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Geochemistry and petrogenesis of the Sabalan Plio-Quaternary volcanic rocks: implication for post-collisional magmatism

H. Shahbazi Shiran*[1], H. Shafaii Moghadam[2]

1- Department of Archaeology, University of Mohagheghe Ardabili, Ardabil, Iran
2- Faculty of Earth Sciences, Damghan University, Damghan, Iran

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Abstract: Trachyandesites, trachytes and latites associated with ignimbrite and pyrocalstic rocks, characterized by shoshonitic affinity are the main Plio-Quaternary volcanic rocks in the Sabalan region (Ardabil). Plagioclase, K-feldspar, biotite associated with clinopyroxene and glass are the main constituents of these lavas. Plagioclases are andesine to labradorite while clinopyroxenes have augitic composition. The Sabalan volcanic rocks show enrichment in LREE relative to HREE and are characterized by enrichment in LILE and depletion in HFSE. Petrological observations along with geochemistry of rare earth and trace elements of these lavas suggest shoshonitic affinity and derivation from a subduction zone. The Sabalan volcanic rocks are isotopically characterized by derivation from an enriched mantle source (with/without crustal influence) with tendency to plot in a field defined by island-arc basalts (IAB) and OIBs (in εNd vs. $^{87}Sr/^{86}Sr$ diagram). The geochemical and isotopic signatures of the Sabalan lavas suggest that their magma has been issued via low degree partial melting of a subduction-metasomatized continental lithospheric mantle. The formation of these lavas is linked to slab steepening and break-off in a post-collisional regime.

Keywords: *Geochemistry; Sr-Nd isotopes; Petrogenesis; Plio-Quaternary lavas*; *Sabalan.*

Introduction

Cenozoic magmatism occurs mostly in the peri-Arabic region, north of the Bitlis-Zagros suture zone (Fig. 1) and range in age from Eocene to Plio-Quaternary. The timing of their eruptions and pooling as plutons, mostly coincides with and postdates a series of continental collisional events in northern Bitlis-Zagros suture zone region [1, 2]. The Eocene magmatism in the peri-Arabic region, mostly in the Urumieh-Dokhtar magmatic belt and in south of the Anatolian block, is calc-alkalic to shoshonitic, which resulted from subduction of the Neotethyan Ocean beneath the central Iranian-Anatolian blocks. The Plio-Quaternary alkaline-ultrapotassic magmatism occupies most of the Turkish-Iranian high plateau (in NW of Iran and NE of Turkey) and is mostly characterized by within-plate and/or subduction- related geochemical characteristics [3-5]. The variations in the lava chemistry of the late Cenozoic magmatism indicate a geochemical progression from calc-alkaline to alkaline compositions with time [2].

The Turkish-Iranian high plateau is bounded on the north by the Eastern Pontide arc and the Lesser Caucasus magmatic belt and to the south by continental blocks including Bitlis-Puturg-Sanandaj-Sirjan blocks. Plio-Quaternary volcanic cones and flows are scattered in this plateau (such as Mt. Ararat, Sahand, Sabalan, Nemrut….) and most of them indicate post-collisional shoshonitic-alkaline affinities [6-9]. The Sabalan volcano (Ardabil) is among youngest volcanic calderas, in eastern border of the Turkish-Iranian plateau, consisting of Miocene trachy-andesites and latites

* Corresponding author, Tel: 09142891624, Fax: (0451) 4448129, Email: shahbazihabib@yahoo.com

and younger, Plio-Quaternary trachy-andesites, pumiceous andesites and dacites with ultrapotassic-shoshonitic signatures. The aim of this study is to recognize the major, trace, REE and Sr-Nd isotopes characteristics of the Sabalan volcano and to present a consistent tectono-magmatic model for the formation and evolution of the Sabalan Plio-Quaternary lavas.

Regional geology

The southern Sabalan region is characterized by occurrence of Miocene lavas with calc-alkaline and high K calc-alkaline to shoshonitic lavas [10]. Moreover, late Miocene sodic alkaline lavas are present in south of the Sabalan region [11]. Eocene and Oligo-Miocene lavas have been also distributed in NW regions of Ardabil, near Meshkin Shahr- Ahar volcanic belt (Fig. 2). The Eocene lavas are mostly andesites, trachy-andesites, trachy-basalts and analcime-bearing tephrites with shoshonitic to alkaline geochemical signatures. Volcanic breccias, tuffs and interbedded lavas, with columnar joints are common in the N-NE of the Sabalan region. Andesitic to analcime-bearing tephritic dikes crosscut the pyroclastic sequence, mainly at NE of Meshkin Shahr. Granitic, monzonitic and monzogabbroic intrusive rocks are found in the Ahar-Meshkin Shahr magmatic belt with Eocene age and shoshonitic geochemical affinity [12].

The Sabalan volcano consists of Late Miocene and Plio-Quaternary andesitic to dacitic lavas with huge bodies of ignimbrites-density pyroclastic flows [14]. The Sabalan magmatic activity can be divided into two stages: 1) huge masses of ignimbrites and volcanic ashes associated with interbedded dacitic to trachy-andesitic lavas have erupted in early stages. After several eruptional phases, during collapse of the central domain, a caldera has been formed. 2) This stage is dominant with growth of dacitic to andesitic domes in the central part of the old caldera. The Plio-Quaternary Sabalan lavas are suggested to be high K calc-alkaline to shoshonitic by [15] with highly differentiated REE patterns in chondrite-normalized diagrams. [16] suggested a latite composition for the Sabalan volcanic rocks with high K calc-alkaline and shoshonitic signatures.

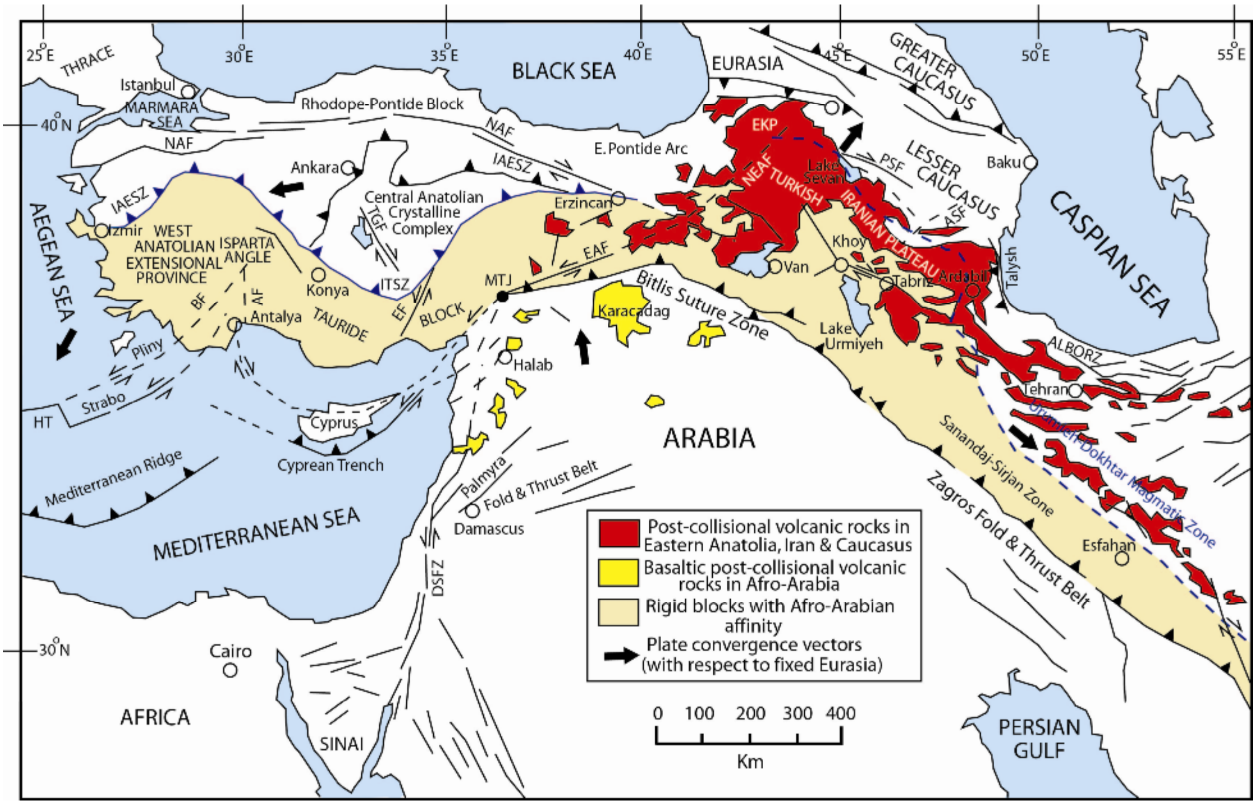

Figure 1 Simplified tectonic map of the eastern Mediterranean-Persian Gulf region showing the active plate boundaries and post-collisional volcanic rocks in the Peri-Arabian region Modified after [13].

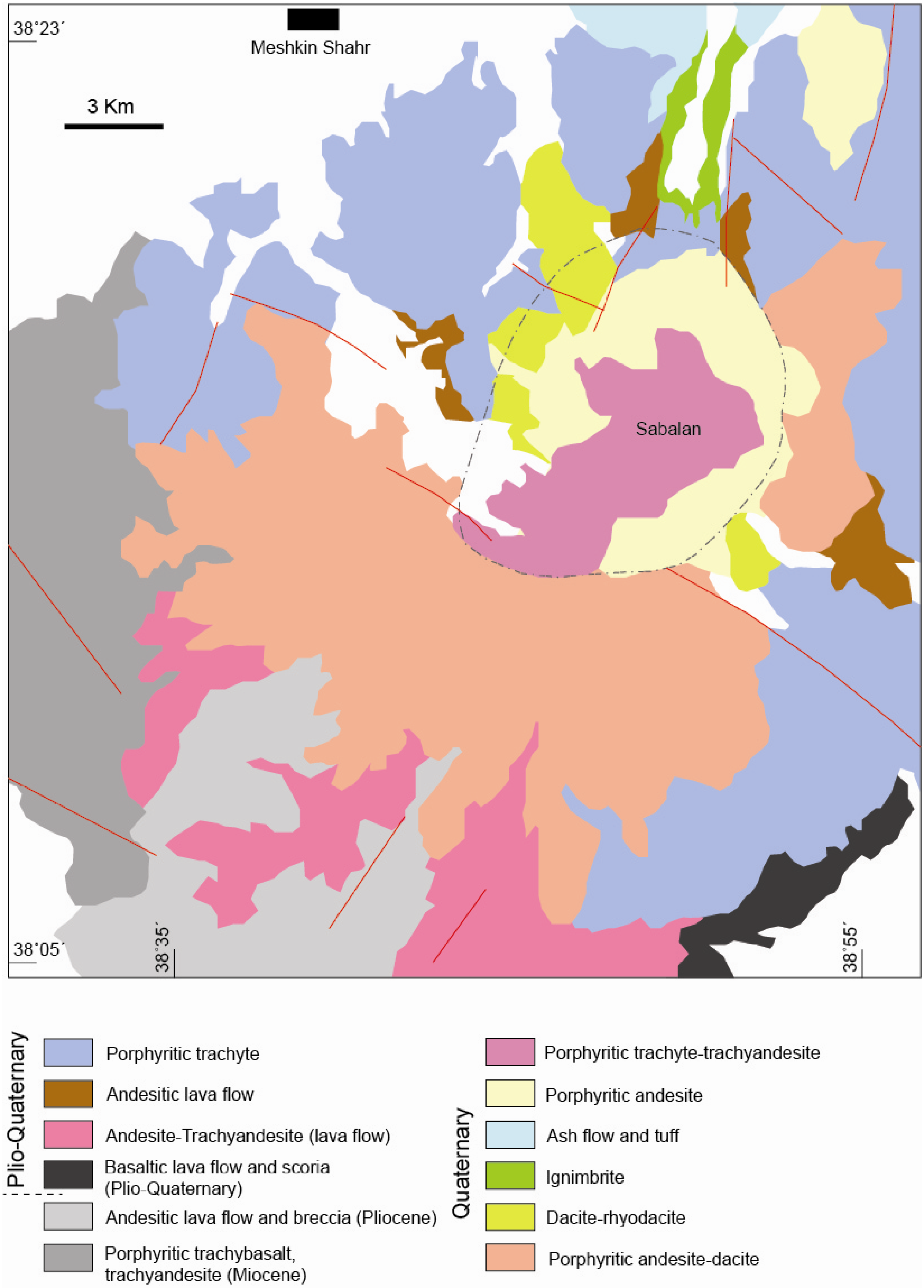

Figure 2 Simplified geological map of the Sabalan region with emphasis on the distribution of Sabalan Miocene to Plio-Quaternary and lower Tertiary volcanic rocks.

Trachybasalts are minor in the Sabalan volcano and occur mostly as Miocene lavas (Fig. 2). They are distributed in the southwestern parts of the Sabalan caldera. These rocks grade upward into trachyandesitic lavas and occasionally are interbedded with pyroclastic rocks. Trachyandesites-porphyritic andesites occur mostly in the southern to western parts of the Sabalan caldera and are associated with pumiceous andesites. Trachytes are characterized by occurrence of elongated amphibole and biotite crystals in the field. These rocks usually are vesicular. Quaternary porphyritic trachyandesites are mostly distributed in the central parts of the caldera and are the main constituents of the Quaternary Sabalan lavas (Fig. 2). These lavas (trachyandesites) are intebedded with ignimberites. Dacite are minor in the Sabalan region and occur mostly as aphyric lavas associated with trachyandesites.

Ignimbrites constitute the major part of the pyroclastic eruptions and compressed fiammes with andesitic composition are floated through the rocks. Pumice and scoria flows are common. Lahar deposits, showing the latest stages of the volcanic activity are predominant in the Sabalan region.

Petrography of Plio-Quaternary volcanic rocks:

Trachyandesites are porphyritic with large (1-2 cm) K-feldspar phenocrysts with slight alteration into clay minerals. Biotite is other rock-forming mineral and occurs as euhedral to subhedral phenocrysts in these rocks. Plagioclases show zoning and sometimes alteration into clay minerals and sericite. The groundmass indicates alteration into clay and chlorite, pseudomorph phases after glass shards. Plagioclase-K-feldspar microlites occur in groundmass. Amphibole in trachyandesites is rare while clinopyroxene in trachybasalts is common. Plagioclase, K-feldspar, biotite and quartz are predominant phases of dacitic lavas. Trachytes have more K-feldspar than plagioclase and biotite and are without quartz compared to dacites. Plagioclase microlites and glass shards are common in the groundmass. Latites are characterized by nearly equal amounts of plagioclase and K-feldspar phenocrysts and occurrence of clinopyroxene microphenocrysts. Plagioclase microlites are dominant in the groundmass of the rocks. Ignimbrites are characterized by high modal of biotite associated with K-feldspar, plagioclase and rarely quartz with flowed glass shards (eutaxitic texture). These rocks sometimes show layering, dark layeres rich in biotite and white layer rich in feldspar, due to the gravity flow of the crystal aggregates after explosion of the volcano. Oxidized andesite fiammes are characteristic of some ignimbrite flows. Andesitic scoria flows with large and abundant vesicles are common. Pumices and compressed pumices with fiammes are other rocks that accompany the pyroclastic units. Andesitic scoria flows rarely have plagioclase and clinopyroxene microphenocrysts with large amount of glass.

Geochemistry of Plio-Quaternary lavas:

1- Analytical methods:

For this study we selected ten fresh samples from Plio-Quaternary Sabalan volcanic rocks for major, trace and REE elements at ALS lab, Canada, using ICP-AES for major elements and ICP-Ms for trace and REE elements. Mineral analyses have been performed at Paris VI University using Cameca SX 100. Sr and Nd isotopic composition were determined for three samples at the Laboratorio de Geologia Isotopica da Universidade de Aveiro, Portugal.

2- Mineral chemistry:

2-1- plagioclase: plagioclases in trachyandesites and latites are characterized by andesine to labradorite in composition (37 to 65% An, Table 1). Their K_2O content ranges between 0.3 and 1.4 %wt (Table 1).

2-2- Clinopyroxene: Clinopyroxene of trachybasalts and latites are characterized by augitic composition with two exceptions that show tendency to plot in low Ca clinopyroxenes field (Opx, pigeonite) (Fig. 3A). Their TiO_2 and Al_2O_3 range between 0.28-0.95 and 1.1-2.8 %wt. respectively while Cr_2O_3 content shows lower values of 0.1 to 0.7 %wt (Table 1). In Ti + Cr vs. Ca diagram of [17], the Sabalan clinopyroxenes have tendency to plot in volcanic arc basalts (Fig. 3B) indicating a arc-related environment for the formation of the Sabalan volcanic rocks.

2-3- Glass shards: Glass shards in the groundmass of some volcanic rocks have minor trace of alteration and then were candidate for EMP analysis. Their SiO_2 content is variable, changing from 66.7 to 75.7%wt. (Table 1), higher than SiO_2 content of whole rocks (57.6- 65.4 %wt.). The K_2O content of these glasses vary between 3.6 and 8.1 %wt., with low content of MgO (0.003-0.07 %wt.) and TiO_2 (0.2-1.1). This glass composition is expected from an evolved-fractioned magma after crystallization of mafic minerals and plagioclase.

Table 1 Composition of clinopyroxene, plagioclase and glass shards in the Sabalan volcanic rocks.

Name	S2	S2	S2	S5	S5	S5	S9	S9	S9	S9	S9	S4	S4	S4	S4
Mineral	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Opx	Cpx	Cpx
SiO_2	53.2	52.9	53.0	51.3	52.4	52.6	50.1	52.3	51.7	52.8	50.5	50.6	52.8	52.7	52.2
TiO_2	0.8	0.5	0.7	0.8	1.0	0.4	0.8	0.5	0.7	0.5	0.9	0.6	0.2	0.3	0.4
Al_2O_3	2.2	2.0	2.8	2.4	2.5	1.3	2.7	1.2	1.9	1.1	2.1	2.8	2.4	2.7	2.5
Cr_2O_3	0.1	0.0	0.0	0.3	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.7	0.2
FeO*	8.3	8.9	23.2	8.7	8.9	9.5	8.8	9.1	8.4	8.9	9.4	8.4	13.4	6.4	6.5
MnO	0.4	0.7	0.1	0.6	0.5	0.6	0.6	0.4	0.2	0.5	0.4	0.4	0.4	0.3	0.2
MgO	15.1	15.0	12.6	14.7	14.3	14.8	14.9	14.8	15.2	15.4	15.3	15.4	28.5	16.6	16.8
CaO	20.0	19.4	7.5	19.8	19.9	19.7	20.1	19.2	20.5	20.1	20.1	20.2	1.6	19.6	20.2
Na_2O	0.5	0.5	0.7	0.6	0.5	0.5	0.4	0.3	0.5	0.4	0.7	0.3	0.1	0.4	0.4
K_2O	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.1
NiO	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.2	0.1	0.0
Total	100.9	100.1	101.8	99.2	100.3	99.7	98.3	98.1	99.1	100.1	99.7	98.8	99.8	100.2	99.6
En	0.44	0.44	0.41	0.43	0.43	0.43	0.43	0.44	0.44	0.44	0.44	0.44	0.77	0.48	0.48
Fs	0.14	0.15	0.42	0.15	0.15	0.15	0.14	0.15	0.14	0.14	0.15	0.14	0.20	0.10	0.10
Wo	0.42	0.41	0.17	0.42	0.43	0.41	0.42	0.41	0.43	0.42	0.41	0.42	0.03	0.41	0.42

Name	S2	S2	S2	S9	S9	S9	S9	S5	S5	S4	S4	S4
Mineral	Plg	Plg	Plg	Plg	Plg	Plg	Plg	Plg	Plg	Plg	Plg	Plg
SiO_2	57.0	57.4	57.8	58.7	58.5	58.3	55.2	51.1	50.7	52.3	52.6	55.4
TiO_2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.0
Al_2O_3	26.2	26.2	25.6	25.6	24.4	23.4	26.4	29.9	29.6	28.5	29.0	27.2
FeO	0.5	0.6	0.7	0.5	0.5	0.4	0.6	0.5	0.9	0.7	0.5	1.1
MnO	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MgO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
CaO	8.8	8.8	7.7	7.1	7.1	7.5	9.5	12.9	12.5	12.1	12.0	9.8
Na_2O	5.6	5.8	6.2	6.6	6.7	6.9	5.8	4.2	3.7	4.8	4.9	5.4
K_2O	0.9	1.0	1.2	1.1	1.3	1.4	0.9	0.3	0.3	0.4	0.3	0.6
Total	99.3	100.0	99.4	100.1	99.2	98.2	98.8	99.5	98.2	99.1	99.5	100.1
An%	46.6	45.5	40.6	37.4	37.0	37.7	47.8	62.8	64.9	58.1	57.7	50.2

Name	S2	S2	S5	S5	S9	S9	S9	S4	S4
Mineral	glass	glass	glass	glass	glass	glass	glass	glass	glass
SiO_2	75.3	75.7	73.4	74.5	68.3	72.3	66.7	72.3	72.8
TiO_2	0.8	0.8	0.8	0.8	0.2	1.0	0.3	1.1	1.1
Al_2O_3	12.9	12.6	14.0	14.1	17.4	13.5	18.6	14.2	14.0
Cr_2O_3	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1
FeO	0.8	1.9	0.8	0.7	0.6	1.4	0.9	1.4	2.7
MnO	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
MgO	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1
CaO	0.3	0.3	0.2	0.3	1.1	0.3	2.2	0.3	0.2
Na_2O	2.6	2.2	2.5	3.0	5.3	3.3	6.4	2.1	2.1
K_2O	6.1	7.2	7.9	8.2	6.1	6.0	3.6	7.4	5.9
Total	99.3	100.9	99.5	101.7	100.1	98.5	99.1	99.0	99.1

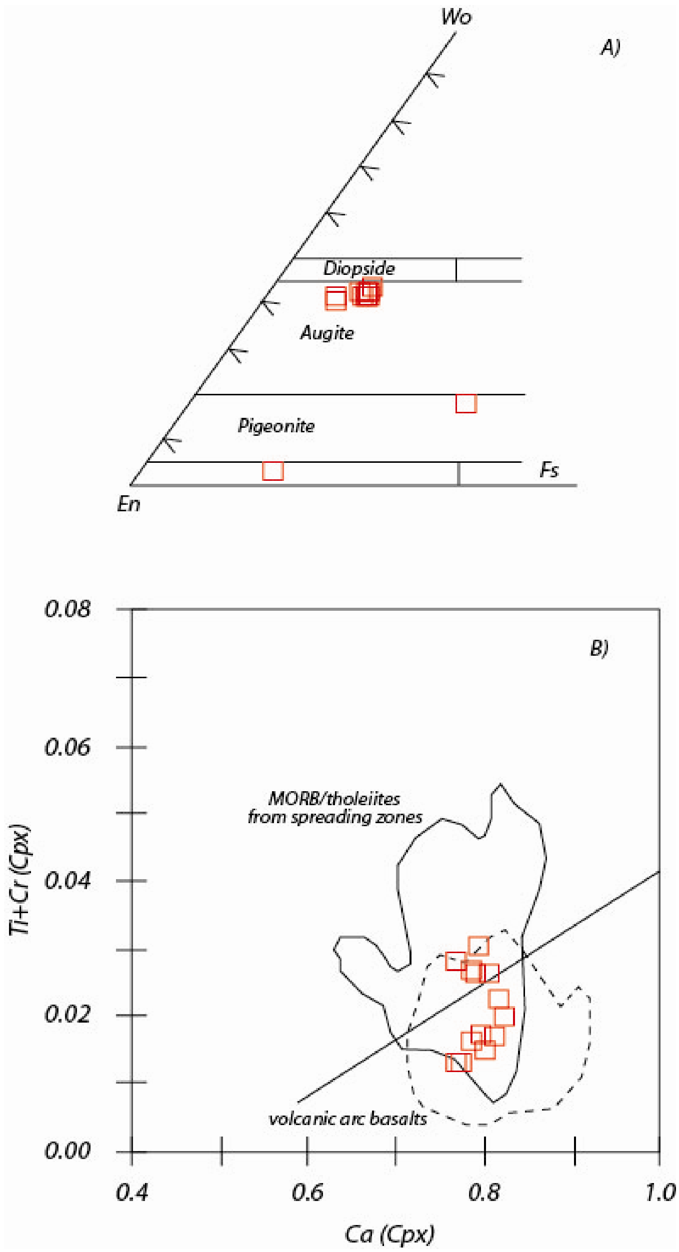

Figure 3 A) Pyroxene composition of the Sabalan lavas in Wo-En-Fs diagram. B) Composition of pyroxenes in a plot of Ti + Cr vs. Ca [17], indicating their formation in an arc-related setting.

3- Whole rock geochemistry

The Sabalan lavas have slight alteration, characterized by low content of LOI values (1.1-1.9 %wt., Table 2), except sample S08-7 with 3.2 %wt. LOI, relating to sericitization of feldspars. The lavas are intermediate to acidic in composition with SiO_2 contents ranging from 57.6 to 65.4 %wt. (Table 2). In total alkalis vs. SiO_2 diagram of [18], the lavas (bulk rock) show tendency to plot in trachyandesitic to trachydacitic fields, similar to other shoshonitic lavas from NW Iran (Dilek et al., 2010) (Fig. 4). These lavas tend to plot in trachydacite and rhyolite domains based on the composition of the glass shards of the rock groundmass. K_2O and TiO_2 contents of the Sabalan lavas vary between 2.5-4.8 and 0.7-0.9 %wt. (Table 2). In K_2O against SiO_2 diagram [19], the lavas have affinity to high-K calc-alkaline and shoshonitic rocks, a feature that is characteristic of post-collisional alkaline rocks from NW Iran and NE Turkey [2] (Fig. 5).

Table 2 Whole rock and Sr-Nd isotope composition of the Sabalan volcanic rocks.

Name	S08-3	S08-1	S08-2	S08-4	S08-5	S08-6	S08-7	S08-8	S08-9	S08-10
SiO_2	61.2	58.8	65.4	60.4	64.9	57.6	63.5	64.4	64.6	65.2
Al_2O_3	16.8	16.8	15	16.5	15.2	16.5	14.6	14.9	14.95	15
FeOt	5.09	6.06	3.69	5.08	3.97	6.08	3.62	3.73	3.82	3.75
CaO	5.45	6.17	2.62	5.37	2.64	5.8	2.61	2.69	2.73	2.65
MgO	2.4	2.46	1.09	2.41	1.08	2.99	1.08	1.1	1.1	1.06
Na_2O	3.57	4.01	4.11	3.52	4.25	3.97	4.08	4.06	4.03	4.02
K_2O	2.86	2.83	4.68	2.81	4.6	2.49	4.17	4.58	4.69	4.78
TiO_2	0.7	0.89	0.7	0.7	0.71	0.88	0.68	0.71	0.71	0.7
MnO	0.1	0.1	0.09	0.1	0.09	0.11	0.09	0.09	0.09	0.08
P_2O_5	0.27	0.42	0.25	0.26	0.25	0.41	0.24	0.25	0.28	0.25
LOI	1.54	1.68	1.32	1.49	1.88	1.09	3.24	1.36	1.59	1.45
Total	100	100.5	99.2	98.8	99.8	98.1	98.1	98	98.7	99.1
Ba	844	1500	829	809	1140	784	1015	748	744	775
Ce	78.5	98.1	127.5	78.3	127.5	90	124.5	125.5	123.5	125
Cr	60	90	450	40	140	90	80	30	230	20
Cs	2.07	1.63	5.07	2.01	4.98	1.5	4.92	4.81	4.78	4.89
Dy	3.15	3.84	4.06	3.18	4.2	3.55	4.04	3.99	4.06	4.06
Er	1.88	2.27	2.48	1.87	2.6	2.01	2.47	2.5	2.45	2.56
Eu	1.29	1.65	1.36	1.31	1.4	1.53	1.33	1.37	1.39	1.35
Gd	4.62	5.78	6.27	4.54	6.43	5.29	6.14	6.13	6.15	6.18
Hf	4.9	5.7	8.7	4.8	9	5.1	8.5	8.6	8.5	8.7
Ho	0.64	0.77	0.82	0.63	0.85	0.7	0.84	0.81	0.82	0.83
La	46.6	57.5	73.4	46.3	73.5	52	71.9	72	70.4	72
Lu	0.27	0.32	0.41	0.27	0.42	0.27	0.39	0.39	0.39	0.4
Nb	20.9	28.3	48.8	21	49.3	25.1	47.1	46.9	46.4	47.5
Nd	27.6	35.4	41.4	27.4	41.5	32.3	41	40.7	40.7	40.4
Ni	28	32	8	28	9	36	6	7	8	7
Pb	13	16	21	14	23	13	20	24	19	23
Pr	7.9	10.05	12.45	7.92	12.5	9.1	12.4	12.4	12.25	12.3
Rb	72	71.5	180.5	72.4	180	64.5	173.5	176.5	176	179
Sm	4.79	5.88	6.61	4.66	6.62	5.46	6.52	6.58	6.46	6.44
Sr	626	837	401	622	410	751	448	415	421	415
Ta	1.4	1.8	3.4	1.4	3.6	1.6	3.3	3.4	3.3	3.4
Tb	0.61	0.75	0.79	0.59	0.83	0.69	0.78	0.77	0.77	0.78
Th	9.28	10.1	26.3	9.2	26.7	9.08	25.7	25.5	25.1	25.8
Tm	0.26	0.31	0.38	0.26	0.38	0.28	0.36	0.36	0.36	0.37
U	2.75	2.67	7.11	2.72	7.11	2.37	6.87	6.89	6.81	6.98
V	100	121	59	99	58	118	58	58	60	57
Y	17.7	21.2	23.7	17.9	23.9	19.2	23.5	23.4	23.3	23.6
Yb	1.78	2.02	2.61	1.77	2.7	1.85	2.58	2.55	2.52	2.56
Zn	72	89	102	98	81	89	72	95	68	92
Zr	210	253	368	211	376	230	356	356	354	357
87Sr/86Sr							0.70511		0.70452	0.70443
143Nd/144Nd							0.51273		0.51269	0.51271
εNd							1.8		1.04	1.4

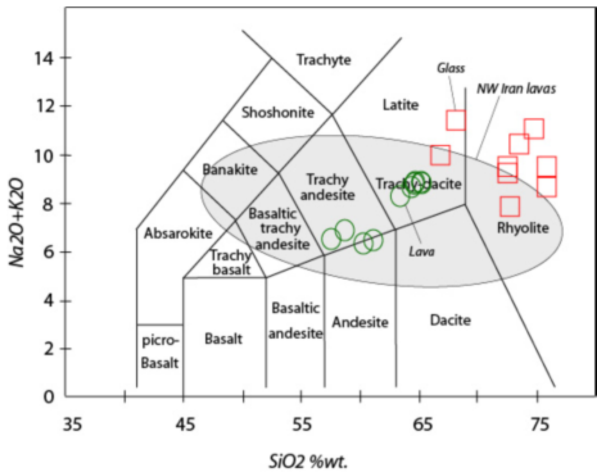

Figure 4 Total alkali vs. SiO_2 classification diagram of the Sabalan volcanic rocks [18]. Data source of NW Iran lavas is from [2].

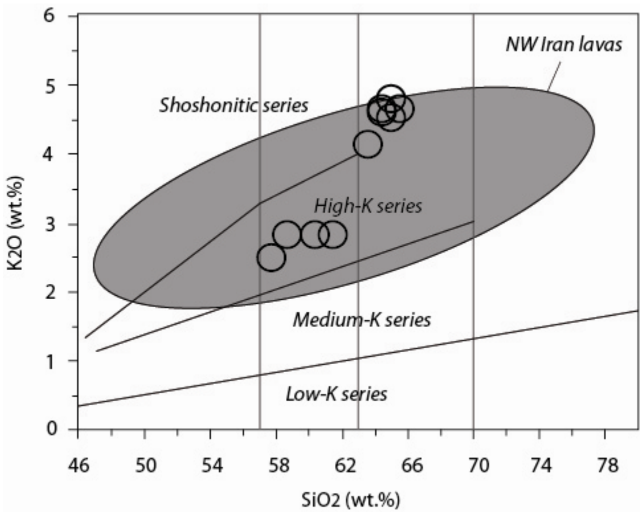

Figure 5 K_2O vs. SiO_2 diagram [19] of Sabalan volcanic rocks. Data source of NW Iran lavas is from [2].

In chondrite-normalized REE diagram (Fig. 6), Sabalan lavas show a fractionated REE trend, with enrichment in LREEs relative to HREEs ($La_{(n)}/Yb_{(n)}$ = 18.8-20.4). Some samples show slight depletion in Eu, relating to plagioclase fractionation.

The lavas show conspicuous depletion in Nb, Ta, Ti and P (e.g., Nb(n)/La(n) = 0.5-0.6) with positive anomalies in most large ion lithophile elements (LILE) including Rb, Th, U and Pb relative to LREEs (e.g., Th(n)/La(n) = 1.4-2.9 and U(n)/La(n) = 1.5-3.2) (Fig. 6). These REE and trace elements patterns are mostly consistent with rocks of shoshonitic series, relating to magmatism along an active continental margin.

4- Nd-Sr isotopes:

Trachyandesitic to trachydacitic samples have uniform initial (t = 2 Ma) $^{87}Sr/^{86}Sr$ values (0.704-0.705) with εNd ranging from ~+1 to +1.8. In the initial $^{8}7Sr/^{86}Sr$ vs. εNd variation diagram (Fig. 7), the Sabalan volcanic rocks are characterized by derivation from an enriched mantle source (with/without crustal influence), and all samples show tendency to plot in a field defined by island-arc basalts (IAB) and OIBs. The samples mostly show affinity to plot near the Ghoshchi alkali gabbros (unpublished data), Suffi-abad I-type granites [20] and Eastern Pontides adakites [21] (Fig. 7). The Sabalan shoshonitic lavas have higher εNd than Plio-Quaternary Salmas lavas (unpublished data), indicating mantle source of the Sabalan lavas is slightly depleted compared to that of Salmas lavas.

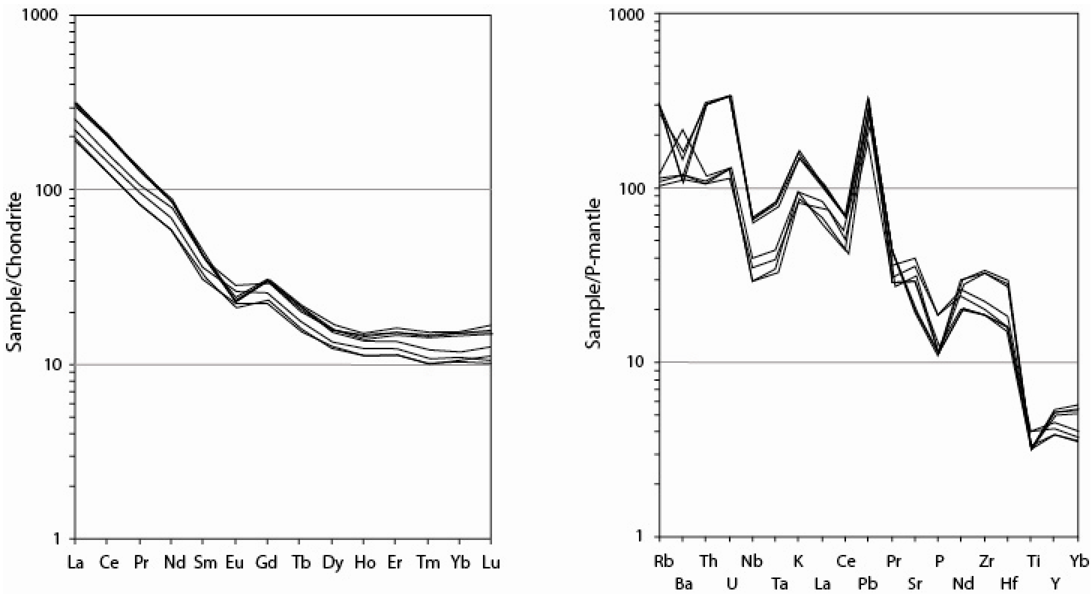

Figure 6 Chondrite-normalized REE and mantle-normalized trace elements patterns of the Sabalan volcanic rocks. Normalized data are from [22].

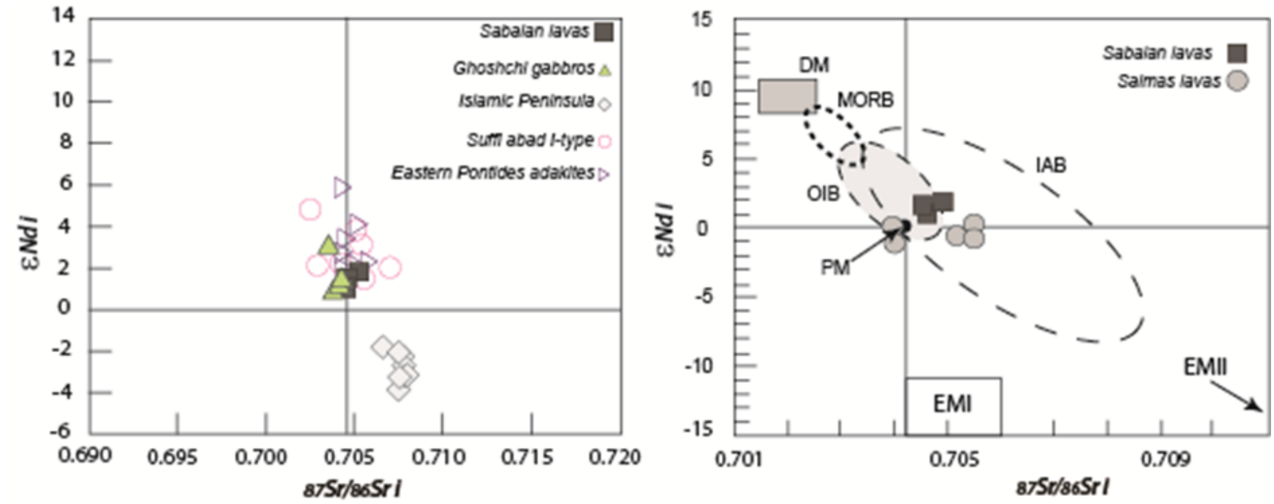

Figure 7 εNd vs. $^{87}Sr/^{86}Sr$ diagrams for Sabalan lavas. Data from other Turkish-Iranian post-collisional intrusive and extrusive rocks are shown for comparison, right diagram modified after [23].

Discussion

1- Petrogenesis:

The Sabalan volcanic rocks are characterized by fractionated REE pattern, with high LREE/HREE ratio, resemble shoshonitic rocks from the active continental margins and/or post-collisional magmatism after closure of oceanic basin. Depletion in high field strength elements and enrichment in large lithophile elements are conspicuous. Such shoshonitic volcanism is characteristics of the Turkish-Iranian high plateau [2, 24]. The galss shards in the groundmass of these rocks are characterized by more fractionated nature, with higher SiO_2 and K_2O contents, indicating quenching products of more-evolved melt after fractionation of mafic minerals. The Sabalan lavas are similar to Goshchi alkali gabbros, both of them are characterized by derivation from an isotopically enriched mantle source (OIB mantle source). They are clearly different from crustal contaminated, post-collisional Islamic peninsula shoshonites and ultrapotassic rocks. When compared to other Iranian, post-collisional Plio-Quaternary lavas, like as the Salmas basalts, the Sabalan rocks show higher εNd values, may show a slight depleted mantle source for the Sabalan lavas than Salmas lavas and/or contamination of the Salmas lavas with crustal materials during their ascent to the surface. The interaction with crustal rocks along with derivation from a subduction-contaminated source for the Sabalan volcanic rocks is also clear from Th/Yb vs. Ta/Yb diagram [25] (Fig. 8). In this diagram, the Sabalan lavas are represented by higher Th/Yb ratio, far from within plate mantle trend, resemble those lavas erupted above an active continental margin. Higher Th content could be also resulted from interaction of ascending lavas with crustal rocks, via assimilation-fractional crystallization (AFC) process. The Sabalan lavas seem to show contamination with high Th (and high $^{87}Sr/^{86}Sr$) crustal rocks during their ascent to the surface beneath the volcano. In order to evaluate the partial melting degree of the mantle source for which generate the Sabalan lavas, we used the Sm/Yb vs. La/Sm diagram [26]. The Sabalan lavas relatively are similar to Salmas Plio-Quaternary basalts, characterized by low degree of partial melting (<0.1 %) of a mantle source containing clinopyroxene-garnet lherzolites (Fig. 9). Because the Sabalan lavas are characterized by higher La/Sm ratio, it seems that their mantle source contains more modal garnet content, than model source in Fig. 9 and/or contain other minor phases like as phlogopite.

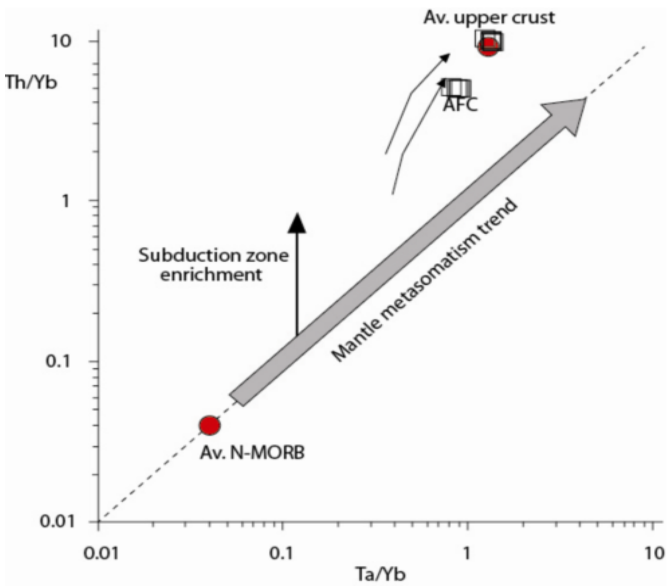

Figure 8 Th/Yb vs. Ta/Yb diagram [25] for the Sabalan Plio-Quaternary lavas.

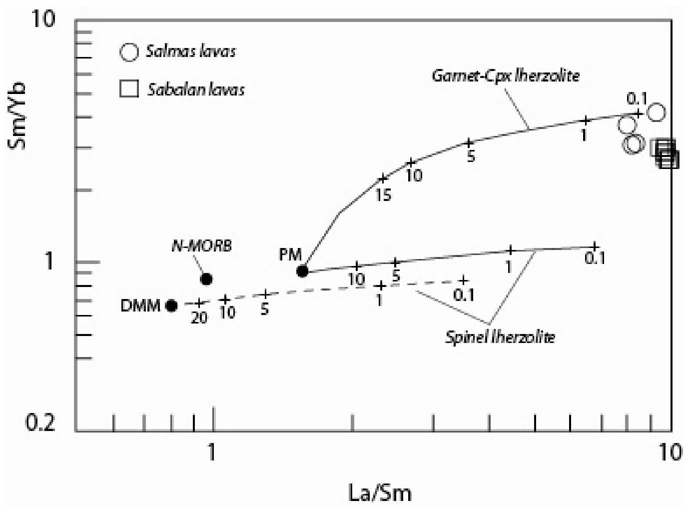

Figure 9 Sm/Yb vs. La/Sm diagram for the Sabalan volcanic rocks with melting curves obtained using the non-modal batch melting modelling, modified after [26].

2- Geodynamic setting

Plio-Quaternary volcanism in the Peri-Arabian region (in Turkish-Iranian high plateau) postdates the subduction of Neotethyan lithosphere since ~ 13 Ma [2]. These volcanic rocks become more alkaline with time and towards the south [2,4,5,27]. However, most of volcanic rocks likes as Sabalan, Salmas and/or Maku Plio-Quaternary lavas, still show a subduction zone geochemical signature including enrichment in LILE and/or depletion in HFSE despite the lack of subduction system in that time. These observation and isotopic characteristics of the lavas suggest that their magma were probably derived from partial melting of a subduction-metasomatized continental lithospheric mantle in the garnet/spinel lherzolite field [2]. Widespread volcanism across the Turkish-Iranian plateau throughout the late Cenozoic until Plio-Quaternary is strictly ascribed to post-collisional mantle upwelling during slab steeping and break-off beneath a subduction-accretion complex [4,28].

Conclusions

The Sabalan Plio-Quaternary volcanism includes a sequence of trachyandesites, dacites, latites, trachytes with huge bodies of ignimbrites and pyroclastic rocks. Plagioclase with andesine to labradorite and clinopyroxene with augitic composition are predominant phases in these volcanic rocks. Lavas show shoshonitic geochemical signature with a fractionated REE trend, enrichment in LREEs relative to HREEs, and depletion in HFSE. The Sabalan volcanic rocks are isotopically characterized by derivation from an enriched mantle source (with/without crustal influence), and all samples show tendency to plot in a field defined by island-arc basalts (IAB) and OIBs in term of their εNd value and $^{87}Sr/^{86}Sr$ ratio. The lavas are characterized by higher Th/Yb ratio, resembling those lavas erupted above an active continental margin with geochemical evolution via assimilation-fractional crystallization (AFC) process. The geochemical and isotopic signatures of the Sabalan lavas suggest that their magma has been issued via low degree partial melting of a subduction-metasomatized continental lithospheric mantle post-collisional during Neotethyan slab steeping and break-off beneath the Turkish-Iranian high plateau.

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