir Y and Valley J W 2009 Crustal evolution and recycling in a juvenile continent: Isotope ratio of zircon in the northern Arabian–Nubian Shield; *Lithos* **107** 169–184.
- Beeri-Shlevi Y, Katzir Y, Blichert-Toft, Kleinhanns I C and Whitehouse M 2010 Nd–Sr–Hf–O isotope provinciality in the northernmost Arabian–Nubian Shield: Implications for crustal evolution; *Contrib. Mineral. Petrol.* **160** 181–201.
- Berberian M and King G C P 1981 Towards a paleogeography and tectonic evolution of Iran; *Can. J. Earth Sci.* **18**(2) 210–265.
- Bhattacharya S, Das P, Chaudhary A K and Saw A K 2010 Mafic granulite xenoliths in the Eastern Ghats belt: Implications for lower crustal processes in the south eastern Indian peninsula; *Ind. J. Geol.* **80** 55–69.
- Bhattacharya S, Das P, Chaudhary A K and Saw A K 2011 Mafic granulite xenoliths in the eastern Indian shield: Evidence for recycled continental crust in the Archean mantle; *Lithosphere* **3**(2) 155–169.
- Bickle M J 1986 Implications of melting for stabilisation of the lithosphere and heat loss in the Archean; *Earth Planet Sci. Lett.* **80**(3–4) 314–324.
- Boily M and Ludden J N 1991 Trace element and Nd isotopic variations in Early Proterozoic dyke swarms emplaced in the vicinity of the Kapuskasing structural zone: Enriched mantle or assimilation and fractional crystallization process?; *Can. J. Earth Sci.* **28**(1) 26–36.
- Chesley J T and Ruiz J 1998 Crust–mantle interaction in large igneous provinces: Implications from the Re–Os isotope systematics of the Columbia River flood basalts; *Earth Planet Sci. Lett.* **154**(1–4) 1–11.
- Cloetingh S and Wortel R 1985 Regional stress field of the Indian Plate; *Geophys. Res. Lett.* **12**(2) 77–80.
- Cloetingh S and Wortel R 1986 Stress in the Indo-Australian Plate; *Tectonophysics* **132** 49–67.
- Condie K C, Bobnow D J and Card K D 1987 Geochemistry of Precambrian mafic dykes from the southern Superior Province; In: *Mafic Dyke Swarms* (eds) Halls H C and Fahrig W D, *Geol. Assoc. Can. Spec. Papers* **34** 95–108.
- Condie K C 1990a Geochemical characteristics of Precambrian basaltic greenstones; In: *Early Precambrian basic magmatism* (eds) Hall R P and Hughes D J, Blackie Publication, Glasgow, UK, pp. 40–55.

- Condie K C 1990b Growth and accretion of continental crust: inferences based on Laurentia; *Chem. Geol.* **83**(3–4) 183–194.
- Cummins L E, Arthur J D and Ragland P C 1992 Classification and tectonic implications for early Mesozoic magma types of the circum-Atlantic; In: *Eastern North American Mesozoic Magmatism* (eds) Puffer J H and Ragland P C, *Geol. Soc. Am. Spec. Paper* **268** 119–135.
- Daliran F 2002 Kiruna-type iron oxide-apatite ores and apatites of Bafq district, Iran, with an emphasis on the REE geochemistry of their apatite's; In: *Hydrothermal iron oxide copper-gold and related deposits* (ed.) Porter T M, PGC Publishing, Linden Park, South Australia, pp. 303–320.
- Daliran F, Stosch H G and Williams P 2009 A review of the Early Cambrian magmatic and metasomatic events and their bearing on the genesis of the Fe oxide-REE apatite deposits (IOA) of the Bafq District, Iran; In: *Smart science for exploration and mining* (eds) Williams *et al.*, Proceedings of the 10th Biennial SGA Meeting, Townsville, Australia, 17–20th August.
- Daliran F, Stosch H G, Williams P, Jamali H and Dorri M B 2010 Early Cambrian iron oxide-apatite-REE (U) Deposits of the Bafq District, east-central Iran; In: *Exploring for Iron oxide copper-gold deposits: Canada and Global analogues* (eds) Corriveau L and Mumin H, *Geol. Assoc. Can. Short Course Notes* **20** 143–155.
- Dasgupta S, Bose S and Kaushik D 2013 Tectonic evolution of the Eastern Ghats Belt, India; *Precamb. Res.* **227** 247–258.
- Davies J F, Grant R W E and Whitehead R E S 1979 Immobile trace elements and Archean volcanic stratigraphy in the Timmins mining area, Ontario; *Can. J. Earth Sci.* **16**(2) 305–311.
- Devey C V and Cox K J 1987 Relationship between crustal contamination and crystallization in continental flood basalt magmas with special reference to the Deccan traps of the Western Ghats, India; *Earth Planet. Sci. Lett.* **84**(1) 59–68.
- Drury S A 1983 The petrogenesis and tectonic setting of Archaean metavolcanics from Karnataka state, south India; *Geochim. Cosmochim. Acta* **47**(2) 317–329.
- Eby N 1985 Sr and Pb isotopes, U and Th chemistry of alkaline Montregian and White Mountain igneous provinces, eastern North America; *Geochim. Cosmochim. Acta* **49**(5) 1143–1153.
- Ellam R M 1992 Lithospheric thickness as a control on basalt geochemistry; *Geology* **20**(2) 153–156.
- Ernst R E and Buchan K L 1997 Layered mafic intrusions: A model for their feeder systems and relationship with giant dyke swarms and mantle plume centres; *S. Afr. J. Geol.* **100**(4) 319–334.
- Ernst R E and Buchan K L 1997 Giant radiating dyke swarms: Their use in identifying pre-Mesozoic large igneous provinces and mantle plumes; In: *Large Igneous Provinces: Continental, Oceanic, and Planetary Volcanism* (eds) Mahoney J and Coffin M, *Geophys. Monograph Ser. Am. Geophys. Union* **100** 297–333.
- Ernst R E and Buchan K L 2001 Large mafic magmatic events through time and links to mantle plume heads; In: *Mantle plumes: Their identification through time* (eds) Ernst R E and Buchan K L, *Geol. Soc. Am. Boulder CO*, pp. 483–575.
- Eyal M, Livinovsky B, Jan B M and Katzir Y 2010 Origin and evolution of post-collisional Magmatism: Coeval Neoproterozoic calc-alkaline and alkaline suites of the Sinai peninsula; *Chem. Geol.* **269**(3–4) 153–179.
- Floyd P A 1993 Geochemical discrimination and petrogenesis of alkalic basalt sequences in part of the Ankara mélange, central Turkey; *J. Geol. Soc. London* **150** 541–550.
- Gallagher K and Hawkesworth C 1992 Dehydration melting and the generation of continental flood basalts; *Nature* **358** 57–59.
- Genna A, Nehlig P, Goff E L E, Guerrot C and Shanti M 2002 Proterozoic tectonism of Arabian Shield; *Precamb. Res.* **117**(1–2) 21–40.
- Gibson S A, Thompson R N, Leonardo O H, Dickin A P and Mitchell J G 1995 The Late Cretaceous impact of the Trinidad mantle plume: Evidence from large-volume, mafic, potassic magmatism in SE Brazil; *J. Petrol.* **36**(1) 189–229.
- Ghorbani M 2013 The economic geology of Iran: Mineral deposits and natural resources; *Springer Geol. Springer Sci. Bus. Med. Dordrecht* **45** 569p, <https://doi.org/10.1007/978-94-007>.
- Greenough J D, Fryer B J and Robinson P T 1990 Geochemical effects of alteration on mafic rocks from Indian Ocean Site 706; In: *Proceedings of the Ocean Drilling Program* (eds) Duncan R A, Backman J and Peterson L C, *Sci. Results* **115** 85–92.
- Greenough J D, Dostal J and Greenough L M M 2007 Incompatible element ratios in French Polynesia basalts: Describing mantle component fingerprints; *Austr. J. Earth Sci.* **54**(7) 947–958.
- Haghipour A 1974 Etude géologique de la région de Biabanak Bafq (Iran Central); pétrologie et tectonique du précambrien et de sa couverture, Ph.D. thesis, université scientifique et médicale de Grenoble, France, 403p.
- Haghipour A 1977 *Geological Map of the Biabanak-Bafq Area*; Geological Survey of Iran.
- Hanson G N 1980 Rare earth elements in petrogenetic studies of igneous rocks; *Ann. Rev. Earth Planet. Sci.* **8** 371–406.
- Hassanzadeh J, Stockli D F, Horton B K, Axen G J, Stockli L D, Grove M, Schmitt A K and Walker J D 2008 U–Pb zircon geochronology of late Neoproterozoic–Early Cambrian Granitoids in Iran: Implications for paleogeography, magmatism, and exhumation history of Iranian basement; *Tectonophysics* **451**(1–4) 71–96.
- Hart W K 1985 Chemical and isotopic evidence for mixing between depleted and enriched mantle, northwestern USA; *Geochim. Cosmochim. Acta* **49**(1) 131–144.
- Hart S R 1988 Heterogeneous mantle domains: Signatures, genesis and mixing chronologies; *Earth Planet. Sci. Lett.* **90**(3) 273–296.
- Hergt J M, Chappell B W, McCulloch M T, McDougall I and Chivas A R 1989 Geochemical and isotopic constraints on the origin of the Jurassic dolerites of Tasmania; *J. Petrol.* **30** 841–883.
- Hoffman P F 1991 Did the breakout of Laurentia turn Gondwana inside-out?; *Science* **252**(5011) 1409–1412.
- Horan M F, Hanson G N and Spencer K J 1987 Pb and Nd isotope and trace elements constraints on the origin

- of basic rocks in an early Proterozoic igneous complex, Minnesota; *Precamb. Res.* **37**(4) 323–342.
- Huang S, Pollack H N and Shen P Y 2000 Temperature trends over the past five centuries reconstructed from borehole temperatures; *Nature* **403** 756–758.
- Irvine T N and Barager W R A 1971 A guide to the chemical classification of the common volcanic rocks; *Can. J. Earth Sci.* **8**(5) 523–548.
- Jackson J and McKenzie D 1984 Active tectonics of the Alpine-Himalayan Belt between western Turkey and Pakistan; *Geophys. J. Roy. Astron. Soc.* **77** 185–264.
- Jarrar G, Wachendorf H and Zachmann D 1993 A Pan-African alkaline pluton intruding the Saramuj conglomerate, south-west Jordan; *Int. J. Earth Sci.* **82**(1) 121–135.
- Jensen L S 1976 *A New Cation Plot for Classifying Subalkalic Volcanic Rocks*; Ontario Division of Mine, Miscellaneous Paper **66**, 22p.
- Kröner A 1985 Ophiolites and the evolution of the tectonic boundaries in the late Proterozoic Arabian-Nubian Shield of northeast Africa and Arabia; *Precamb. Res.* **27**(1–3) 277–300.
- Kumar A and Ahmad T 2007 Geochemistry of mafic dykes in parts of Chhotanagpur Gneissic Complex: Petrogenetic and tectonic implications; *Geochem. J.* **41**(3) 173–186.
- Longjam K C and Ahmad T 2012 Geochemical characterization and petrogenesis of Khairanagh volcanics: Implications for crustal evolution; *Geol. J.* **47**(2–3) 130–143.
- LeCheminant A N and Heaman L M 1989 Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening; *Earth Planet. Sci. Lett.* **96**(1–2) 38–48.
- Merri J G 2003 A synopsis of events related to the assembly of eastern Gondwana; *Tectonophysics*. **362**(1–4) 1–40.
- Molzahn M, Reisberg L and Worner G 1996 Os, Sr, Nd, Pb, O isotope and trace element data from the Ferrar flood basalt, Antarctica: Evidence for an enriched subcontinental lithospheric source; *Earth Planet. Sci. Lett.* **144**(3–4) 529–546.
- Mullen E D 1983 MnO–P₂O₅–TiO₂: A minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis; *Earth Planet. Sci. Lett.* **62** 53–62.
- Nabavi M H 1976 An introduction to the Iranian geology; *Geological Survey of Iran*, 110p. (in Persian).
- Nadimi A 2007 Evolution of the central Iranian basement; *Gondwana Res.* **12**(3) 324–333.
- Nelson S T and Davidson J P 1993 Interactions between mantle derived magmas with mafic crust, Henry mountains, Utah; *J. Geophys. Res.* **98**(B2) 1837–1852, <https://doi.org/10.1029/92JB02689>.
- Nesbitt R W, Sun S S and Purvis A C 1979 Komatiites: Geochemistry and genesis; *Can. Mineral.* **17** 165–186.
- Neumann W, Breuer D and Spohn T 2014 Differentiation of Vesta: Implications for a shallow magma ocean; *Earth Planet. Sci. Lett.* **395** 267–280.
- Pearce J A 1996 A user's guide to basalt discrimination diagrams; In: *Trace element geochemistry of volcanic rocks: Applications for massive sulphide exploration* (eds) Bailes A H, Christiansen E H, Galley A G *et al.*, Short Course Notes, *Geol. Assoc. Can.* **12** 79–113.
- Peng Z X, Mahoney J J, Hooper P R, and Beane J 1994 A role for lower continental crust in flood basalt genesis? Isotopic and incompatible element study of the lower six formations of the western Deccan Traps; *Geochim. Cosmochim. Acta* **58**(1) 267–288.
- Pollard P J, Millburn D, Taylor R G and Cuff C 1983 *Mineralogical and textural modifications in granites associated with mineralization, Herberton-Mt Garnet Tinfield, Queensland*; Geological Society of Australia Queensland Division, pp. 413–430.
- Puchtel I S, Brugmann G E and Hofmann A W 1999 Precise Re–Os mineral isochron and Pb–Nd–Os isotope systematics of a mafic-ultramafic sill in the 2.0 Ga Onega plateau (Baltic Shield); *Earth Planet. Sci. Lett.* **170**(4) 447–461.
- Ramezani J and Tucker R D 2003 The Saghand region, Central Iran: U–Pb geochronology, petrogenesis and implications for Gondwana tectonics; *Am. J. Sci.* **303**(7) 622–665.
- Rollinson H 1993 *Using Geochemical Data: Evaluation, Presentation, Interpretation*; Longman, London, 352p.
- Samani B 1988 Metallogeny of the Precambrian in Iran; *Precamb. Res.* **39**(1–2) 85–106.
- Schmidt D L, Hadley D G and Stoesser D B 1978 Late Proterozoic crustal history in southern Najd province, Saudi Arabia (abstract); *Precamb. Res.* **6** A35.
- Shervais J W 1982 Ti–V plots and petrogenesis of modern and ophiolitic lavas; *Earth Planet. Sci. Lett.* **59**(1) 101–118.
- Sillitoe R H 1979 Metallogenic consequences of late Neoproterozoic suturing in Arabia, Egypt, Sudan and Iran; In: *Evolution and mineralization of Arabian–Nubian shield (volume 1)* (ed.) Tahoun S A, Instit. Appl. Geol., Pergamon Press Ltd., Oxford **3** 110–120.
- Stern R J 1994 Arc assembly and continental collision in the Neoproterozoic East African Orogeny: Implications for the consolidation of Gondwana land; *Ann. Rev. Earth Planet. Sci.* **22** 319–351.
- Stern R J and Voegeli D A 1987 Geochemistry, geochronology, and petrogenesis of a late Precambrian (~590 Ma) composite dike from the northeastern desert of Egypt; *Geo. Rundschau*. **76** 325–341.
- Stern R J, Gottfried D and Hedge C E 1984 Late Precambrian rifting and crustal evolution in the Northeastern Desert of Egypt; *Geology* **12** 168–171.
- Stöcklin J, Ruttner A and Nabavi M 1964 New data on the lower Paleozoic and Precambrian of North Iran; *Geol. Surv. Iran* **1** 29p.
- Stöcklin J 1968 Structural history and tectonics of Iran: A review; *Am. Assoc. Petrol. Geol. Bull.* **52** 1229–1258.
- Stöcklin J 1974 Possible Ancient Continental Margins in Iran; In: *The Geology of Continental Margins* (eds) Burke C A and Drake C L, Springer Verlag, New York, pp. 873–887.
- Stöcklin J, Eftekharneshad J and Hushmandzadeh A 1972 Central Lut reconnaissance, East Iran; *Geol. Surv. Iran* **22** 62p.
- Sun S S and Nesbitt R W 1977 Chemical heterogeneity of the Archean mantle composition of the bulk earth and mantle evolution; *Earth Planet. Sci. Lett.* **35**(3) 429–448.
- Sun S S and McDonough W F 1989 Chemical and isotopic systematics of oceanic basalts: Implications for mantle

- composition and processes; In: *Magmatism in the Ocean Basins* (eds) Saunders A D and Norry M J, *Geol. Soc. London Spec. Publ.* **42** 313–345.
- Tarney J, Wood D A, Varet J, Saunders A D and Cann J R 1979 Nature of mantle heterogeneity in the North Atlantic: evidence from Leg 49 Basalts; In: *Results of Deep Sea Drilling in the Atlantic* (eds) Talwani M, Harrison C G and Hayes D E, Maurice Ewing Series, *Am. Geophys. Union* **2** 285–301.
- Tarney J and Weaver B L 1987 Mineralogy, petrology and geochemistry of the Scourie dykes: Petrogenesis and crystallization processes in dykes intruded at depth; In: *Evolution of the Lewisian and Comparable Precambrian High Grade Terrains* (eds) Park R G and Tarney J, *Geol. Soc. Spec. Publ.* **27** 217–233.
- Tarney J 1992 Geochemistry and significance of mafic dyke swarms in the Proterozoic; In: *Proterozoic Crustal Evolution: Developments in Precambrian Geology* (ed.) Condie K C, Elsevier Amst. **10** 151–179.
- Taylor S R and McLennan S M 1985 *The continental crust: Its composition and evolution*, Blackwell Scientific Publication, Oxford, 312p.
- Taylor R G and Pollard P J 1988 Pervasive hydrothermal alteration in tin-bearing granites and implications for the evolution of ore-heating magmatic fluids; In: *Recent advances in the geology of granite-related mineral deposits, Quebec* (eds) Taylor R P and Strong D F, *Can. Instit. Mining Metallurgy*, pp. 86–95.
- Turner S, Hawkesworth C, Gallagher K, Peate D and Mantovani M 1996 Mantle plumes, flood basalts, and thermal models for melt generation beneath continents: Assessment of a conductive heating model and application to the Paraná; *J. Geophys. Res.* **101(B5)** 11,503–11,518.
- Verdel C, Wernicke B P, Ramezani J, Hassanzadeh J, Renne P R and Spell T R 2007 Geology and thermochronology of Tertiary Cordilleran-style metamorphic core complexes in the Saghand region of central Iran; *Geol. Soc. Am. Bull.* **119(7/8)** 961–977.
- Walker R J, Morgan J W, Beary E S, Smoliar M I, Czamanske G K and Horan M F 1997 Applications of the ^{190}Pt – ^{186}Os isotope system to geochemistry and cosmochemistry; *Geochim. Cosmochim. Acta* **61(22)** 4799–4808.
- White R S and McKenzie D 1989 Magmatism at rift zones: the generation of volcanic continental margins and flood basalts; *J. Geophys. Res.* **94(B6)** 7685–7729.
- Whitney D L and Evans B W 2010 Abbreviations for names of rock-forming minerals; *Am. Mineral.* **95** 185–187.
- Winchester J A and Floyd P A 1977 Geochemical discrimination of different magma series and their differentiation products using immobile elements; *Chem. Geol.* **20** 325–344.
- Yu X, Lee C A, Chen L H and Zeng G 2015 Magmatic recharge in continental flood basalts: Insights from the Chifeng igneous province in Inner Mongolia; *Geochem. Geophys. Geosyst.* **16** 2082–2096.

Corresponding editor: N V CHALAPATHI RAO