



## رفتار خاص عناصر کمیاب بازالت‌های پشته‌های میان اقیانوسی کمی تحول یافته: بخش جنوبی افیولیت‌های بیرجند

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**چکیده:** سنگ‌های مافیک شامل بازالت‌ها و گابروها بخش عمدی از افیولیت‌های جنوب بیرجند را تشکیل می‌دهند. این سنگ‌ها به طور کلی در چندین ناحیه یافت شده و متحمل یک دگرگونی درجه پائین شده‌اند. الگوی نورمالیزه شده عناصر نادر خاکی (نسبت به کندریت) برای بازالت‌ها و گابروها به ترتیب نشان می‌دهند که این سنگ‌ها مرتبط با بازالت‌های پشته میان اقیانوسی غنی شده-حدوایست تا بازالت‌های تهی شده می‌باشند. از طرف دیگر الگوی نورمالیزه شده عناصر کمیاب (نسبت به N-MORB) برای بازالت‌ها و گابروها نشان می‌دهد که این سنگ‌ها از برخی عناصر با شعاع یونی بزرگ غنی می‌باشند. تهی شدگی در تیتان و همچنین نیوبیوم (در مورد گابروها) از دیگر مشخصات این سنگ‌ها می‌باشد. بنابراین می‌توان یک رژیم فرورانشی ناکامل و کوتاه مدت را برای این ناهمگونی‌های مشاهده شده پیشنهاد نمود. الگوی نورمالیزه شده عناصر کمیاب (نسبت به گوشه‌های اولیه) برای یک نمونه هارزبورزیت افیولیت‌های جنوب بیرجند نیز این غنی شدگی از عناصر با شعاع یونی بزرگ را تائید می‌نماید.

**واژه‌های کلیدی:** بازالت‌ها، گابروها، عناصر نادر خاکی، غنی شدگی از عناصر با شعاع یونی بزرگ، رژیم فرورانش.





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## The distinctive trace elements signature of the less-evolved MORB materials in the south of Birjand ophiolites

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**Abstract:** Mafic rocks including basalts and gabbros are the main constituents of Birjand ophiolites. They are found in several places and show low grade metamorphism in the field and under the microscope. Chondrite-normalized REE patterns for basalts and gabbros indicate that these rocks are transitional-enriched to depleted mid-oceanic ridge basalts respectively. Otherwise, N-MORB normalized trace elements patterns for basalts and gabbros are considered to be enriched in some LIL elements. Depletion in Ti and also in Nb (in gabbros) is other characteristic of these rocks. Therefore an incomplete short-lived subduction regime for generation of those heterogeneities can be suggested. The primary mantle-normalized trace elements pattern for Birjand harzburgite also confirms some LIL enrichments.

**Keywords:** Basalts, Gabbros, Rare earth elements, LIL elements enrichment, subduction regime.

## Introduction

Around Lut continental block, in the Eastern Iranian Ranges [1], there is a highly crushed, fragmented and sheared ophiolitic complex known as Birjand ophiolites (Fig. 1). This complex is considered as a part of the Sistan suture zone of eastern Iran [2]. The existence of various ophiolitic belts (also Birjand complex) around Lut block has been interpreted as the remnant of narrow ocean basins similar to the Red sea, developed due to multi-branched rifting during late Paleozoic to middle Triassic compressional event [3]. According to [2], the Sistan suture zone essentially comprises two sub-zones: the Ratuk complex composed of upper Cretaceous flysch like sediments and the Neh complex with Senonian to early Eocene age. Ophiolitic rocks can be traced among the Neh complex. The formation of Sistan suture zone was considered as a result of the closure of a relatively short-lived branch of Neo-Tethys realm during Campanian to Paleocene period [2]. The Birjand ophiolitic complex is highly faulted and metamorphosed and their rock units are dominantly marked with fault contacts. Along the most of the major faults, the trace of  $S_1$  foliation can be traced. This complex is considered as several piles of tectonic slices composed essentially of harzburgites (with minor lherzolites, dunites and chromitites), gabbros, basaltic rocks (as flow or pillow) and limestone along with cherts in which they have been accumulated during upper Cretaceous. These ophiolites were firstly studied and mapped in detail by [4]. In addition to [2] and [4], this complex has been reviewed by some other geologists (e.g., [5-7]) whereby their works essentially have been focused on the peridotites, listweanites and metamorphic rocks. In this paper, we attempt to study geochemistry and petrogenesis of gabbroic and basaltic rocks in the

## Field relationships of mafic rocks

Gabbroic and basaltic rocks in Birjand ophiolites occur both as individual small bodies in fault contact with other rock units especially with peridotites or as lenses dispersed locally in metamorphosed flysch like-sediments (now as phyllite and/or schist). Gabbroic rocks are also characterized as dikes injected into depleted harzburgites. These are coarse-grained rocks and southern parts of this complex.

because of rodingitization, some secondary minerals have been formed. Basaltic flows (as pillow) predominantly in the south of Birjand town in Band-e-Omarshah region are named meta-spilitic rocks on Birjand geological map [8]. These rocks have undergone low grade metamorphism and are also marked in the field by weak foliation. Mixing of basaltic materials with cherts and limestones is common. In the south of Dehno village, in Nokand region, huge bodies of harzburgites associated with listweanites, gabbros and basaltic rocks crop out. Here, sandstones, tuffaceous sandstones, limestones and phyllites along with cherts (in some

locality pyrite bearing cherts) and spillitized diabasic-basaltic rocks feature fault contact with above-mentioned mafic-ultramafic sequences. Gabbros are essentially found as dikes and exhibit rodingitization process. In the northwest region of Kahi village small outcrop of isotropic gabbros commonly embedded in harzburgites is also present. These rocks have suffered minor alteration compared with other gabbroic rocks in this complex.

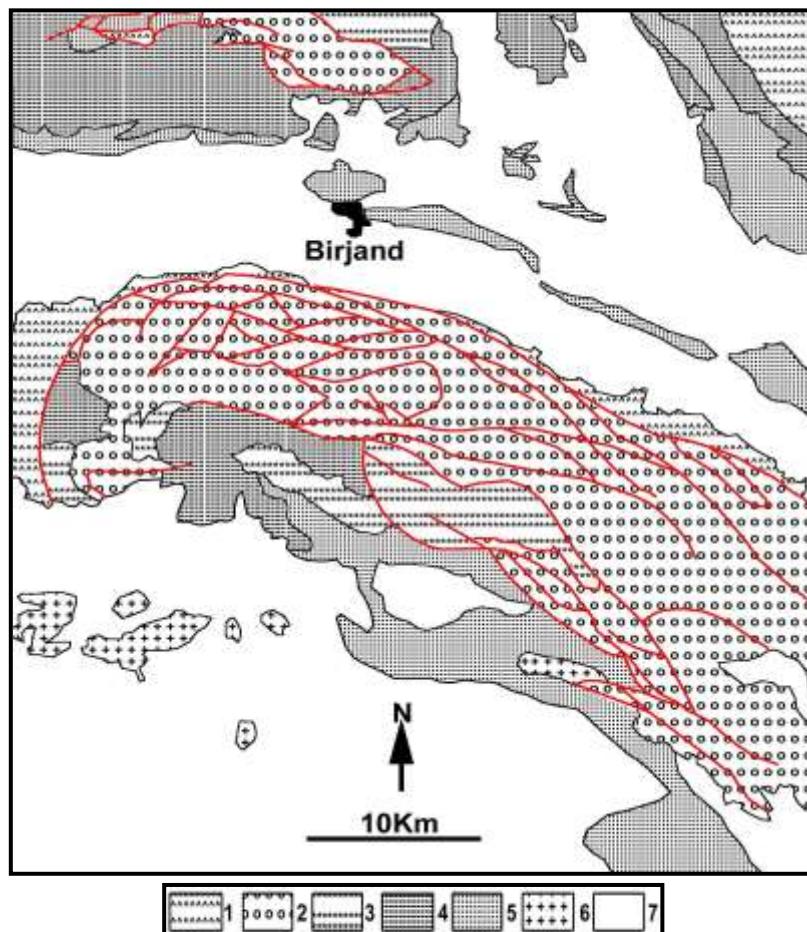


Figure 1: Simplified geological map of Birjand ophiolites. 1- Flysch-type sediments, 2- ophiolites and ophiolitic mélange, 3- Paleogene sedimentary rocks, 4- paleogene volcanic and sub-volcanic rocks, 5- Neogene sedimentary rocks, 6- Neogene volcanic rocks, 7- Quaternary and recent sediments (Modified after [4]).

**Petrography and mineral assemblage**

Less altered gabbros indicate clinopyroxene grains as interstices between plagioclase, defining intergranular texture. Plagioclases are characterized by various degrees of alteration into clay minerals, sericite, epidote and clinozoisite. Chlorite and actinolite are common secondary minerals, formed especially at the expense of clinopyroxenes. In more-evolved gabbros, hornblende is a minor phase, altered partly into chlorite. Magnetite grains are also present as minor mineral. In more altered gabbros (meta-gabbros) plagioclases exhibit high degree of saussuritization. Clinopyroxenes have been converted into an assemblage consisting of chlorite, euralite, actinolite and tremolite. In addition, pumpellyite veins locally crosscut the rock. A minor phase of some of these meta-gabbros is relatively large grains of hydrogrossular formed during rodingitization process (deduced from optical and microprobe data). Basalts are characterized by the presence of altered plagioclase laths and well-preserved clinopyroxene grains. Groundmass has been highly transformed into clay materials and chlorite. Chlorite also defines pseudomorph texture, after mafic minerals. As a result of the spilitization process, epidote and quartz are the other types of secondary minerals. Additionally, the main feature of basalts in Band-e-Omarshah is the presence of tiny fragments of Cr-spinel in the matrix of the rock.

**Bulk rock geochemistry of mafic rocks**

I- method and materials: in order to study the geochemical properties of mafic rocks, the ICP-MS and ICP-AES analyses were performed in Centre de Geochimie de la surface, Strasbourg (France). For this reason, about 1 gram of agate-crushed sample was dried first at 110°C and then that charred at 1000°C during 3 hours. 100 mg of the charred sample was mixed with 750 mg of lithium tetraborate in graphite furnace. This mixture was melted at 1000°C during 30 minutes. After cooling, the obtained bead was directly solved in furnace by a solvent containing diluted nitric acid and glycerin. The final solution is 4g/L (100mg of rock in 25ml of solvent), after filtering directly entered into ICP-AES. The same solution, diluted 10 times, was otherwise introduced into ICP-MS. For ICP-AES, the relative limit of measurement is +10% while ICP-MS permits the measurement with relative limit of +5%.

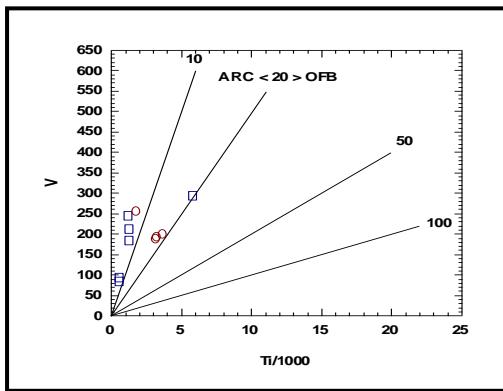
II- discussion: geochemically, gabbroic and basaltic rocks are discussed here separately. As it is obvious in Table 1, the meta-gabbroic samples (and sample B.N.16) show low values of SiO<sub>2</sub> in which this oxide loss is contemporary to the excess gain of CaO, Na<sub>2</sub>O, LOI and also Fe<sub>2</sub>O<sub>3</sub>t (in basaltic sample, B.N.16). This feature is due to the higher alteration degree,

especially rodingitization of these rocks.  $\text{TiO}_2$  content of these rocks is low and in  $\text{V}/\text{Ti}$  diagram [9]; samples are considered to be of low Ti and very low Ti series (Fig.2). The Nb content of basaltic rocks is in good accordance with MORB (2.33 in N-MORB and 8.3 in E-MORB [10]) while gabbroic samples are found to be depleted in this element. As proposed by [11-12] the Sr content of MORB materials is about 100 ppm, but in Birjand mafic rocks this element shows fluctuation in content. The Zr content of these mafic rocks is also characterized by low values. According to [13], Birjand mafic rocks based upon their Zr, Nb, Y and Sr are classified as depleted and highly depleted materials. In Cl-chondrite normalized [14] diagram (Fig.3), basaltic samples are ascribed to be transitional to enriched MORB as supposed also by [13].  $\text{La}_n/\text{Sm}_n$  ratio of basaltic rocks is higher than 2, related to the enrichment of the light REE in these rocks. On the other hand, when the chondrite normalized values (Fig.4) for gabbros are considered, the existence of a depleted pattern can be attributed to gabbros. This pattern is regarded to be strictly depleted in LREE rather than HREE. In gabbros, Eu content, like basalts, features main enrichment that can be related to the plagioclase accumulation in these rocks. Therefore, the gabbros are slightly different from their extrusive equivalents. In the small scale, these compositional variations are attributed to the crystal fractionation processes in a large steady state magma chamber located underneath the mid-ocean ridges [15-16]. This interpretation was corroborated by studies on Oman ophiolites [17]. Otherwise this argument that some trace elements such as Ti, Nb, Pb and Ta are the best indicators of eruptive environment of lavas cannot be neglected.

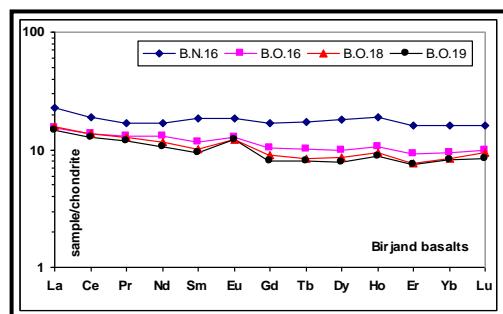
Basaltic samples have variably higher content of some elements such as Rb, Ba, Th, U, Pb compared to the N-MORB (Fig.5). In this diagram, the composition of average arc basalts [18] has been drawn for comparison. Nb depletion, as it is characteristic of average arc basalts, is not the distinctive feature here. In the case of gabbroic rocks the Nb depletion and Pb enrichment are common (Fig6). Higher content of Cs, Ba, Rb and Sr can be achieved for some gabbroic samples. The enrichment of K-group elements (Rb, Sr, Ba, Cs) in the rock reflects either the unique initial composition or refractory mineralogy of the magma source or crustal contamination during ascent [19], although the later argument can not be considered here. Therefore, the distinctive signature of Birjand mafic rocks is the high LIL/HFS elements ratios and in particular relatively low Ti (and in the case of some gabbros Ta and Nb) contents.

**Table1** Bulk rock geochemistry of Birjand mafic rocks and harzburgitic sample (MGabbro:metamorphosed gabbro, Harz:harzburgite). La and Sm have been normalized to N-MORB.

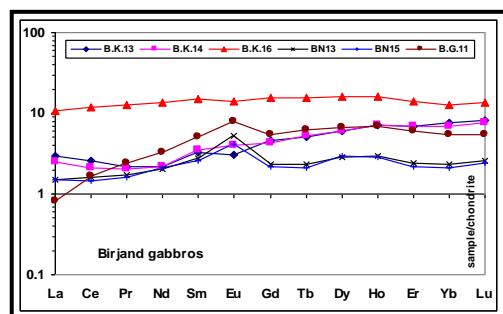
Rock	Gabbro	Gabbro	Gabbro	MGabbrro	MGabbrro	MGabbrro	Basalt	Basalt	Basalt	Basalt	Harz
Name	B.K.13	B.K.14	B.K.16	BN13	BN15	B.G.11	B.N.16	B.O.16	B.O.18	B.O.19	BN12
SiO <sub>2</sub>	48.5	46.1	45.4	37.6	38.4	27.8	33.6	49	47.4	47.3	37.8
TiO <sub>2</sub>	0.248	0.249	1.01	0.136	0.133	0.25	0.337	0.653	0.572	0.581	0.027
Al <sub>2</sub> O <sub>3</sub>	11.3	11.8	16.4	14.4	15.8	17.8	14.2	15	14.8	14.7	0.969
Fe <sub>2</sub> O <sub>3</sub> T	6.73	7.67	9.83	3.5	3.02	4.01	25.3	8.2	7.71	7.81	9.44
MnO	0.103	0.128	0.148	0.111	0.063	0.082	0.444	0.135	0.139	0.138	0.076
MgO	12.3	13.6	9.05	16.7	10.7	8.38	5.42	8.32	10.6	10.6	39.3
CaO	16.2	15.6	11.8	20.1	26.5	20.4	13.3	11.7	11.5	10.3	0.309
Na <sub>2</sub> O	0.15	0.12	0.98	0	0.05	14	0.3	2.19	2.1	2.37	0
K <sub>2</sub> O	0.06	0.02	1.55	0.02	0	3.11	0.23	0.034	0.339	0.491	0.11
P <sub>2</sub> O <sub>5</sub>	0.05	0.02	0.09	0.03	0.03	0.47	0.16	0.07	0.063	0.054	0.02
LOI	3.22	3.96	3.23	6.6	4.41	2.77	5.47	4.25	4.11	4.69	12.06
Total	98.75	99.33	99.46	99.12	99.15	99.03	98.75	99.5	99.26	98.99	100.11
Ba	5	6	145	18	11	594	32	11.2	71.3	90.5	16
Rb	0.341	0.205	17.3	0.008	ND	8.09	0.342	0.982	3.65	7.16	0.148
Sr	12	11	493	27	19	227	29	170	52.1	74.7	19
Y	10	9.68	21.9	3.73	3.81	9	25	14.3	12.7	13	0.722
Zr	15	12.8	59.5	4.22	4.24	11	54	40.9	38.1	36.1	1.38
Nb	0.408	0.382	1.69	0.096	0.024	0.133	7.37	3.51	4.55	3.95	0.039
Th	0.34	0.207	0.315	0.097	0.059	0.066	0.761	0.358	0.442	0.372	0.149
Pb	1.74	1.51	3.41	1.9	1.51	1.52	1.59	2.29	2.81	4.82	3.26
Zn	85	56	52	26	19	ND	49	55.4	51.5	44.1	119
Cu	8.64	15.8	13.4	77.3	40.3	14.2	47	104	80.3	80.1	13.4
Ni	209	300	81	478	325	151	143	134	246	275	1983
V	238	206	286	78	86	177	249	194	181	186	27
Cr	786	1049	252	482	774	2512	339	399	743	822	1440
Hf	0.463	0.478	1.57	0.182	0.164	0.318	1.75	1.16	0.999	0.932	0.022
Cs	0.003	0.204	0.77	0.365	0.132	1.67	0.95	0.119	2.88	5.78	0.063
Sc	42	36	44	20	21	46	35	35.8	33.2	33.7	5
Ta	0.039	0.042	0.757	ND	ND	0.012	0.535	0.278	0.332	0.29	ND
Co	52.5	49.3	38.6	34	27	22.7	45	42.1	44.2	42.1	114
U	0.154	0.179	0.076	0.013	0.013	0.023	0.152	0.111	0.096	0.085	0.003
W	1.45	0.289	1.56	0.593	0.288	0.445	0.706	ND	1.36	0.36	1.93
La	0.71	0.6	2.57	0.355	0.35	0.195	5.35	3.66	3.7	3.45	0.12
Ce	1.6	1.3	7.16	0.976	0.897	1.02	11.5	8.44	8.44	7.89	0.236
Pr	0.205	0.19	1.19	0.16	0.15	0.223	1.57	1.21	1.17	1.1	0.025
Nd	1	0.997	6.23	0.943	0.95	1.48	7.69	5.95	5.28	4.83	0.111
Sm	0.49	0.521	2.22	0.41	0.385	0.747	2.74	1.74	1.51	1.4	0.026
Eu	0.171	0.222	0.777	0.298	0.232	0.438	1.03	0.715	0.68	0.685	0.009
Gd	0.918	0.85	3.14	0.457	0.44	1.09	3.33	2.07	1.81	1.6	ND
Tb	0.183	0.19	0.566	0.083	0.075	0.221	0.622	0.368	0.301	0.29	ND
Dy	1.49	1.47	3.91	0.695	0.725	1.64	4.47	2.45	2.12	1.95	0.024
Ho	0.394	0.393	0.87	0.161	0.154	0.378	1.02	0.573	0.511	0.478	0.006
Er	1.12	1.12	2.22	0.384	0.353	0.955	2.57	1.47	1.24	1.2	0.029
Tm	0.183	0.189	0.338	0.059	0.051	0.161	0.411	0.216	0.202	0.189	0.002
Yb	1.21	1.12	2.02	0.372	0.335	0.884	2.56	1.51	1.35	1.32	0.035
Lu	0.2	0.19	0.334	0.064	0.059	0.136	0.396	0.244	0.234	0.208	0.011
La(N)	0.284	0.24	1.028	0.142	0.14	0.078	2.14	1.464	1.48	1.38	ND
Sm(N)	0.18631	0.1981	0.84411	0.15589	0.14639	0.28403	1.04183	0.6616	0.57414	0.53232	ND
La/Sm(N)	1.52432	1.21152	1.21786	0.91088	0.95636	0.27462	2.05409	2.21283	2.57775	2.59243	ND



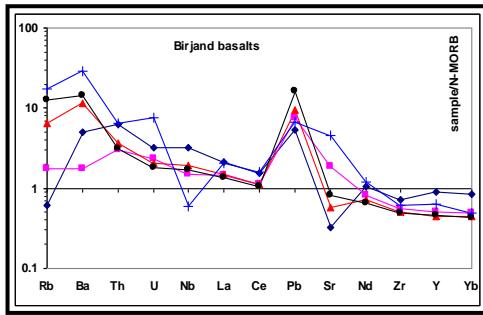
**Figure 2** In V/Ti diagram [9] Birjand mafic rocks are characterized by low and very low  $\text{TiO}_2$  contents (symbols are as following; basalts: circles; gabbros: squares).



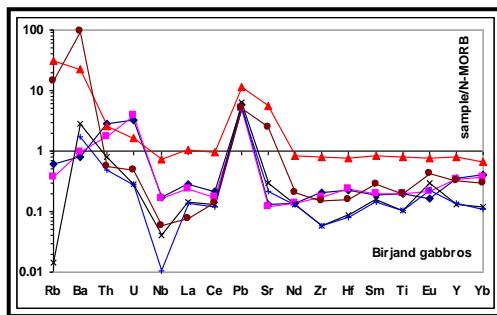
**Figure 3** Chondrite normalized REE patterns for Birjand basaltic rocks. As deduced in this figure, basalts indicate enrichment in light REE and are ascribed to be enriched-transitional MORBs. Data for normalization is from [14]



**Figure 4** Chondrite normalized REE patterns for Birjand gabbroic rocks. The gabbroic rocks are marked by low LREE content and are similar to depleted MORBs. Anomaly in Eu is the main feature and is related to plagioclase accumulation in these rocks. Data for normalization is from [14].



**Figure 5** N-MORB normalized trace elements patterns for Birjand basalts. Basalts have tendency to be enriched in some LIL elements such as Rb, Ba, U, Th and Pb. For comparison, the composition of average arc basalts has been shown in this diagram (plus sign). Data for normalization is from [10] and for average arc basalts is from [18].

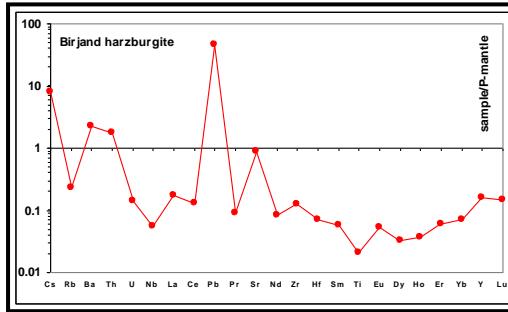


**Figure 6** N-MORB normalized trace elements patterns for Birjand gabbros. Some samples show enrichment in Ba, U and Pb. Ditto, depletion in Nb is distinctive signature. Data for normalization is from [10].

### Conclusions

Birjand mafic rocks have rare earth elements signature that behaves like MORB materials, although geochemical differences in REE patterns of basaltic and gabbroic rocks can be observed. These small scale variations, suggesting the operation of some fractional mechanisms, are dominated in the mid-ocean ridge related magma reservoirs. In contrast, some trace elements (particularly LIL elements) indicate several degree of enrichment in mafic rocks compared to the normal mid-ocean ridge basalts. These high LIL/HFS element ratios can reflect the introduction of LIL elements from the subducted slab [19-23]. However, any comment on LIL/HFS element fractionation in upper mantle requires evidence supporting the presence of rocks that have been relatively slightly affected by low pressure

crystallization of Fe-Ti oxides. In summary, after long period of MORB generation at an ocean realm, (as an oceanic branch separating Lut and Afghan blocks), an incomplete intra-oceanic subduction regime has been activated. As a result of this subduction, Birjand mafic rocks have tendency to show the higher content of subduction components. However, this regime is believed to be active for a short time, because the mafic rocks do not show composition similar to island arc basalts. If we accept this model, the source region(s) of mafic rocks should have been affected by subduction-related components. On the other hand, the variations in incompatible element ratios may simply result from a multistage melt extraction process in a lherzolitic mantle [24] or the presence of a veined mantle made of pyroxenite lenses enclosed in lherzolites [25]. Detailed observations on the Birjand peridotites along with other study done by [5] confirm that these peridotites are depleted harzburgites with high amount of refractory minerals. In order to test the effect of LIL enrichment on Birjand peridotites (source region) we use also primary mantle-normalized values of one sample of those peridotites. In this pattern (Fig.7), peridotite sample has been distinctly enriched in Cs, Th, Ba and Pb. Lead concentration reaches up to 40 times of its concentration in primary mantle. Primary mantle-normalized diagram (Fig.7) for peridotite sample resembles that of highly depleted arc-related peridotites described by Parkinson and Pearce [26], from the Izu-Bonin-Mariana arc, and/or ancient supra-subduction zone peridotites with a two stage history of melt extraction. Considering all observations discussed above, we suggest that multi-stage melt extraction or the presence of mantle heterogeneity for the generation of LIL enriched Birjand mafic rocks can not be valid here. Instead a slight contribution of subduction components can be regarded as a main process.



**Figure 7** Primary mantle normalized trace elements pattern for Birjand harzburgite. This sample is a depleted serpentinized harzburgite with simple mineralogy consisting of olivine, chromite and orthopyroxene. Serpentine, talc, chlorite, magnetite and bastite are the minor phases. Data for normalization is from [10].

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