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Geochemistry and Emplacement Environment of Post Eocene I-type South Ardestan granitoid, NE Isfahan, Iran

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ABSTRACT

The South Ardestan granitoid stock is located in NE Isfahan and is a part of Urumieh-Dokhtar magmatic assemblage in Central Iran. This plutonic rock is Post Eocene, probably of Oligo-Miocene age and is the result of extensive magmatism which occurred during and after the Alpine Orogeny. The Plutonic composition is Granodiorite to Tonalite. South Ardestan granitoid stock is similar to those of the subalkaline, calc-alkaline series, metaluminous, and displays typical features of I-type granites. The South Ardestan granitoid rocks are characterized by enrichment in large ion lithophile elements (LILE) such as Rb, Ba, K, Ce and depletion in high field strength elements (HFSE) such as Y, Nb and Zr. The Chondrite normalized REE patterns are characterized by moderate to high LREE enrichment and unfractionated HREE. Granitoid with the least fractionated HREE and has a weak negative of Eu anomalies are indicative of feldspar involvement during fractionation and/or melting. This granitoid magma involves partial melting of crustal protoliths and mantle-derived basaltic magmas emplaced into the lower crust. The South Ardestan granitoid stock has mineralogical field and geochemical characteristics typical of volcanic arc granites related to an active continental margin. Probably, the South Ardestan granitoid stock is the result of the subduction of Neo-Tethyan oceanic plate below the Lut microcontinent and this oceanic residual plate during Mesozoic to Cenozoic time.

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INTRODUCTION

The Zagros Orogenic Belt is situated within the Alpine–Himalaya orogenic system and extends in a northwest–southeast direction for about 2000 km from the Taurus Mountain of southeastern Turkey to the Bandar–Abas syntax in southern Iran. The Zagros orogenic belt of Iran consists of three parallel tectonic subdivisions from northwest to southeast: (1) the Urumieh-Dokhtar magmatic assemblage, (2) the Sanandaj-Sirjan zone and (3) the Zagros folded-thrust belt [4].

The Urumieh-Dokhtar magmatic assemblage,150 km wide, forms a subduction related, distinctively linear and voluminous magmatic arc composed of tholeiitic, calc–alkaline, and K-rich alkaline intrusive and extrusive rocks (with associated pyroclastic and volcaniclastic successions) along the active margin of the Iranian plate. Although magmatic activity continued from the Cretaceous to recent times, the peak activity in the Urumieh–Dokhtar Magmatic Assemblage occurred in Eocene times [13]. The magmatic activity was generally calc-alkaline[1]; [32] but alkaline rocks of Miocene age were also reported [24]. The steep dip of the subducting oceanic slab and the presence of a ‘slab window’ may have been responsible for the formation of scattered alkaline rocks in the volcanic belt [31]. Zagros orogenic belt has been proposed to have resulted from the opening and subduction of the Neotethyan oceanic realm and subsequent oblique collision of Afro-Arabia (Gondwana) with the Iranian microcontinent in the Late Cretaceous–Early Tertiary [8,3,23].

The South Ardestan granitoid stock is located in latitudes of 33^0 - 33^o 09` and longitudes of $52^0$22`30”- $52^0$30` and in 63 km NE of Isfahan, Central Iran (Fig. 1,2). In the structural classification of Iran (Nabavi, 1976), the South Ardestan area is located in the central part of the Urumieh-Dokhtar magmatic assemblage (UDM) in the Zagros Orogenic Belt (Fig. 1). The South Ardestan volcanic and plutonic rocks were intruded as part of an extensive magmatic event which occurred in the Cenozoic, during and after the Alpine Orogeny. Previous geologic studies in the South Ardestan region include, study of the magmatic rocks in Natanz-Nain-

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Surk areas [5]. [21] wrote a M.Sc. thesis on the petrography of the west South Ardestan intrusive rocks. The earliest petrographic study of the South Ardestan magmatic rocks were carried out by [6,9] and [17]. On the base of these studies, mostly Eocene volcanic and intrusive rocks of South Ardestan are related to the calc-alkaline magmatic series. These petrographic and geochemical data are then used to shed light on the origin and tectonic setting of these rocks, particularly in relation to the initiation of Neotethys subduction.

The greater part of the South Ardestan area is covered by Eocene volcanic rocks (Fig. 2). The volcanic sequence is composed of tuffs and volcano clastic rocks of dacite, andesite, basaltic andesite and basalt with sedimentary rocks [2]. The South Ardestan volcanic rocks are considered to be of Eocene in age. The South Ardestan granitoid stock cuts these Eocene volcanic rocks, therefore intruded in post-Oligocene time (Oligo-Miocene). This is composed of two rock types distinguished by their color and mineralogy: light gray granodiorite and dark grey tonalite. The granodiorite and tonalities have a gradational boundary. The contact between them was not seen and is, therefore, considered to be broadly contemporaneous. Also dioritic enclaves of various types and sizes (centimeters to meters) are found throughout the stock, being particularly abundant in the north part where they form massive clusters.

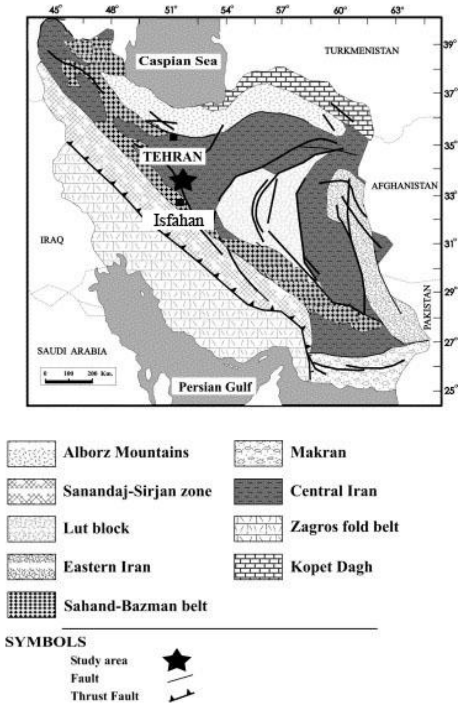

Fig. 1: Geological map of Iran (modified from [31])

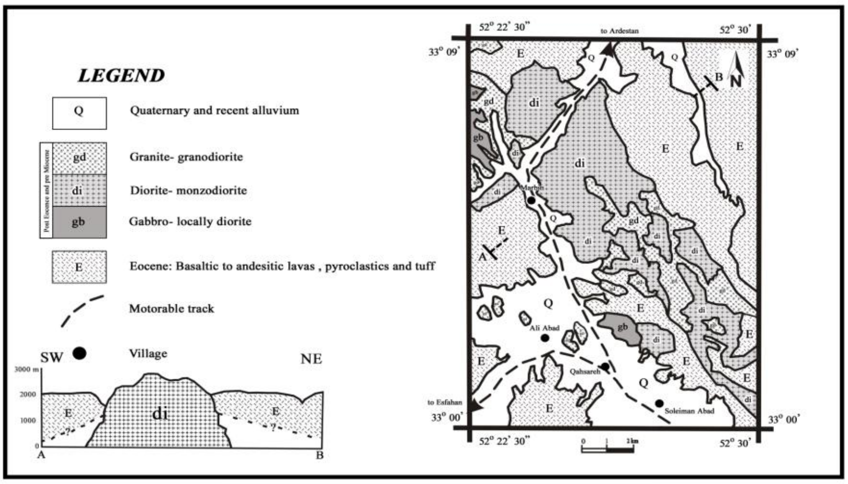

Fig. 2: Geological location of South Ardestan granitoid stock [2]

MATERIALS AND METHODS

A total of 46 samples have been collected from the South Ardestan granitoid stock. Polished thin sections were prepared for all of these samples for petrographic examination. On the basis of petrographic observations, 7 samples with minimal effects of late hydrothermal alteration were selected for whole-rock geochemical analysis (Table 1) and were analyzed for major and minor elements on a Varian inductively coupled plasma atomic emission spectrometer (ICP-AES) and trace elements (including rare-earth elements, REE) by inductively coupled plasma mass spectrometry (ICP-MS) at ALS Chemex lab, North Vancouver, Canada.

Table 1: Major and trace data for sample rocks from the South Ardestan granitoid pluton (Oxides: %wt and minor and trace elements:ppm)

Sample	SAr-2	SAr-4	SAr-7	SAr-9	SAr-10	SAr-11	SAr-14
SiO_2	60.1	58.6	59.8	58.8	59.7	59.9	52.5
Al_2O_3	16.45	16.1	15.85	15.65	15.6	15.85	17.8
Fe_2O_3	7.67	8.14	8.23	8.1	7.83	7.99	7.48
CaO	5.8	6	6.05	5.99	5.89	5.84	8.5
MgO	2.34	2.87	2.55	2.63	2.46	2.61	4.5
Na_2O	3.72	3.69	3.8	4.04	3.82	3.99	4.71
K_2O	1.15	1.31	1.63	1.59	1.66	1.46	0.44
Cr_2O_3	0.03	0.02	0.03	0.05	0.02	0.04	0.02
TiO_2	0.8	0.96	0.99	0.94	1	0.95	0.93
MnO	0.2	0.17	0.14	0.14	0.13	0.13	0.09
P_2O_5	0.21	0.17	0.21	0.21	0.23	0.21	0.19
SrO	0.03	0.03	0.03	0.03	0.03	0.03	0.05
BaO	0.04	0.05	0.05	0.05	0.05	0.05	0.01
LOI	1.6	1.99	0.2	0.9	0.6	1.48	2.8
Total	100	100	99.6	99.1	99	100.5	100
Ag	<1	<1	<1	<1	<1	<1	<1
Ba	371	411	416	417	418	412	108
Ce	26.2	33.6	36.2	36.4	38	36.6	14
Co	14.2	18.7	18.7	19	17.9	18.3	17.9
Cr	220	130	180	340	120	260	150
Cs	2.03	1.52	1.65	1.52	1.08	1.4	5.15
Cu	34	56	59	56	60	73	<5
Dy	4.72	5.81	6.17	6.07	6.35	5.99	4.45
Er	2.97	3.72	3.88	3.86	4.01	3.85	2.7
Eu	1.08	1.24	1.31	1.25	1.35	1.25	0.96
Ga	17.8	16.8	17.1	17.3	17.1	17.1	16.2
Gd	4.35	5.43	5.96	5.89	6.22	5.74	4.01
Hf	3.8	4.8	5.3	5.8	5.6	5.4	2.8
Ho	0.96	1.25	1.28	1.27	1.37	1.27	0.94
La	12.1	15.8	16.7	16.7	17.7	16.9	4.7
Lu	0.45	0.55	0.58	0.61	0.59	0.59	0.39
Mo	3	2	4	4	3	6	<2
Nb	4.8	7.1	7.8	7.5	8.1	7.6	5.2
Nd	14.6	19.1	20.7	19.8	21	19.6	12.4
Ni	6	10	11	16	9	15	26
Pb	9	14	18	15	15	15	8
Pr	3.44	4.41	4.78	4.75	4.94	4.77	2.41
Rb	28.5	28.2	47.2	46.4	45.9	36	18.6
Sm	3.57	4.64	4.95	4.7	5.04	4.87	3.47
Sn	2	1	2	2	2	2	1
Sr	233	258	241	238	232	261	402
Ta	0.3	0.5	0.5	0.5	0.5	0.5	0.3
Tb	0.78	0.95	1.01	1.05	1.05	0.99	0.7
Th	3.24	4.77	5.34	5.61	6.11	5.64	1.83
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Tm	0.46	0.53	0.57	0.57	0.55	0.57	0.39
U	0.86	1.12	1.35	1.37	1.47	1.41	0.48
V	164	210	209	204	196	203	231
W	14	8	5	21	4	7	7
Y	25.8	32	34	34.5	35.4	34.1	23.7
Yb	3.06	3.48	3.69	3.63	3.92	3.69	2.47
Zn	83	107	95	91	81	85	34
Zr	121	159	177	198	192	183	100

RESULTS AND DISCUSSION

Results of whole-rock geochemical analysis of all samples are presented in Table 1.

A plot of SiO_2/(K_2O + Na_2O) [12] shows that the South Ardestan intrusive rocks plot in the field of granodiorite plots in the field of diorite.

Fig. 3a and b show that the South Ardestan granitoid rocks are subalkaline and plot in the calc–alkaline field on an AFM diagram [20].

Classification of these rocks by the aluminum saturation index (ACNK or ASI, [39] indicates that total of the granitoid rocks and diorite enclaves are metaluminous (i.e. Al index <1.1; Fig. 3c). Overall, the mineralogy of the South Ardestan granitoid rocks, which include biotite, hornblende, magnetite, apatite and zircon, strongly suggests a metaluminous source.

A discriminationplot of Zr vs. SiO_2 (after [37] and Na_2O+K_2O-CaO vs. SiO_2 diagram show that the South Ardestan granitoid and enclave samples plot within the I-type granite field (Fig. 4). The SiO_2 and Na_2O contents, molecular A/CNK ratio, K_2O/Na_2O ratio, abundance of Cr and Ni, microgranitoid enclaves, key modal minerals (such as hornblende and zircon) all suggest that South Ardestan granitoid shows I-type characteristics on the basis of the [10].

a) b)

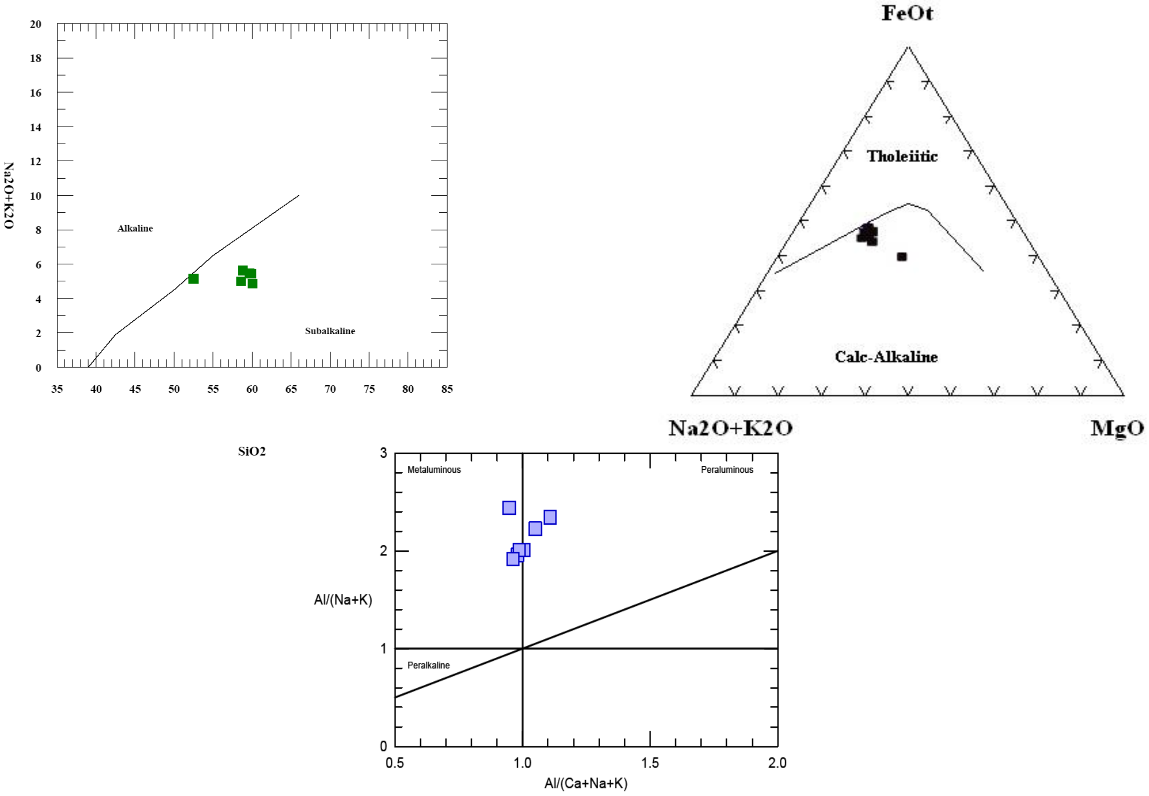

Fig. 3: Classification of the South Ardestan granitoid and enclave samples: (a) alkali versus silica diagram [18] ;(b) AFM diagram [20]; (c) plot of A/ NK vs. A/CNK ([22], [A/NK = molar Al_2O_3/ (Na_2O+K_2O) and A/CNK = molar Al_2O_3/ (CaO + Na_2O+K_2O)

a) b)

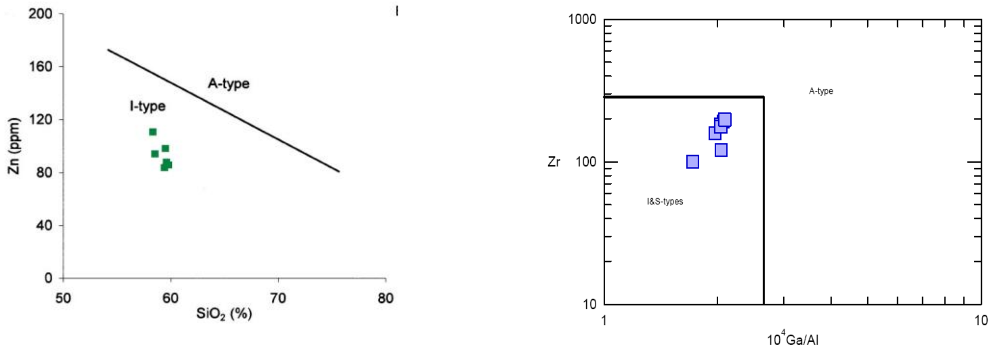

Fig. 4: (a) Zn versus SiO_2 wt% diagram distinction between I-Type and A-Type granites; (b) Zr vs. 10^4Ga/Al diagram distinction between I&S-Type and A-Type granites

Trace and rare earth elements (REEs):

In general the Chondrite normalized REE patterns of all South Ardestan granitoid rocks are characterized by moderate to high LREE enrichment and unfractionated HREE (Fig. 5). The unfractionated HREE (and Y) patterns and low Sr and Eu contents suggest that the magma was produced outside the garnet stability field (i.e., plagioclase stable without garnet; Cullers [16] and [15] and; [29,33,27]; . These rocks have small negative or no Eu anomalies ($(Eu/Eu^*)_N < 1.0$).

The negative Eu anomalies are indicative of feldspar involvement during fractionation and/or melting [30].

Well-defined negative anomalies are observed for P, Ti, Sr, and Nb. Fractionation or presences of some minerals in the restites explain the negative anomalies, for example, apatite (P) and ilmenite and/or titanite (Ti). Sampling rocks are normalized to primitive mantle [34]. Rocks are enriched in LILE (e.g., Rb, Ba, Th, U, and Pb), relatively depleted in HFSE (e.g., Nb, Ti).

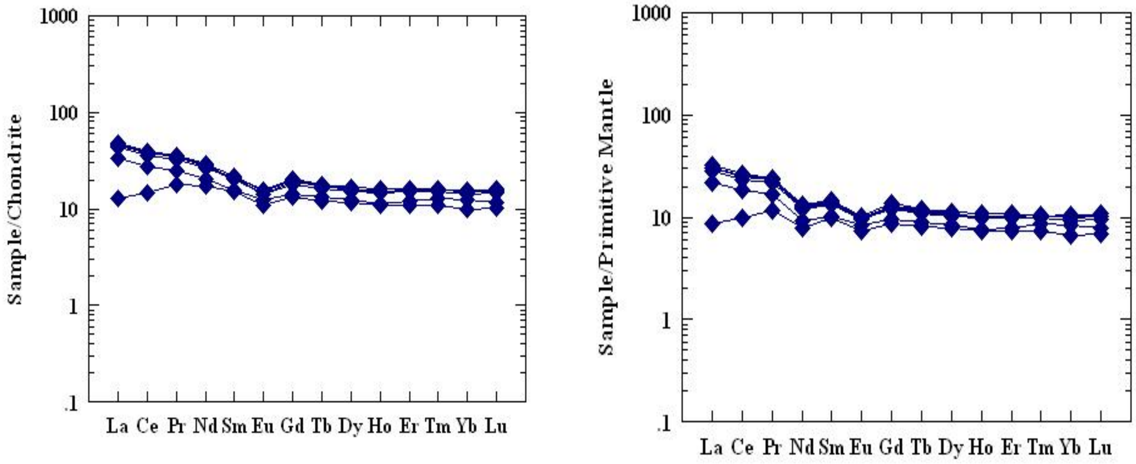

Fig. 5: Chondrite-normalized REE plot of the South Ardestan rocks. Normalization Irvine and Baragar, 1971 factors from Taylor and McLennan, 1985. The South Ardestan rocks normalized with primitive mantle (normalized data from [35] and McLennan.

Tectonic setting:

Trace element discrimination diagrams depict the probable tectonic settings of intrusive rocks containing 56–80% SiO_2 [28]. These are effective at discriminating different tectonic environments in the formation of granitoids. Fig. 6a, Rb vs. Y+Nb shows that the South Ardestan granitoid rocks plot within the volcanic arc granite. In the R1-R2 diagram samples plot mainly in the pre-plate collision field (Fig. 6b).

Fig. 6c shows that the South Ardestan granitoid plots in the field of continental margin arc. Furthermore, the high rate of La/Yb (2.7-13.17) shows that South Ardestan granitoid rocks belong to continental felsic magmas arc. In Th/Ta vs. Yb diagram samples are located in primitive island arc / continental margin arc (Fig 6d). Therefore, trace element compositions (i.e., Rb, Y, Nb, Th, Ta, Zr and Yb) suggest that the South Ardestan granitoid rock is similar to intrusive rocks from Phanerozoic arcs. The primitive mantle diagram of the South Ardestan granitoid shows selective enrichment in large ion lithophile elements (LILE) and depletion in high field strength elements (HFSE) (Fig. 5c–d). This type of multi-element patterns shows that the South Ardestan granitoid is similar to volcanic arc granites [28]. Moreover, the distinctly negative Nb anomalies (Fig.7d) are typical of magmas derived from a subduction-metasomatized mantle [38].These diagrams show that the South Ardestan pluton formed as part of a volcanic arc, consistent with the tectonomagmatic setting proposed for the northeast Isfahan in the Post Eocene(probably Oligo-Miocene, [23].

Petrogenesis:

Granitoid rocks are an important component of continental crust and different model envisaged for their generation (e.g. direct partial melting of the mantle, fractional crystallization from basaltic magma, etc.). The geological setting and the chemical composition of the rock types within the South Ardestan granitoid, all support the hypothesis that the igneous activity occurred above an active subduction zone. The relatively low contents of Zr, Y, Nb, La strongly suggest that South Ardestan granitoid is an I-type granitoid formed in an arc environment. Normally for continental arc granitoids a fundamental role is assigned to mantle derived mafic magmas. They may be parental magmas, end members in mixing or assimilation processes, material for lower crustal source regions, and/or heat sources that derived crustal melting [35,36] and references there in). In the Sr/Y versus Y diagram (Fig.7), the South Ardestan granitoid rocks have low Sr/Y values and plot in the field of mantle-derived arc magmas. The South Ardestan rocks are characterized by low ratios for

Al_2O_3/FeO+MgO+TiO_2, Na_2O+K_2O/FeO+MgO+TiO_2 and Al_2O_3/MgO+FeOt and a rather high range of CaO/ (FeO+MgO+TiO_2). These values support that these magmas cannot be originated by partial melting of pelites. This feature, associated with relatively high Mg# values precludes a derivation from felsic pelite and/ or metagreywacke. Thus, the possible implication of a mafic source (diorite?) with addition of some recycled material (sediments?) in the source region is considered here.

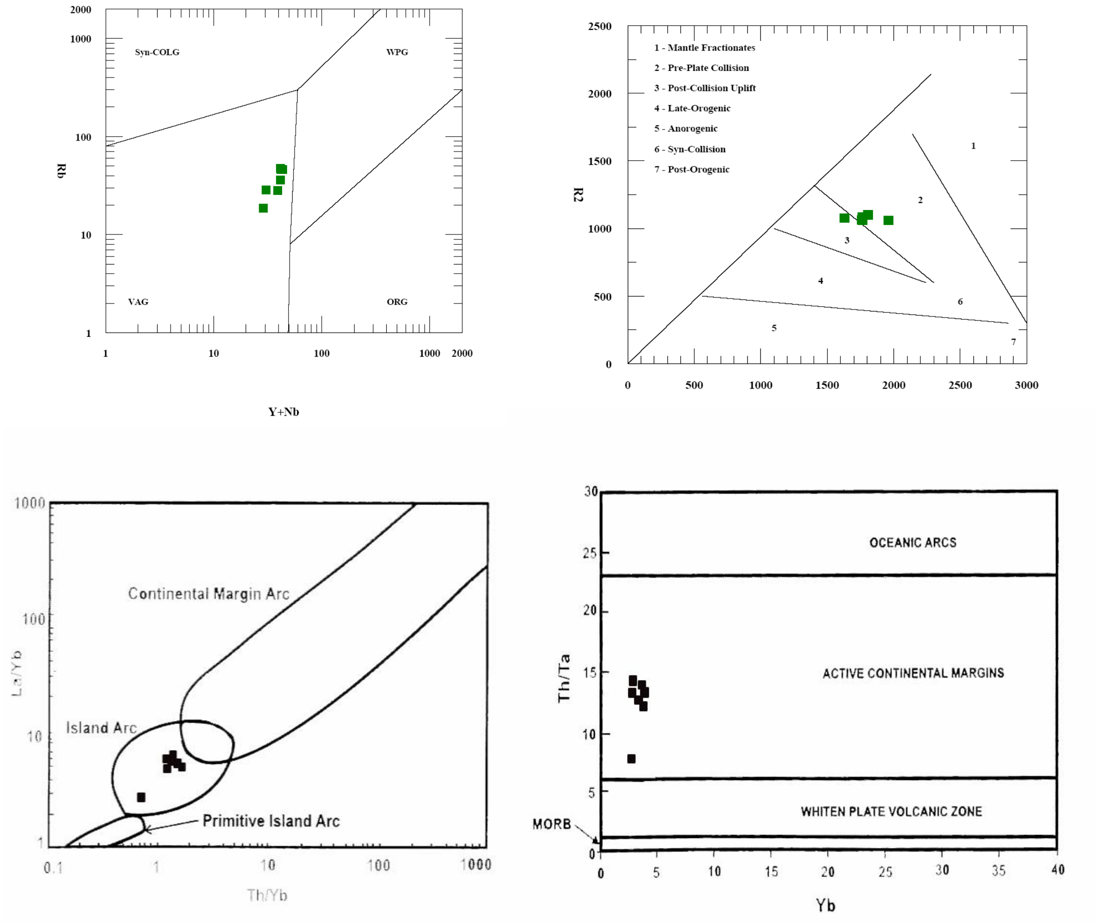

Fig. 6: Tectonomagmatic diagrams :(a) Rb vs. Y+Nb diagram (after [28] suggesting a volcanic arc setting for South Ardestan pluton. [COLG, syncollision granite; VAG, volcanic arc granite; WPG, within plate granite; ORG, ocean ridge granite]. (b) R1-R2 diagram shows that South Ardestan samples, plot mainly in the pre-plate collision field (c) La/Yb vs. Th/Yb diagram (after [11], (d) Th/Ta vs. Yb diagram (after [9]. All trace elements are in ppm

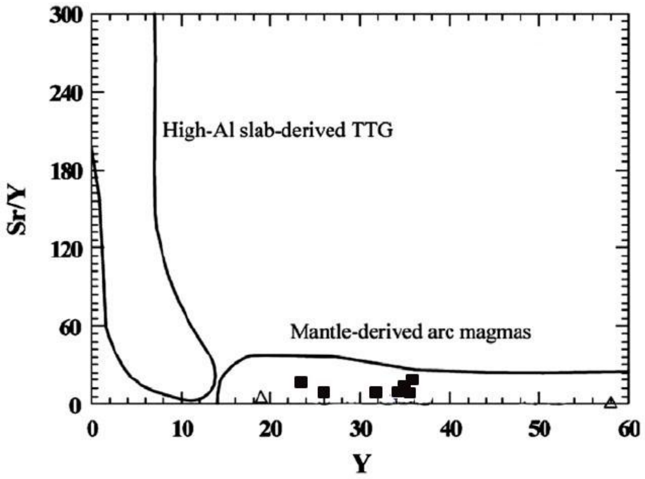

Fig. 7: Petrogenetic diagram of Sr/Y vs. Y.

A model of fractionation crystallization from a mafic parental magma may be possible in the South Ardestan granitoid. In order to evolve to a granodiorite from mantle-derived basic parental magma would require a prominent fractionation [14]. Low MgO concentrations of the samples of the felsic intrusion and other geochemical parameters rule out a direct derivation from mantle wedge. All these indicate a later and new parental melt for the felsic part rather than generation from the mafic rocks by fractional crystallization. This indicates necessity of an additional process in the generation of the felsic rocks. On the other hand, partial melts, particularly from tholeiitic basalts and to lesser extent calc-alkaline basaltic amphibolites, yield parent magmas that have lower K_2O and higher SiO2 contents, similar to South Ardestan granitoid rock. Their low Al2O3 (<18 wt %), low Sr contents, lack of any prominent Eu anomaly, flat to slightly LREE enrichment and flat HREE patterns suggest their formation at low pressure (65 k bar) and presence of plagioclase and lack of garnet as a residue in their genesis [29,7,33]. Experimental studies have shown that granitoid magmas were produced at different water fugacity during partial melting of basaltic compositions or an amphibolitic source and that water fugacity strongly influences melt composition and residuum mineralogy [36] and references there in). They stated that lithologic diversity among the granitoid is primarily the result of variable water fugacity during melting and variations in the water contents of mantle derived basalts may reflect variability in the amount of water given off by the subducted slab. Field and petrological observations (e.g., oscillatory zoning in plagioclase and presence of microgranular enclaves), low Rb/Sr values indicate that the sub-solvus South Ardestan granitoid evolved in an open system and that the magma mixing may also contribute to its generation, though its extent is unclear.

Experimental melts derived from partial melting of different crustal source rocks such as felsic pelites, metagreywackes, gneisses and amphibolites fall into distinct fields based on the major oxide ratios or molar ratios [26].

Conclusion:

The South Ardestan rocks belong to metaluminous, medium to high- K calc-alkaline series, and displays geochemical characteristics typical of volcanic arc granites related to an active continental margin. Two separate magmatic cycles have been identified. One is represented by diorites that form a part of the enclave population for which a primary origin from an enriched mantle source is proposed. The second cycle is more silicic. It is formed by Qtz-diorites and granodiorites, the most abundant rocks in the South Ardestan intrusion. An origin by partial or total melting of a composite source with amphibolites and sediments (subducted mélange) is proposed for this silicic magmatic cycle. Direct melting or fractionation from a diorite source is very unlikely. This granitoid magma involves partial melting of crustal protoliths and mantle-derived basaltic mamas emplaced into the lower crust. The South Ardestan granitoid has mineralogical field and geochemical characteristics typical of volcanic arc granites related to an active continental margin. Probably, the South Ardestan granitoid is the result of the subduction of Neo-Tethyan oceanic plate below the Lut micro continent and this oceanic residual plate during Mesozoic to Cenozoic time. Dehydration of subducted oceanic crust and partial melting of mantle wedge caused partial melting of subcontinental lithosphere, which resulted in the formation of metasomatised and enriched mafic arc magmas, and led to the formation of the South Ardestan granitoid stocks.

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