Geochemistry and mineral composition of lamprophyre dikes, central Iran: implications for petrogenesis and mantle evolution

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Late Proterozoic–Early Cambrian magmatic rocks that range in composition from mafic to felsic have intruded into the Hour region of the central Iranian micro-continent. The Hour lamprophyres are alkaline, being characterized by low contents of SiO₂ and high TiO₂, Mg# values, high contents of compatible elements, and are enriched in LREE and LILE but depleted in HFSE. Mineral chemistry studies reveal that the lamprophyres formed within a temperature range of ~1200° to 1300°C and relatively moderate pressure in subvolcanic levels. The Hour lamprophyres have experienced weak fractional crystallization and insignificant crustal contamination with more primitive mantle signatures. They were derived from low degree partial melting (1–5%) of the enriched mantle characterized by phlogopite/amphibole bearing lherzolite in the spinel-garnet transition zone at 75–85 km depth, and with an addition of the asthenospheric mantle materials. We infer the Hour lamprophyres to be part of the alkaline rock spectrum of the Tabas block and their emplacement, together with that of other alkaline complexes in the central Iran, was strongly controlled by pre-existing crustal weakness followed by the asthenosphere-lithospheric mantle interaction during the Early Cambrian.

Keywords. Central Iran; alkaline lamprophyre; mineral chemistry; asthenosphere-lithospheric mantle.

1. Introduction

Lamprophyres are alkaline/calc-alkaline, silica-undersaturated, mafic or ultramafic rocks with high MgO, K₂O, Na₂O, Ni and Cr. They are hypabyssal porphyritic rocks with a panidiomorphic texture, whose abundant mafic phenocrysts consist of mica ± amphibole ± pyroxene and/or olivine, set in a matrix of the same minerals, plus feldspar (Green and Ringwood 1970;

Rock 1991; Woolley *et al.* 1996). Lamprophyres are most commonly injected into the extensional parts of a continent (Rock 1991), where they form peripheral parts of larger intrusive bodies. Lamprophyric melts provide information on their mantle source and geodynamic setting (e.g., Tappe *et al.* 2006; Jiang *et al.* 2010). It is generally believed that lamprophyre originates from mantle-derived magma (Rock 1987; Foley 1992) that itself had formed from partial melting of a phlogopite- and/or

Figure 1. (a) Map of Iran showing the Late Neoproterozoic–Early Cambrian igneous and sedimentary rocks in central Iran (after Alavi 1991). (b) Geological map of the Hour area (modified after Sahandi 1995).

amphibole-bearing lherzolite in the spinel-garnet transition zone (e.g., Rock 1987; McKenzie 1989). Alkaline lamprophyres with similar composition and tectonic setting occur on Gorringe Bank, SW Portugal (Cornen 1982), and in the Canary Islands (Ahijado *et al.* 2001). Although alkaline lamprophyres are found on oceanic islands (Ahijado *et al.* 2001), they are typical of continental rifts. In the Hour area of central Iran, alkaline lamprophyres and associated gabbros were emplaced into limestone, sandstone, and acidic to basic volcanic and sub-volcanic rocks in a single Late Neoproterozoic–Early Cambrian episode (figure 1).

The lamprophyre dikes are characterized by coarse mafic phenocrysts set into an aphanitic groundmass. They are interpreted to have been emplaced in a rifting basin (Ramezani and Tucker 2003; Jami *et al.* 2007; Stosch *et al.* 2011). In Greenland, similar, alkaline lamprophyres were emplaced in association with mid-Proterozoic rifting are described from Greenland (Brooks and Platt 1975; Pearce and Leng 1996).

Here, we report major and trace element geochemistry of phenocrysts and whole-rock geochemistry of the Iranian lamprophyres, with the objective to better understand the origin of these

dikes and the larger tectonic regime that prevailed in central Iran during Late Neoproterozoic–Early Cambrian.

2. Geological background

Geologically speaking, Iran, consists of a tectonic collage of Gondwana-derived terranes, that are separated by narrow belts of ophiolite (Moghadam and Stern 2014, 2015), which accreted to the southern margin of Eurasia over a long interval of time (Şengör *et al.* 1991, 1993). The oldest magmatic rocks in Iran are Late Neoproterozoic to Early Cambrian granites and gneissic rocks (~500 to 600 Ma; Cadomian), formed along the northern margin of Gondwana during Pan-African orogeny (Hassanzadeh *et al.* 2008; Rossetti *et al.* 2015). Igneous rocks of this age occur in the western (Golpayegan), northwestern (Khoy-Salmas, Zanzan-Takab), northeastern (Torud, Takanar), northern (Lahijan granites), and central Iranian micro-continent (Saghand) (Hassanzadeh *et al.* 2008; Moghadam *et al.* 2016). In turn, the central Iranian micro-continent consists, from east to west, of four major crustal domains: The Lut, Tabas, Poshte-Badam and the Yazd blocks. These blocks are bounded by a series of intersecting regional-scale faults (Berberian and King 1981; Alavi 1991; Verdel *et al.* 2011) (figure 1a). The Tabas block consists of acidic to basic volcanic and sub-volcanic rocks and dikes of Precambrian–Cenozoic age (Samani 1993, 1998) (figure 1b). The oldest unit is a thick pile of felsic volcanic tuffs and volcano-sedimentary sequences that have been locally intruded by gabbroic to granitic and trachytic to doleritic small plutons and associated lamprophyre dikes (Jami *et al.* 2007; Stosch *et al.* 2011) (figure 2a and b). The volcano-sedimentary unit is overlain by gypsum, micaceous shale and fine-grained sandstone, limestone and dolomite recognized as Rizu and Dezu series (Samani 1993, 1998). The Hour lamprophyre dikes are situated in the southern part of the Tabas block and hosted by Rizo and Dezo series.

The lamprophyric dikes vary from 100 to 300 m in strike length, and 1–5 m in thickness. These rocks are characterized by their black colour and inequigranular texture, due to the abundance of brown amphibole and clinopyroxene in a fine-grained feldspathic groundmass (orthoclase) (figure 2e and f).

The Cambrian units are conformably overlain by intermediate to basic Silurian volcanic rocks.

Sedimentary units of Devonian to Jurassic age comprise sandstone, silty shale, well-bedded limestone and thickly bedded dolomites (Sahandi 1995).

3. Petrography

The Hour lamprophyres are melanocratic, holocrystalline rocks with porphyritic textures, containing phenocrysts of euhedral–subhedral pyroxene, brown amphibole and olivine. The matrix consists of subhedral–anhedral pyroxene, brown amphibole, K-feldspar, and carbonate. Accessory minerals mainly include apatite and opaque minerals. Altered minerals consist of calcite, zeolite, chlorite and ore minerals. Brown amphibole minerals are euhedral–subhedral (figure 2e), whereas others are anhedral (figure 2e and f). Pleochroic (greenish brown to pinkish brown) amphibole constitutes up to 50% of the phenocrysts, occurring as elongate and prismatic crystals of up to 5 mm, and as micro-lites up to 0.5 mm size. Some display marginal resorption. Clinopyroxene (0.5–3 mm) constitutes 30–40% of total volume of the phenocrysts. Olivine possesses a network-style texture and is highly fractured with pseudomorph features that are filled by the secondary minerals such as calcite and chlorite.

4. Analytical methods

Tables 1–4 provide representative electron microprobe chemical analyses of amphibole, pyroxene, olivine, and feldspar. Silicon, Ti, Al, Cr, Fe, Mn, Mg, Ca, Na, and K were determined in polished thin sections using an SX100 electron microprobe (EMP) at the Mineral Processing Research Centre, Karaj, Iran (MPRCI). Operation conditions were 15 kV accelerating potential voltage, and 20 nA probe current. Beam sizes used for phenocrysts and matrix were 3 and 1 µm, respectively. Natural and synthetic standards, minerals of known compositions included albite (Na), periclase (Mg), corundum (Al), wollastonite (Ca, Si), orthoclase (K), pyrophanite (Mn, Ti) and magnetite (Fe). Counting times were 10–30 s for peaks and 10 s for background. Analytical accuracy varies between 1 and 5% depending on the abundance of the element. Deer *et al.* (1992) describe the details of calibration and analysis.

Analysis of bulk rock was carried by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) for major elements, and by Inductively

Figure 2. (a) and (b) Shale and sandstones layers of the Rizu Formation (lower Cambrian) injected by Hour lamprophyric dikes. (c) Hand specimen of lamprophyric dikes of the Hour area. (d) and (e) Olivine with framework structure and elongate phenocryst of amphibole in an aphanitic groundmass of mainly feldspar. (f) Coarse grains of amphibole and clinopyroxene in a groundmass of felsic minerals (in ppl).

Coupled Plasma Mass Spectrometry (ICP-MS) for the trace elements (table 5) at the ACME Analytical Laboratories (Vancouver), Canada. Powdered samples (50 mg) were dissolved in high-pressure Teflon bombs using a HF+HNO₃ mixture acid. The precision of analysis, based on the repeated analyses, is $\pm 1.0\%$ for major elements, whereas most trace elements have an uncertainty of $\pm 5.0\%$.

5. Results

5.1 Mineral chemistry

Amphibole: Electron microprobe analyses (table 1) reveal a narrow compositional range that is

characterized by high Al (12.7–16.3 wt.%) and Ti content (3.65–6.56 wt.%) and low Cr content (<0.07 wt.% Cr₂O₃). The amphiboles are calcic according to the Leake *et al.* (1997) and Molina *et al.* (2009) classification schemes, plotting as kaersutite (figure 3a) and alkaline (figure 3b).

Clinopyroxene: Clinopyroxenes compositions range from En₃₂ to En₅₄ and Wo₄₉ to Wo₆₂. They have low MnO (0.08–0.12 wt.%), SiO₂ (44–48 wt.%) and Al₂O₃ (6.5–9.5 wt.%) and CaO (20.7–23.0 wt.%) contents (table 2). Strikingly high Ti contents (maximum 2.64 and 2.1 wt.% average), likely reflect high Ti in the parental magma. Data

Table 1. Selected electron probe micro-analyses (EPMA) of amphiboles on the basis of 13 cations of lamprophyre dykes of the Hour area, Central Iran.

Point. no	S.3	S.4	S.6	S.8	S.9	S.10	S.11	S.12	S.13	S.14	S.17	S.18	S.19	S.20	S.21	S.22
SiO ₂	38.22	40.09	40.13	40.24	40.35	39.07	39.89	39.84	37.08	38.23	38.73	38.13	38.96	40.33	39.95	39.10
TiO ₂	5.31	4.46	3.96	4.34	4.05	4.20	4.83	4.12	4.17	4.02	3.98	4.74	4.39	3.74	3.79	3.74
Al ₂ O ₃	14.33	13.37	13.13	12.97	13.31	16.37	13.83	14.99	19.52	13.98	13.20	13.36	12.98	13.49	12.32	12.89
FeOt	10.81	10.79	12.03	11.92	12.15	8.74	8.56	9.15	8.06	10.91	11.04	9.97	10.96	10.35	10.51	10.56
MnO	0.12	0.13	0.18	0.17	0.17	0.10	0.08	0.12	0.08	0.16	0.15	0.11	0.11	0.14	0.14	0.14
MgO	12.76	12.77	10.91	10.73	10.98	12.96	14.32	13.85	12.32	11.88	11.79	12.46	12.27	13.14	12.15	12.68
CaO	11.15	11.84	11.77	11.78	11.63	11.78	12.30	11.69	11.31	11.67	11.84	12.14	12.56	11.89	12.87	12.84
Na ₂ O	2.55	1.11	2.54	2.49	2.93	2.86	2.40	3.08	3.28	4.98	4.82	5.22	2.48	2.42	2.66	3.31
K ₂ O	1.86	1.72	1.66	1.64	1.63	1.76	1.77	1.82	1.84	1.73	1.74	1.72	1.77	1.66	1.70	1.75
Cr ₂ O ₃	0.03	0.08	0.02	0.02	0.03	0.04	0.03	0.01	0.02	0.06	0.06	0.03	0.01	0.08	0.07	0.07
P ₂ O ₅	0.05	0.00	0.04	0.04	0.07	0.11	0.04	0.05	0.04	0.02	0.02	0.03	0.00	0.01	0.07	0.05
H ₂ O*	2.01	2.02	1.98	1.98	2.00	2.04	2.04	2.05	2.04	1.99	1.98	2.00	1.98	2.02	1.98	1.99
Total	97.22	96.38	96.39	96.34	97.30	98.00	98.07	98.72	97.74	97.65	97.39	97.91	96.49	97.26	96.24	97.15
Al ^{iv}	2.31	2.04	1.93	1.92	1.95	2.26	2.15	2.18	2.55	2.24	2.15	2.28	2.11	2.01	1.95	2.11
Al ^{vi}	0.21	0.30	0.41	0.39	0.40	0.57	0.25	0.40	0.82	0.24	0.20	0.09	0.21	0.36	0.25	0.18
Si	5.69	5.96	6.07	6.08	6.05	5.74	5.85	5.82	5.45	5.76	5.85	5.72	5.89	5.99	6.05	5.89
Ti	0.59	0.50	0.45	0.49	0.46	0.46	0.53	0.45	0.46	0.46	0.45	0.54	0.50	0.42	0.43	0.42
Cr	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01
Fe ³⁺	0.26	0.31	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	1.09	1.03	1.52	1.51	1.52	1.07	1.05	1.11	0.99	1.37	1.39	1.25	1.39	1.28	1.33	1.33
Mn	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.02
Mg	2.83	2.83	2.46	2.42	2.45	2.84	3.13	3.02	2.70	2.67	2.66	2.79	2.77	2.91	2.74	2.85
Ca	1.78	1.89	1.91	1.91	1.87	1.85	1.93	1.83	1.78	1.88	1.92	1.95	2.04	1.89	2.09	2.07
Na	0.74	0.32	0.74	0.73	0.85	0.81	0.68	0.87	0.93	1.45	1.41	1.52	0.73	0.70	0.78	0.97
K	0.35	0.33	0.32	0.32	0.31	0.33	0.33	0.34	0.34	0.33	0.34	0.33	0.34	0.31	0.33	0.34
OH*	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Total	17.87	17.53	17.84	17.79	17.90	17.95	17.92	18.04	18.04	18.44	18.39	18.48	17.98	17.91	17.97	18.19
(Ca+Na) (B)	2.00	2.00	2.00	2.00	2.03	2.00	2.00	2.04	2.06	2.67	2.66	2.80	2.11	2.00	2.20	2.38
Na (B)	0.22	0.11	0.09	0.09	0.16	0.15	0.07	0.21	0.28	0.79	0.75	0.85	0.07	0.11	0.11	0.30
Mg/(Mg + Fe ²⁺)	0.72	0.73	0.62	0.62	0.62	0.73	0.75	0.73	0.73	0.66	0.66	0.69	0.67	0.69	0.67	0.68

Table 1. (Continued.)

Point. no	S.23	S.24	S.25	S.26	S.27	S.28	S.29	S.30	S.31	S.32	S.34	S.35	S.36	S.37	S.38	S.40	S.41	S.43
SiO ₂	39.62	40.04	39.03	39.47	38.79	39.84	38.95	39.12	39.28	38.98	38.29	38.83	39.19	38.71	39.27	38.95	39.24	37.63
TiO ₂	4.53	4.39	4.20	4.32	4.50	4.14	4.57	3.99	4.30	4.45	4.14	4.39	5.53	5.59	5.65	4.79	4.35	5.71
Al ₂ O ₃	13.65	12.34	14.17	13.50	14.26	13.26	13.58	13.61	13.48	12.99	12.66	12.60	14.34	14.37	13.18	13.40	13.71	14.35
FeO _t	9.83	9.84	9.70	9.72	9.92	9.93	10.24	9.94	9.89	12.84	12.91	12.80	9.80	9.92	9.67	13.50	13.44	10.23
MnO	0.08	0.11	0.12	0.13	0.11	0.11	0.14	0.12	0.10	0.16	0.13	0.13	0.08	0.09	0.12	0.21	0.19	0.10
MgO	12.51	12.12	12.98	12.98	13.71	12.25	12.22	12.48	12.78	11.16	10.74	11.39	13.00	12.63	13.31	11.24	10.19	12.62
CaO	12.57	12.14	11.89	12.24	12.12	11.81	12.07	12.98	12.96	11.86	11.73	11.83	12.18	12.29	12.47	11.83	11.73	11.97
Na ₂ O	2.82	4.98	2.49	2.45	2.73	2.92	2.56	3.16	2.63	2.43	3.25	2.47	2.23	2.30	2.54	2.65	2.34	1.99
K ₂ O	1.66	1.68	1.70	1.75	1.79	1.67	1.82	1.69	1.76	1.86	1.76	1.76	1.91	2.03	1.66	1.74	1.68	1.81
Cr ₂ O ₃	0.02	0.05	0.03	0.03	0.04	0.04	0.03	0.05	0.01	0.01	0.01	0.02	0.01	0.00	0.03	0.00	0.00	0.04
P ₂ O ₅	0.04	0.06	0.08	0.03	0.02	0.03	0.03	0.02	0.06	0.05	0.06	0.06	0.07	0.11	0.02	0.03	0.09	0.05
H ₂ O*	2.01	2.01	2.00	2.00	2.03	1.99	1.99	2.00	2.01	1.97	1.94	1.96	2.04	2.02	2.02	2.00	1.98	1.99
Total	97.33	97.75	96.40	96.62	98.00	96.02	96.22	97.18	97.27	96.79	95.69	96.29	98.36	98.08	97.95	98.38	97.03	96.56
Al ^{iv}	2.10	2.01	2.14	2.09	2.26	2.00	2.12	2.14	2.13	2.57	2.09	2.07	2.23	2.26	2.18	2.16	2.05	2.33
Al ^{vi}	0.30	0.16	0.36	0.30	0.23	0.36	0.30	0.27	0.25	0.35	0.22	0.20	0.26	0.25	0.12	0.21	0.40	0.21
Si	5.90	5.99	5.86	5.91	5.74	6.00	5.88	5.86	5.87	5.43	5.91	5.93	5.77	5.74	5.82	5.84	5.95	5.67
Ti	0.51	0.49	0.47	0.49	0.50	0.47	0.52	0.45	0.48	0.59	0.48	0.50	0.61	0.62	0.63	0.54	0.50	0.65
Cr	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ³⁺	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Fe ²⁺	1.22	1.23	1.22	1.22	1.17	1.25	1.29	1.25	1.24	1.39	1.67	1.64	1.21	1.23	1.20	1.69	1.70	1.26
Mn	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.03	0.02	0.01
Mg	2.78	2.70	2.90	2.90	3.02	2.75	2.75	2.79	2.85	2.52	2.47	2.59	2.85	2.79	2.94	2.51	2.30	2.83
Ca	2.01	1.94	1.91	1.96	1.92	1.91	1.95	2.08	2.08	2.03	1.94	1.94	1.92	1.95	1.98	1.90	1.90	1.93
Na	0.81	1.44	0.72	0.71	0.78	0.85	0.75	0.92	0.76	0.84	0.97	0.73	0.64	0.66	0.73	0.77	0.69	0.58
K	0.32	0.32	0.33	0.33	0.34	0.32	0.35	0.32	0.34	0.38	0.35	0.34	0.36	0.38	0.31	0.33	0.32	0.35
OH*	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Total	17.96	18.31	17.94	17.93	18.04	17.93	17.94	18.10	18.00	18.12	18.11	17.97	17.87	17.90	17.92	17.99	17.84	17.86
(Ca+Na) (B)	2.14	2.71	2.00	2.01	2.04	2.08	2.05	2.33	2.17	2.25	2.26	2.01	2.00	2.00	2.02	2.00	2.00	2.00
Na (B)	0.13	0.76	0.09	0.05	0.12	0.17	0.10	0.24	0.10	0.22	0.32	0.07	0.08	0.05	0.04	0.10	0.10	0.07
Mg/(Mg + Fe ²⁺)	0.69	0.69	0.70	0.70	0.72	0.69	0.68	0.69	0.70	0.64	0.60	0.61	0.70	0.69	0.71	0.60	0.57	0.69

Table 3. Selected electron probe micro-analyses (EPMA) of olivine of lamprophyre dykes of the Hour area, Central Iran.

Point. no	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9	S.10	S.11	S.12
SiO ₂	38.36	37.75	37.73	38.16	38.17	39.88	38.89	40.81	38.80	39.28	38.73	37.73
Na ₂ O	0.07	0.09	0.88	0.12	0.85	0.29	0.93	0.14	0.07	0.09	0.46	2.86
K ₂ O	0.01	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.01
MgO	40.12	39.74	41.19	41.42	41.08	40.80	40.45	39.38	40.63	41.11	40.65	39.85
CaO	0.27	0.25	0.23	0.26	0.24	0.25	0.25	0.04	0.25	0.24	0.25	0.26
MnO	0.26	0.24	0.27	0.23	0.24	0.27	0.25	0.07	0.25	0.26	0.25	0.27
FeO	18.99	19.28	19.18	19.33	19.14	19.24	19.47	18.12	19.19	19.30	19.31	19.07
NiO	0.15	0.14	0.13	0.13	0.07	0.10	0.08	0.03	0.09	0.09	0.11	0.09
Al ₂ O ₃	0.00	0.06	0.05	0.07	0.00	0.00	0.03	0.06	0.00	0.00	0.05	0.02
Cr ₂ O ₃	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
TiO ₂	0.02	0.01	0.03	0.01	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.03
P ₂ O ₅	0.04	0.00	0.00	0.00	0.02	0.03	0.02	0.01	0.00	0.03	0.04	0.03
Total	98.29	97.58	99.69	99.76	99.82	100.86	100.37	98.67	99.32	100.43	99.86	100.22
Structural formula based on the 4 Oxygens												
Te	0.28	0.26	0.29	0.24	0.26	0.29	0.27	0.08	0.27	0.28	0.27	0.30
Fo	78.21	78.11	78.80	78.77	78.80	78.57	78.24	79.37	78.56	78.66	78.46	78.30
Fa	20.84	21.26	20.58	20.62	20.59	20.78	21.12	20.48	20.81	20.71	20.91	21.02
Ca-Ol	0.38	0.35	0.31	0.35	0.33	0.34	0.34	0.05	0.34	0.33	0.34	0.36

Table 4. Selected electron microprobe analyses (EPMA) of feldspar of lamprophyre dykes of the Hour area, Central Iran.

Point. no	S.1	S.2	S.3	S.4
SiO ₂	59.95	60.71	60.32	60.88
TiO ₂	0.00	0.02	0.01	0.00
Al ₂ O ₃	19.63	19.57	20.21	18.97
Fe ₂ O ₃	3.71	1.24	3.39	3.40
MnO	0.02	0.02	0.01	0.04
MgO	4.04	1.79	3.48	4.46
CaO	0.15	0.03	0.06	0.24
Na ₂ O	0.31	0.44	0.00	0.30
K ₂ O	11.24	14.79	13.01	10.72
Total	99.05	98.61	100.49	99.01
Si	2.42	2.46	2.40	2.46
Al	1.06	1.06	1.07	1.02
Ti	0.00	0.00	0.00	0.00
Fe ³⁺	0.30	0.10	0.27	0.27
Mn	0.00	0.00	0.00	0.00
Mg	0.33	0.15	0.28	0.36
Ca	0.01	0.00	0.00	0.02
Na	0.05	0.07	0.00	0.05
K	1.82	2.40	2.07	1.73
Total	5.98	6.24	6.10	5.92
Or	96.69	97.02	99.77	96.23
Ab	2.67	2.89	0.00	2.69
An	0.65	0.10	0.23	1.08

for, clinopyroxene phenocrysts plot close to the Quad (figure 3c) and diopside fields (figure 3d) in the Morimoto (1988) classification.

Olivine: Olivine phenocrysts are rounded and prismatic subhedral to anhedral. In some samples, all of the anhedral olivine has been replaced by secondary iddingsite. Chemical compositions and formulae for fresh olivine grains (table 3) are rich in MgO (39.4–41.4 wt.%, Fo78.2 to Fo79.4) with negligible CaO (0.04–0.26 wt.%) and MnO (0.07–0.27 wt.%) concentrations.

Feldspar: Feldspar, which is restricted to the matrix (figure 2) is mostly K-feldspar. Compositions in the range of Or₉₆ to Or₁₀₀ are classified as orthoclase (Deer *et al.* 1992) (table 4; figure 3e).

5.2 Bulk rock major and trace-element geochemistry

Bulk rock major and trace-element compositions (table 5) are characterized by low SiO₂ (38.1–44.3 wt.%), Al₂O₃ (1–5 wt.%), high MgO (12–21 wt.%), and TiO₂ (1.9–3.7 wt.%), and variable alkalis (Na₂O+K₂O) contents of 2.9–5.9 wt.%. The CIPW normative quartz is absent, and normative (i.e., calculated) and modal nepheline (observed) are present in most samples (Middelmost 1989). The lamprophyre affinity of the dikes is evident by plotting samples on the MgO–K₂O–Al₂O₃ diagram (Rock 1991) (figure 4a). The Hour lamprophyres plot in the alkaline lamprophyre group in the SiO₂ vs K₂O diagram (figure 4b). Due to

Table 5. Major (wt.%) and trace element (ppm) compositions of lamprophyre dikes of Hour area, Central Iran.

Sample	MR-15	MR-16	MR-17	MR-18	MR-20	MR-25	MR-27	RA-2	RA-7	RA-71
SiO ₂	39.2	40.6	37.9	39.3	39.7	38.1	40.7	42	43.1	44.3
Al ₂ O ₃	13.1	13.5	13.35	13.6	13.7	11.35	11.85	12.9	13.7	14.15
Fe ₂ O ₃	13.45	13.2	13.15	13.2	13.55	16	13	11.3	12.45	12.5
CaO	10.65	10.65	8.16	9.36	9.13	12.9	12.5	6.83	7.04	6.58
MgO	10.4	10.4	10.1	10.2	9.98	8.81	9.98	9.97	8.24	8.34
Na ₂ O	1.33	1.29	1.3	1.28	1.38	1.21	1.24	2.45	1.72	1.78
K ₂ O	2.63	2.83	3.2	3.32	3.1	1.72	1.74	0.46	4	4.18
Cr ₂ O ₃	0.03	0.03	0.02	0.03	0.02	0.03	0.04	0.05	0.05	0.05
TiO ₂	3.57	3.68	3.58	3.69	3.73	2.84	3.03	1.9	3.21	3.26
MnO	0.13	0.13	0.16	0.13	0.13	0.19	0.17	0.14	0.15	0.15
P ₂ O ₅	0.31	0.33	0.34	0.34	0.37	0.35	0.33	0.39	0.27	0.28
SrO	0.08	0.08	0.07	0.07	0.08	0.09	0.08	0.02	0.06	0.07
BaO	0.12	0.12	0.08	0.09	0.1	0.12	0.06	0.09	0.06	0.07
LOI	5.03	5.08	7.65	4.87	5	7.11	5.42	12.05	5.98	5.58
Total	100.03	101.92	99.06	99.48	99.97	100.82	100.14	100.55	100.03	101.29
Ba	1080	1050	708	847	924	1095	525	838	588	591
Ce	88.3	90.5	98.8	95.1	101	81.1	76.1	94.4	64.4	65.4
Co	62.4	63.5	61.2	61.1	61.6	65.4	68.1	50.8	55	55.1
Cr	230	230	180	210	180	240	320	370	380	370
Cs	2.3	2.7	2.6	2.8	2.5	1.9	2.5	0.3	2.5	2.7
Cu	75	46	64	42	37	187	44	8	44	34
Dy	5.7	5.8	6.2	5.8	6.1	4.9	4.9	5.2	4.6	4.7
Er	2.4	2.5	2.7	2.5	2.7	2.2	2.1	2.6	2.0	2.1
Eu	2.9	3.0	3.2	3.1	3.2	2.5	2.6	2.3	2.4	2.3
Ga	22.3	22.5	22.8	22.8	23.7	21.8	20.8	17.3	19.3	19.4
Gd	8.07	8.28	8.73	8.31	8.8	6.9	7	6.3	6.23	6.2
Hf	7	6.9	7.2	7	7.5	6.2	6.7	4.9	5.3	5.4
Ho	1.0	1.0	1.1	1.1	1.09	0.9	0.9	0.9	0.8	0.8
La	41.7	43.5	51.1	46	48.8	39.3	36.6	53.3	32.8	34.0
Lu	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.3	0.2	0.2
Nb	52.3	52.1	62.7	55.9	59.8	43.2	40.4	66.7	52.0	53.8
Nd	45.4	46.2	48.2	47.9	50.7	39.8	38.8	38.2	31.9	32
Ni	136	144	122	132	129	160	187	147	126	119
Pr	11.1	11.3	12.0	11.8	12.5	10.1	9.5	10.4	7.8	7.9
Rb	55.3	61.8	64.6	68.6	70.1	35.1	39.7	13	55	56.7
Sm	9.1	9.3	9.8	9.6	10.2	8.1	7.8	7.0	6.9	7.0
Sr	662	633	574	615	673	786	725	177.5	552	588
Ta	3.4	3.4	4	3.6	3.9	2.7	2.7	4.2	3.4	3.5
Tb	1.1	1.1	1.2	1.1	1.2	0.9	0.9	0.9	0.9	0.9
Th	4.3	4.5	5.3	4.8	5.6	4.6	4.2	6.8	4.5	4.7
Tm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.3	0.3
U	1.1	1.1	1.4	1.2	1.3	1.6	1.0	1.8	1.1	1.2
V	32	332	307	326	324	279	302	204	256	258
Y	26.5	27.2	29.3	27.9	29.1	23.8	24.2	27.5	22.8	23.3
Yb	1.8	1.8	1.9	1.8	1.9	1.6	1.6	2.2	1.6	1.7
Zn	150	190	209	229	213	263	414	222	186	180
Zr	280	280	300	290	320	260	270	240	220	220

the high LOI (5–12 wt.%) contents of the samples, we use the Nb/Y vs. Zr/TiO₂ and Sm vs. Ce/Yb diagrams (Winchester and Floyd 1977) to

classify the Hour lamprophyres. The result shows that the Hour lamprophyres are also alkaline type (figure 4c and d). They are characterized by high

Figure 3. Compositional plot of amphibole, pyroxene and plagioclase from Hour lamprophyre, on a $\text{Mg}/(\text{Mg} + \text{Fe}^{2+}) - \text{Si}_T$ diagram (Leake *et al.* 1997). The amphiboles plot in the kaersutite field, (b) the amphiboles show alkaline affinity in the K_2O vs TiO_2 wt.% diagram (Molina *et al.* 2009), (c) the pyroxenes plot in the Quad field in the $\text{Fe}^{2+} + \text{Mg} + \text{Ca}$ vs 2Na wt.% and plot (d) in the diopside field. (e) Classification of the feldspars in lamprophyre based on Or-Ab-An contents.

$\text{Mg\#}$ [atomic $\text{Mg}/(\text{Mg} + \text{Fe}_T)$] values of 0.76–0.83, and low to moderate compatible element contents (e.g., Cr = 180–370 ppm; Ni = 134–303 ppm; V = 204–332 ppm).

Chondrite-normalized rare earth element (REE) patterns are enriched in light REEs (LREEs) relative to heavy REEs (HREEs), with $(\text{La}/\text{Yb})_n$ as high as to 17.7 and Eu anomalies absent ($\text{Eu}/\text{Eu}^* = 1.04\text{--}1.10$) (figure 5a). This LREE-enrichment pattern of the Hour lamprophyres is similar to those of the Nangang lamprophyres (figure 5a). In a primitive mantle-normalized multi-element diagram (Sun and McDonough 1989), large-ion lithophile elements (LILE, such as K, Ba, and Rb) + Th and U are enriched relative to

high-field strength elements (HFSEs, such as Nb, Ti, Zr) (figure 5b).

6. Discussion

6.1 Origin of the lamprophyre dykes

A variety of origins proposed for lamprophyres include fractional crystallization, crustal contamination, and mantle enrichment and melting (Rock 1987, 1991). We first evaluate the processes of magmatic differentiation and crustal contamination before addressing the favored possibility of a mantle magma source.

Figure 4. Classification of the lamprophyres in Hour. (a) Plot of lamprophyres from the current study on the MgO-K₂O-Al₂O₃ classification diagram of Bergmann (1987); (b) showing alkaline affinity on the K₂O vs SiO₂ wt.% diagram. (c) Nb/Y vs Zr/TiO₂ diagram (Winchester and Floyd 1977) for the classification of the Hour lamprophyres. (d) Classification of the Hour lamprophyres by Sm vs. Ce/Yb diagram (after Rock 1991).

Figure 5. (a) Chondrite-normalized REE patterns and (b) primitive mantle-normalized spidergrams for the Hour lamprophyres (Sun and McDonough 1989). Chondrite-normalized REE patterns for the Nangang lamprophyres are shown by the yellow field.

6.1.1 Effect of alteration

High LOI (Loss on Ignition) values of 5–12 wt.% are related to a high degree of secondary alteration of these igneous rocks, resulting in high volatile contents. Fresh lamprophyres may also have high LOI values (e.g., Rock 1991; Hauser *et al.* 2010; Jiang *et al.* 2010) due to the auto-metasomatism. Olivine is altered to altered to serpentine, epidote, talc, or chlorite, but not so for pyroxene, amphibole, and feldspar. There is no correlation between LOI and abundances of major and trace elements

(figure 6). We conclude that the high LOI values are intrinsic to the lamprophyres.

6.1.2 Effect of continental crustal contamination and fractional crystallization

Bulk contamination of mafic lamprophyre magma by continental crust would dramatically increase its SiO₂ content, contrary to observation. Low Th/Ce (<0.07), and Th/La (<0.24) also argue against crustal contamination, as does the absence

Figure 6. Correlation diagrams of LOI vs major and trace elements for the Hour lamprophyres.

of a linear correlation between SiO_2 and Rb/Sr (figure 7a).

6.1.3 Mantle derivation of lamprophyric magma

A primary lamprophyre magma derived directly from the mantle would be characterized by high abundances of compatible elements, with $\text{Mg\#}$ anticipated to be in the range of 76–83, and these values for trace elements: Sc (15–30 ppm), Cr (200–500 ppm), Co (25–80 ppm) and Ni (90–700 ppm) (Rock 1991).

Values for the Hour lamprophyres are in approximate agreement with $\text{Cr} = 119\text{--}160$ ppm; $\text{Co} = 51\text{--}68$ ppm; $\text{Ni} = 119\text{--}187$ ppm. Plots of strongly incompatible elements (Ba and Sr) vs. compatible elements (V and Cr) (figure 7b and c), show a fractional crystallization trend rather than a trend that would result from partial melting. Clinopyroxene and amphibole would have dominated the fractionating assemblage.

Regarding olivine, Fo_{88} to Fo_{94} is typical of primary mafic magmas (Orejana *et al.* 2008), whereas olivine in the Hour lamprophyre dikes ranges from Fo_{78} to Fo_{79} , also suggesting moderate differentiation prior to final emplacement (Orejana *et al.* 2008).

6.2 Intensive variables inferred from mineral compositions

Chemical compositions of pyroxene have been used to the temperature, and oxygen fugacity, and to infer the tectonic setting of magma. The Al_2O_3 and TiO_2 are high in pyroxenes of the Hour lamprophyre (as high as 9.38 and 3.48 wt.%, respectively). The Al contents of pyroxene are used to obtain the solidification pressure via the Al^{IV} vs Al^{VI} diagram (Aoki and Shiba 1973), which suggests that the clinopyroxene has formed in moderate pressure conditions (figure 8a).

The XPT and YPT thermometric equations (Soesoo 1997) are used to obtain temperatures

$$\begin{aligned} \text{XPT} = & (0.446 * \text{SiO}_2) + (0.187 * \text{TiO}_2) \\ & (0.404 * \text{Al}_2\text{O}_3) + (0.346 * \text{FeOt}) \\ & (0.052 * \text{MnO}) + (0.309 * \text{MgO}) \\ & + (0.431 * \text{CaO}) - (0.446 * \text{Na}_2\text{O}) \quad (1) \end{aligned}$$

$$\begin{aligned} \text{YPT} = & (0.369 * \text{SiO}_2) + (0.535 * \text{TiO}_2) \\ & - (0.317 * \text{Al}_2\text{O}_3) + (0.323 * \text{FeOt}) \\ & + (0.235 * \text{MnO}) - (0.516 * \text{MgO}) \\ & - (0.167 * \text{CaO}) - (0.153 * \text{Na}_2\text{O}) \quad (2) \end{aligned}$$

Using these equations and the average composition of pyroxenes, solidification temperatures

Figure 7. (a) SiO_2 vs. Rb/Sr diagram for the Hour lamprophyres. (b) and (c) show plots of the most incompatible elements Sr and Ba vs the compatible elements Cr and V, respectively, indicating that fractional crystallization (FC) rather than partial melting (PM) dominated the compositional variation of the Hour lamprophyres.

of 1200–1300°C have been obtained for the Hour lamprophyres (figure 8b).

Clinopyroxenes are also an important mineral to identifying tectonic setting. On the F_1 vs. F_2 diagram (Nisbet and Pearce 1977), the samples of this study show intra-continental environment (figure 8c).

$$F_1 = (-0.012 * \text{SiO}_2) - (0.0807 * \text{TiO}_2) + (0.0026 * \text{Al}_2\text{O}_3) - (0.0012 * \text{FeOt}) - (0.0026 * \text{MnO}) + (0.0087 * \text{MgO}) - (0.0128 * \text{CaO}) - (0.0419 * \text{Na}_2\text{O}) \quad (3)$$

$$F_2 = (0.0469 * \text{SiO}_2) - (0.0818 * \text{TiO}_2) + (0.0212 * \text{Al}_2\text{O}_3) - (0.0041 * \text{FeOt}) - (0.1435 * \text{MnO}) + (0.0029 * \text{MgO}) - (0.0085 * \text{CaO}) - (0.016 * \text{Na}_2\text{O}) \quad (4)$$

Figure 8. Compositional plot of pyroxene from Hour lamprophyres for showing (a) pressure, (b) temperature, and (c) tectonic setting.

6.3 Implications for source mineralogy

It is believed that some minerals, such as amphibole and/or phlogopite, can be used to examine the metasomatic enrichment history of the magma source, while garnet and/or spinel constrain the depth of the source region.

High K_2O and substantial LILE enrichment of the Hour lamprophyres suggest that hydrous, LILE-enriched potassic mineral phases, such as phlogopite and amphibole, were present in the mantle source (Foley *et al.* 1996; Ionov *et al.* 1997; Grégoire *et al.* 2000; Guo *et al.* 2004; Jiang *et al.* 2010). A phlogopite-bearing sources provides magma with considerably high Rb/Sr (>0.1) and low Ba/Rb (<20) (Furman

Figure 9. (a) Ba/Rb vs Rb/Sr diagram (Furman and Graham 1999). (b) Ba/Nb vs. Ba/Zr diagram for the Hour lamprophyres. (c) and (d) La/Yb vs. Yb (ppm) plot for Hour lamprophyres with melting curves assuming non-modal batch melting of garnet bearing PM (primitive mantle) and EAM (enriched asthenospheric mantle) as source. Initial modal mineralogy: Ol (55%) + Opx (19%) + Cpx (7%) + Gnt (11%) + Phl (8%) and melting phase proportions: Ol (5%) + Opx (12%) + Cpx (20%) + Gnt (40%) + Phl (23%) have been taken from Miller *et al.* (1999). Partition coefficients for olivine, pyroxene and garnet have been taken from Kostopoulos and James (1992), whereas those for phlogopite are from Fujimaki *et al.* (1984). Array for the fractional crystallization (FC) assuming fractionation of olivine (40%) and clinopyroxene (60%) has also been shown for every 10% increment. Degree of partial melting has been shown along the tick marks. Data for PM and EAM are from Sun and McDonough (1989) and Seghedi *et al.* (2004), respectively.

and Graham 1999), whereas an amphibole-bearing source provides magma with high Ba and Ba/Rb values (>20) (Furman and Graham 1999). Compositions of the Hour lamprophyres with low Rb/Sr (0.04–0.11) and variable Ba/Rb (10.4–64.5) favor some source rich in amphibole, rather than phlogopite (figure 9a). However, the good positive linear correlations between Ba/Zr and Ba/Nb (Orejana *et al.* 2008) (figure 9b) argue for phlogopite, which, if it were present in the mantle source, could have contributed LILE-enriched fluids to the lamprophyric magma.

Garnet also could have played a role. The Hour lamprophyres are highly enriched in LREE (>100 times chondrite) relative to HREE (~ 10 times chondrite) (figure 5a), Sequestering of HREEs by garnet that had remained in the source, or a small degree partial melting of the source could have created the observed large ratio of LREE/HREE.

We have performed non-modal batch melting calculations to evaluate the degree of partial

melting an enriched mantle, source containing garnet and phlogopite (as stated in Miller *et al.* 1999). Assumed sources are primitive mantle (PM; Sun and McDonough 1989) or enriched asthenospheric mantle (EAM; Seghedi *et al.* 2004). According to these calculations, the Hour magmas could result from 2 to 5% melting of EAM, subsequently modified by further fractionation (figure 9c). The postulated EAM could have contained either garnet (curve A) or spinel (curve B) (according to Kostopoulos and James 1992) using non-modal batch melting equations combined with a melting model of an enriched asthenospheric mantle source (EAM) (Seghedi *et al.* 2004). Melting curves using EAM as the source material have been calculated for different mantle facies including garnet lherzolite (Kostopoulos and James 1992, curve C), garnet-amphibole lherzolite (Barry *et al.* 2003, curve D) and another garnet amphibole lherzolite with slightly different composition than the latter (new calculations, curve E) (figure 9d). The

Figure 10. Trace element plots of (a) Ta/Yb vs. Th/Yb and (b) Nb (ppm) vs. Nb/U for the Hour lamprophyres show that they have a relatively more primitive affinity with insignificant partial melting and crystal fractionation. The data of mafic intrusion from Tabas come from unpublished data from Raeisi.

calculations suggest 1–3% degrees of partial melting of an enriched garnet peridotite mantle source with Ol (58%), Opx (18%), Cpx (13.4%), Grt (6.6%) and Amph (4.0%) (figure 9d). Partial melting in the spinel stability field, garnet stability field and spinel-garnet transitional stability field would produce a relatively lower Dy/Yb ratio (<1.5) a higher Dy/Yb ratio (>2.4) or intermediate Dy/Yb ratios (1.5–3.0), respectively.

The Dy/Yb ratios of Hour lamprophyre dikes range from 2.4 to 3.2, which is in agreement with lamprophyre generated from the spinel-garnet transitional stability field. However, the average primitive mantle-normalized Sm/Yb ratio of Hour lamprophyre dikes is 5.1, and consistent with melting in the presence of residual garnet (e.g., McKenzie and O’Nions 1991; Orejana *et al.* 2008). McKenzie and O’Nions (1991) suggested the depth of spinel-garnet transition zone is 75–85 km. Therefore, it can be suggested that the Hour lamprophyres are formed by low degree partial melting of the phlogopite/amphibole-bearing lherzolite in the spinel-garnet transition zone at 75–85 km depth. Figure 10 also show the Hour lamprophyres have a relatively more primitive affinity with insignificant partial melting and crystal fractionation.

6.4 Mantle source characteristics and petrogenesis of the lamprophyres

The Hour lamprophyres have high LREE and LILE, and low HFSE, which reflect either a LILE- and LREE-enriched mantle source, or continental crust contamination. Their Nb/Ta (15–16) and Zr/Hf (40.2–48.9) ratios are similar to those of the

primitive mantle (17.5 ± 0.2 and 36.27 ± 2.0), and much higher than those of the continental crust (11 and 33) (Taylor and McLennan 1985; Stolz *et al.* 1996). In addition, their high Mg# values (>70) indicate that they represent near-primary mantle-derived melts. Therefore, crustal contamination seems to have barely affected the enriched elemental geochemistry of these samples.

To interpret the role of crustal materials (subducted sediment) in the petrogenesis, we examined Nb/U ratios in the Hour lamprophyres. In this case, the Hour lamprophyres have slightly lower, to similar, Nb/U ratios (27.1–47.8) in comparison with the MORB and OIB (47 ± 7 ; Hofmann *et al.* 1986), and the lower crust (Nb/U ≈ 25 ; Rudnick and Gao 2003). However, their Nb/U ratios are significantly higher than those of the upper crust (Nb/U ≈ 4.5 ; Rudnick and Gao 2003). Therefore, the metasomatism of melts from the upper crustal materials (subducted sediment), may not form this enriched lithospheric mantle of the Hour lamprophyres. Moreover, Ayers (1998) proposed that the subduction-zone hydrous fluids have very low Nb/U ratio of 0.22. The HFSEs are more likely to be stored in phases such as rutile and/or ilmenite that persisted in the subducted slab, whereas the LILEs easily transfer into the fluids (Foley *et al.* 2000), which makes the subduction-related fluids enriched in LILEs and depleted in HFSEs (e.g., very low Nb/U). Thus, the metasomatism of mantle source by subducted slab-derived hydrous fluids can be ruled out in the petrogenesis. The Hour lamprophyres have probably preserved many of the compositional characteristics of their mantle source. Their

fractionated REE patterns (LREE >100 times and HREE <10 times chondrite) (figure 5a) likely indicate the presence of residual garnet in the source (e.g., McKenzie and O’Nions 1991; Furman and Graham 1999; Andronikov and Foley 2001). Alternatively, small degrees of partial melting of a highly LREE-enriched source could result in these kinds of REE patterns. The Hour lamprophyres have possibly well-preserved much of the features of mantle source.

It is believed that either interaction between lithospheric mantle and volatile-rich low-density melts that have migrated from the asthenosphere and accumulated in the above lithosphere (McKenzie 1989; Gibson *et al.* 1995), or metasomatism by melts/fluids released from the subducting slab (e.g., Maury *et al.* 1992), may play roles in the enrichment of lamprophyric magma.

Enrichment from the first process generally may yield OIB-type signatures with less depletion of HFSEs (such as Nb and Ta). These characteristics are consistent with those of the Hour lamprophyres. Moreover, low La/Nb (0.6–0.9), Ba/Nb (11–25) and Zr/Nb (3.6–6.7) ratios, are similar to those of intraplate igneous rocks worldwide (La/Nb = 0.5–2.5 and Ba/Nb = 1–20), and clearly distinct from most arc igneous rocks. Therefore, we suggest the following implications for Hour lamprophyres formation: (i) chemical data for the Hour lamprophyres, together with data from other mafic rocks from Tabas block, plot in an array defined by non-subduction generated magmas such as MORB and within plate basalts, (ii) they exclude contamination by either continental crust, or by subduction-related components such as pelagic sediments and (iii) all of them show a strong affinity towards OIB type-enriched mantle source, which is in agreement by low degree partial melting (1–5%) of mafic rock in the garnet-spinel stability field.

6.5 Geodynamic significance

Pervasive large-scale magmatism in the Tabas block and throughout the central Iranian micro-continent took place coevally in the latest Proterozoic to Early Cambrian (Ramezani and Tucker 2003). After the Pan-African orogenic event, an extensional regime has dominated central Iran. A commonly proposed model for the Late Neoproterozoic–Early Cambrian (Infracambrian) magmatism and sedimentation in Iran has been crustal extension associated with continental rifting (e.g., Berberian and King 1981). It has been

Figure 11. Schematic picture showing the condition for the formation of the lamprophyres in central Iran (modified after Su *et al.* 2017).

established that the last stages of the Neoproterozoic Pan-African orogeny in central Iran (approximately 686–517 Ma) was associated with emplacement of alkali- (A-type) granites and post-orogenic volcanic rocks of alkaline affinity (Brown and Jackson 1979). Accordingly, the thick pile of carbonate-evaporate deposits from the Persian Gulf, the Zagros Mountains (Hormuz Formation), Oman (Ara Formation), central Iran (Rizu-Desu Series), Pakistan (Salt Range), and their correlative rocks, have been deposited in the rift basins (Ramezani and Tucker 2003). The synchronous alkaline granites and volcanic rocks are interpreted as the products of post-orogenic, extensional magmatism (Berberian and King 1981). These form the basis for the suggested “syn-rift” origin of the rhyolites, felsic tuffs, and quartz-porphyrries of the Rizu-Desu Series (equivalent of the volcano-sedimentary rocks) in central Iran.

The lamprophyre dikes of the Hour area, which are hosted by Rizu-Desu Series, in central Iran are intruded into the lower Cambrian rocks (Förster 1974; Jami *et al.* 2007). They constitute only a very small volume of rock in comparison to the other volcanic and sub-volcanic exposed rocks in Hour area. The high K_2O , TiO_2 , P_2O_5 , Ni and Cr contents of the Hour lamprophyres are characteristic of magmas generated during extensional magmatism, as well as the hot spot activities (Amel 2008) that are similar to the other alkaline rocks of the central Iran (Jami *et al.* 2007).

The mechanisms driving the Late Proterozoic–Early Cambrian extension may have been lithospheric rebound after roll-back of subducted proto-Tethys lithosphere and/or the removal/thinning of the lithospheric mantle and subsequent upwelling of asthenospheric mantle in the rift zone (figure 11).

7. Conclusions

- (1) The Hour lamprophyres from the Tabas block were intruded into lower Cambrian magmatic rocks, and are defined as alkaline lamprophyre that is characterized by high contents of compatible elements, enriched in LREE and LILE, but depleted in HFSE.
- (2) The Hour lamprophyres have experienced modest fractional crystallization and insignificant crustal contamination. They were derived from partial melting of enriched mantle characterized by phlogopite/amphibole bearing lherzolite in the spinel-garnet transition zone at 75–85 km depth with an addition of the asthenospheric mantle materials.
- (3) During Late Neoproterozoic to Early Cambrian time, due to roll back of subducted oceanic lithosphere, the lithospheric mantle thinned, followed by upwelling and partial melting the asthenospheric mantle. This occurred in tandem with an intensive interaction with the lithospheric mantle, which generated the Hour lamprophyres and other coeval magmatic rock.
- (4) The amphiboles are Al and Ti-rich (kaersutite) and their forsterite contents vary from Fo₇₈ to Fo₇₉. Based on the *XPT* and *YPT* calculations, the estimated temperature of pyroxene crystallization (diopside) was between 1200 and 1300°C. These data suggest that the mafic minerals were crystallized under relatively moderate pressure conditions, in subvolcanic levels after low differentiation of magma.

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