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Petrological and Geochemical Constraints in the Origin and Associated Mineralization of A-Type Granite Suite of the Dhiran Area, Northwestern Peninsular India

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Abstract Neoproterzoic, anorogenic, A-type granites of Dhiran area of Malani Igneous Suites is made up wholly of peralkaline-peraluminous alkali feldspar granites and is composed of K-feldspar, quartz, alkali amphibole, plagioclase, biotite and accessory minerals are iron oxides, monozite, zircon, apatite, and annite. This granitoid is associated with acid volcanic and minor basic volcanic-plutonic and dykes. Petrographically, they show cloudy, patchy perthitic texture and graphic texture. They are highly evolved ferroan, alkaline, A-type granites, displaying the typical geochemical characteristics of A-type granites with high SiO_2, Na_2O + K_2O, FeO*/MgO, Ga/Al, Zr, Nb, Ga, Y, Ce and rare earth elements (REE) and low CaO, MgO, Ba and Sr. Their trace and REE characteristics along with the use of various discrimination schemes revealed their correspondence to magmas derived from crustal origin. The extremely high Rb/Sr ratios combined with the obvious Sr, Ba, P, Ti and Eu depletions clearly indicate that these A-type granites were highly evolved and require advanced fractional crystallization in upper crustal conditions. These granites are high to medium content of radioactive element (U, Th, K) together Heat generation and Heat Production (HP). Leucocratic granites show higher Heat Production (4.84-8.75 μWm^{-3}) and total Heat Generation Unit (11.52-20.84 HGU) than pink granite (2.09-2.94 μWm^{-3} (HP), 4.98-7.07 HGU). The granites of the Dhiran area show higher average value of total Heat Generation Unit (16.51 HGU and 5.79 HGU) than the average value of 3.8 HGU for the continental crust. The high Heat Generation Unit values (4.98-20.84) of the Dhiran granites indicate 'hot crust' category and a possible linear relationship between the surface heat flow and crustal heat generation in the Malani Igneous Suite.

Keywords A-type, Alkaline, Anorogenic, Mineralization, Malani Igneous Suite

1. Introduction

Anorogenic, A-type granites are characterized by high SiO_2, Na_2O+K_2O, Fe/Mg, Ga/Al, Rb, Nb, Zr, Ta, Y, Cs, Ga, U, Th, REE (except Eu) and low abundances of MgO, CaO, $Mg^{\#}$, Ba, Sr, P, Ti, Ni, Cr, Co, V([1,2]). The presence of one or more of such ferromagnesian minerals as annite rich biotite, ferrohastingsite, alkali amphibole and Na–pyroxene ([3,4]) are typical for A-type granites. Many models have been proposed to the origin of A-type granitoids includes: 1. remelting of previously melted granulite source rock containing quartz – alkali feldspar – plagioclase ([1,2,5]); 2. partial melting of dehydrated charnockitic lower crust which formed as a residue from the earlier I-type magma, at temperature >900℃ in a subduction–related tectonic setting[4]; 3. dehydration melting of calc-alkaline granitoids([6,7]); 4. differentiation from mantle-derived basaltic magma[8,9]; 5. dehydration melting of amphibole-bearing tonalite at 6-10 Kbar leaving behind a granulitic residue, produce melts that resembles A–type granite, except for their somewhat high Al_2O_3 contents[10]; 6. small degree of partial melting of a felsic infracrustal source region, with water and F contents similar to those recorded in I-type granitoids source region[11]. The remelting residual source idea has been questioned([4,7,10,12]). Creasers et al.,[7] argued that residual source melting could not produce the characteristic major elements composition of A-type granites. Anderson,[6] suggested partial melting of tonalitic to granodiorite crust to form A-type granitic melts. Furthermore, Skjerlic and Johnston ([10,12]) suggested subsolidus dhydroxylation (OH-F) increase the stability of biotite in the lower crust to > 950℃ which upon melting causes F enrichment in the magma. On the other hands, Landenberger and Collins[4] suggested that the halogens (F, Cl) are not a major factor in A-type granite formation. A-type melts are considered to be anhydrous on account of characteristic occurrence of interstitial amphibole and/or biotite ([1,2]).

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The anhydrous nature of A-type granite, low abundance of Rb and fairly high Sr contents contradict the formation of A-type melts by anhydrous mineral fractionation from I-type magma[1]. A-type granites or alkaline, peralkaline and metaluminous-peralumi nous granitoids constitute a considerable volume of the Malani Igneous Suits (MIS) and they have attracted the interest of several researchers, indicating their important in crust formation and cratonization of the shield. Granitoids with chemical and mineralogical characteristics of A-type or within-plate granites as define for instance by Collins et al.,[1], Whalen et al.,[2] and Eby,[3] are quite common in the MIS. These intrusive are considered to represent anorogenic, A-type magma generated in rift related environment of high heat flow and abundant volatile activity, correlative with an extensional tectonic regime[13] and probably including melts generated from both upper mantle and lower crustal source. The purposed of present communication is to provide a detailed petrological and geochemical data on the A-type granite and associated mineralization around Dhiran, so as to infer their petrogenesis and tectonic setting.

2. Regional Geological Aspects

Malani Igneous Suits (MIS) is unique in the geological evolution of the Western Indian Shield as it is characterized by a major period of anorogenic, A-type, within plate, high heat producing (HHP) magmatism[14-20]. The Neoproterozoic MIS (55,000 Km^2; 750± 10Ma) comprising peralkaline (Siwana) metaluminous to mildly peralkaline (Jalor) and peraluminous (Tusham and Jhunjhunu) granites with cogenetic carapace of acid volcanic (welded tuff, trachyte explosion braccia and perlite) are characterized by volcano-plutonic ring structure and redial dykes. The suits is bimodal in nature with minor amounts of basalts, gabbro and dolerite dykes.

The Neoproterozoic magmatism in Western Peninsular India during Delhi Orogenesis led to the formation of intrusive Syntectonic Erinpura granite/ granodiorite (900 Ma)[21]. It is followed by late-tectonic granitoid plutonism of Mount Abu batholiths (800±50 Ma). The continuum of this acid magmatism culminated with outpour of bimodal volcanism and emplacement of A-type granites of MIS[22]. The MIS consists predominantly of acid volcano-plutonic rocks that are seen as scattered outcrops to the West of the Palaeoproterozoic to Mesoproterozoic Aravalli and Delhi Supergroup. Rocks of MIS are underlain by metasediments/granitoids of the Mesoproterozoic Delhi Supergroup and unconformably overlain either by Pokharan boulder bed of glacial origin of Vendian age (680 to 580Ma) or by sediments of Marwar Supergroup (Vendian to Lower Cambrian)[23]. Kochhar,[24] established a close association in space and time between the explosive acid lava and high-level granite that form distinct ring structure and radial dyke. The volcanic-plutonic rocks association of MIS has three episodes of igneous activity[25], the first episode represent by widespread acid and basic lava flows covering about 31,000 sq. km. of MIS. It was followed by a major plutonic activity that comprises discordant plutons, bosses and ring dykes of granite whereas the last stage includes emplacement of acid and basic dyke swarms. The preponderance of acid volcanic rocks relative to intermediate and basic rocks is a distinctive feature of MIS.

Dhiran area is located between longitude 72° 17’ E to 72° 30' E and latitude 25° 27’ N to 25°31’ N in the Northwestern Peninsular India. The area is predominantly occupied (90%) by rhyolite rocks. The area is characterized by A-type granite with cogenetic carapace of acid volcanics and with minor amount of basalt, gabbro and dolerite dyke (Fig. 1). Based on detailed geological mapping and position of xenoliths, Dhiran area is established that extrusive phase (trachyte, rhyolite, welded tuff, basalt) was followed by the intrusive phase (alkali granite) and the magmatic activity was culminated by the dyke phase (Dolerite, rhyolite, microgranite).

The granites are leucocratic, pink in colour, fine to medium grained and show incrustation of iron oxide. The dark pink medium grained granite show altered (cloudy appearance) alkali feldspar with white rim, pink tint (alteration of orthoclase). The cloudiness of alkali feldspar has been reported in many Scottish Caledonian intrusive[26] and in Nigeria Younger Granite[27] as well as from the granites of Dhiran area in MIS which illustrates the post - magmatic fluid interaction. The cross-cutting of granites by numerous quartz veins with iron oxides strain or fluorine incrustation, aplite knots and numerous pegmatite veins indicates the presence of aqueous fluids that are responsible for enrichment of rare metals[28]. Close association of felsic volcanic rocks (rhyolite, trachyte) with granites, mafic volcanic (basalt) and plutonic (gabbro) rocks indicates an interrelationship between the volcanism and plutonism.

3. Petrography

The pink granite consist essential of quartz, K-feldspar (perthite, orthoclase), arfvedsonite, aegirine, riebeckite, aenigmatite, plagioclase and accessory minerals are hematite, ilminite, zircon, annite, apatite, monazite and rutile. Whereas leucocratic granite contains quartz, K-feldspar (perthite, microcline), albite, biotite, muscovite as major phase and minor phase are apatite, zircon, magnetite, hematite, ilmenite and annite. Hypidiomorphic, granophyric and micrograno-phyric textures are preserved in these granites. Quartz shows wavy extinction and occurs as micro-granophyric intergrowth and in the groundmass. Perthites are characterized by cloudy, patchy, incoherent and extensive coarsening nature due to feldspar-fluid interaction at subsolidus temperature ([29,30]) that leads to the replacement of albite at the margin of the perthite, which appears as whitish on turbid portions at the crystal margins or along cracks and cleavages. At place, minute mica flakes are also observable along the margins of perthite as post-magmatic phases due to accumulation of residual fluid. Orthoclase is medium grained, subhedral and shows carlsbad twinning. The arfvedsonite is prismatic in shape, dark green coloured and pleochroic (X=dark bluish green; Y= bluish green; Z= yellowish green) with an extinction angle (X^C) of 13-15°. Short prismatic aegirine shows pleochroism (X= dark green, Y= light green, Z= yellow green) with an extinction angle (X^C) 4-7°. Whereas riebeckite shows pleochroism (X=light blue: Y= blue: Z= dark blue) with an extinction angle (X^C) of 3-5°. Subhedral crystals of bright green colour aegirine are also present along the perthite with groundmass. Albite occurs as lath shaped crystal that exhibit polysynthetic twinning. Biotite is strongly pleochroic (X= yellowish brown: Y= reddish brown: Z= olive green) with corroded and partly or fully resorbed. It also contains pleochrole haloes around minute zircon crystals. Magnetite occurs as anhedral isotropic mineral in the groundmass and inclusion in perthite and quartz. Hematite is subhedral and reddish brown in colour whereas ilmenite is fine grained and silver grey in colour. Both hematite and ilmenite occur in feldspar phenocrysts and in the groundmass as well. Monozite occurs as light yellow fine crystal in the groundmass. In the alkali feldspar-quartz-plagioclase feldspar diagram (Fig. 2), both the granites (leucocratic granite and pink granite) are shown as alkali feldspar granite in nature.

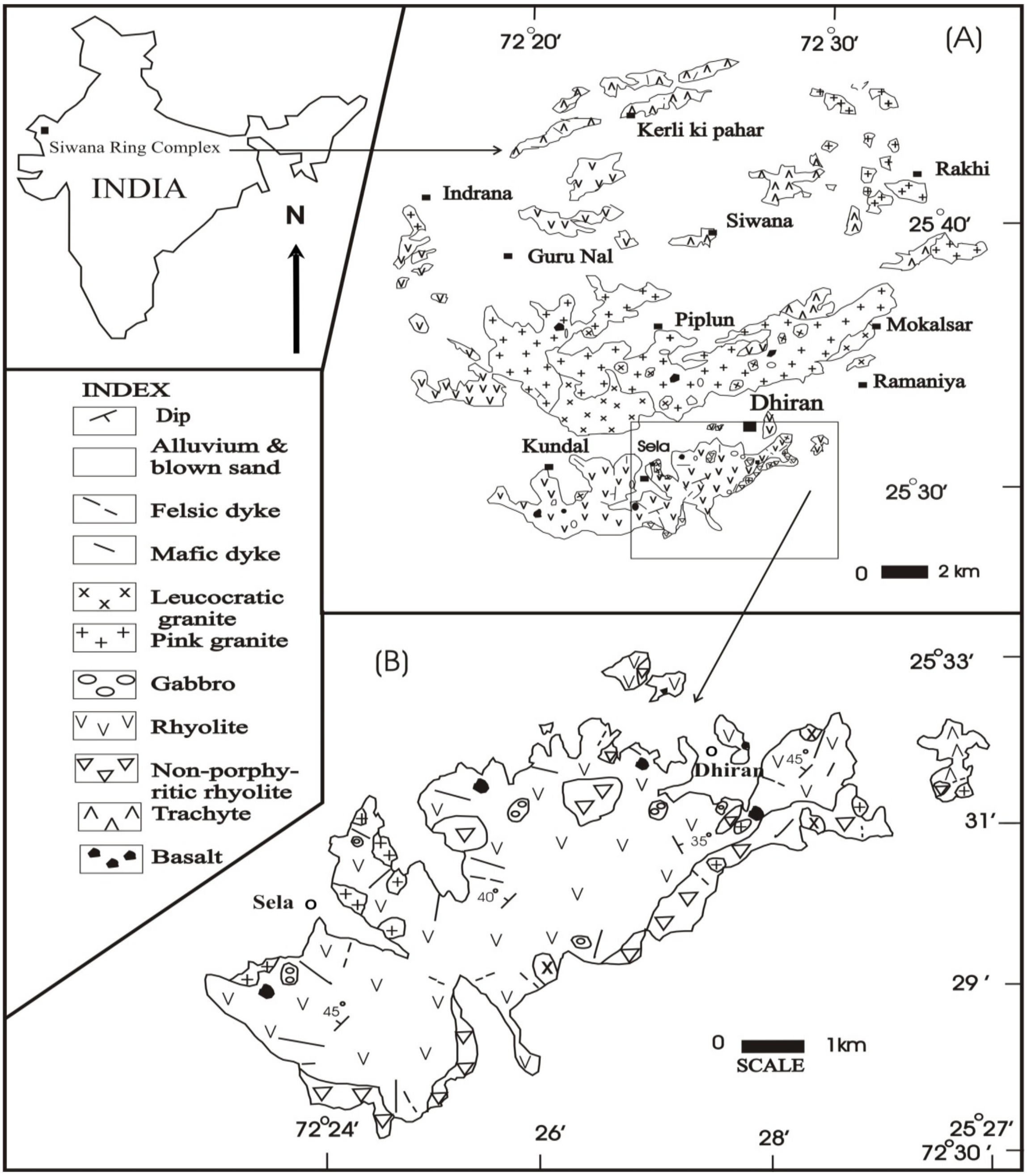

Figure 1. A. Geological Map of Siwana Ring Complex, Malani Igneous Suites (MIS). B. Simplified lithological Map of Dhiran Area

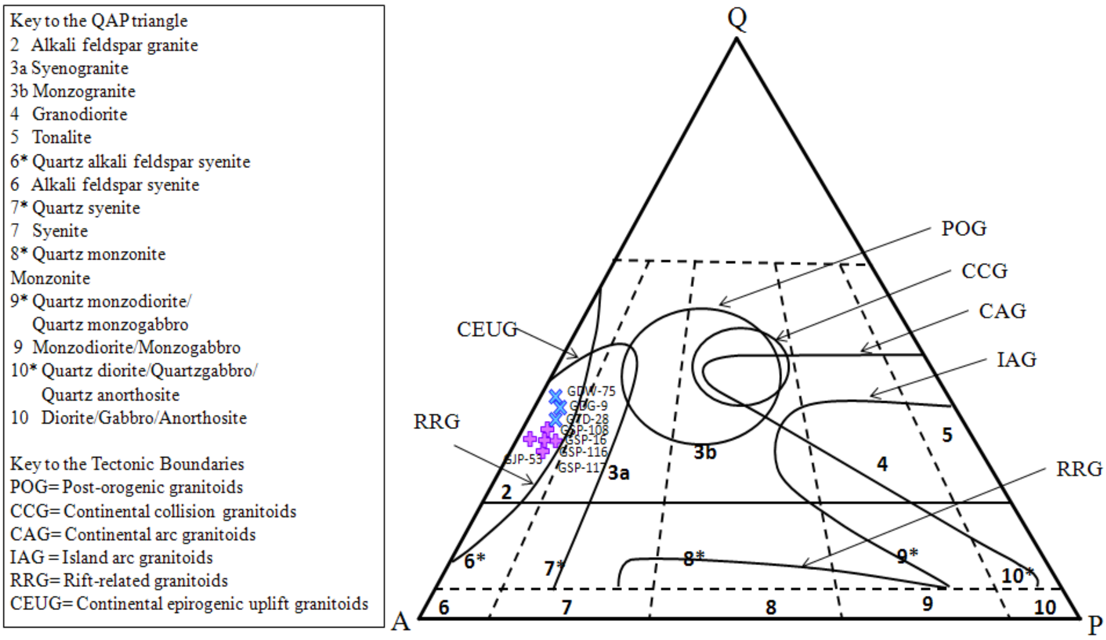

Figure 2. Plots of granites samples on the QAP diagram[31]. Zones of tectonic environments are after Maniar and Piccoli[32]. Symbols: Pink granite ( ) and Leucocratic granite ( )

Moreover, among the tectonic discrimination boundaries adopted by Maniar and Piccoli,[32] on the QAP diagram, they fall in the Anorogenic granites field rift-related granitoids (RRG) and continental epirogenic uplift granitoids (CEUG).

4. Geochemistry

The rocks chemistry of major, trace and REE elements analyses was carried out on Atomic Absorption Spectrophotometry (AAS), Department of Geology, Kurukshetra University Kurukshetra, Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES), School of Environmental Sciences Jawaharlal Nehru University, New Delhi and Inductively Coupled Plasma Emission Mass-spectrometry (ICP-MS), National Geophysical Research Institute (NGRI), Hyderabad. The discrimination and correlation diagram are plotted to characterize each granite type and to discuss the petrogenesis and mineralization of the granites from the study area.

4.1 Major, Trace and REE Element Classification

The result of the chemical analyses are given in the tables 1A, 1B and 1C. Both the granite samples from the Dhiran area are remarkable homogeneous with respect to both major and trace element geochemistry. The analysed rocks show a restricted range in chemical composition. The concentration of SiO_2 in the Pink granite are low SiO_2 (65.85-69.90) and high total iron (5.48-8.39) as compared to leucocratic granites: SiO_2 (73.89-77.74) and total iron (1.10-5.06). The average values of Al_2O_3, TiO_2, Na_2O, K_2O, CaO, MgO and P_2O_5 of the pink granites are 12.49, 0.79, 4.48, 4.96, 1.02, 0.27 and 0.20 which are comparatively same as Leucocratic granites: 12.19, 0.26, 3.60, 4.02, 0.71, 0.12 and 0.01 respectively. Both the granites ranges from peralkaline[(acmite normative >1); Agpaitic Index (AI= molecular portion of Na_2O+K_2O/Al_2O_3) and alumina saturation index (A/CNK = molecular $Al_2O_3/Na_2O + K_2O + CaO$) ratio < 1] peraluminous (corundum and anorthite normative ; AI >1) (Fig. 3). Further, the widely used SiO_2 vs K_2O diagram[33] classify most of the samples as high-K rocks, with exceptional few samples belong to the shoshonite series (Fig. 4). Their very low contents of CaO, MgO with Fe/Mg ratios and AI values signify alkali affinity of these granites[34]. These magmatic rocks attained very high content of sodium and iron as well as strongly depleted in alumina along with calcium and magnesium in their final stages of magmatic and subsolidus processes. Hence, the nature of these low alumina A-type rocks appeared to have been formed under the control of alkali-alumina relationship as evident from this textural and mineralogical data ([35,36]). Dhiran peralkaline and peraluminous granites plots in the normative of Qz – Ab – Or ternary diagram[6]. In this diagram (Fig. 5) peralkaline granites falls varies 5kb to more than 10kb pressure and peraluminous granites lies vary < 2kb to 4kb pressure. It is suggested that the peralkaline granites are emplaced at greater depth (16 – 35 km and 480°C - 840°C) and more fluorine content. Thus, Dhiran peralkaline granites are generated at a greater depth than the peraluminous granite. The geochemical nature of the studied A-type granites are critically tested using the standard common schemes as well as the recently adopted three-tiered geochemical classification scheme of granites rocks[37]. As the extreme Fe*O enrichment relative to MgO (high FeO*/MgO) is a typical signature of A-type granitoids (Fig. 6), all the present granite samples are grouped as ferroan A-type granite (Fig. 7) and on the Fe* {FeO*/(FeO+MgO)} vs SiO_2 diagram[37].

Table 1A. A. Major elements concentration and CIPW norms of the Dhiran granites, Malani Igneous Suite, Northwestern Peninsular India

Rock Type	Pink Granite									Leucocratic Granite				
Sample No.	**GSP1 7**	**GSP1 08**	**GSP1 16**	**GSP1 17**	**GTP1 07**	**GTP1 09**	**GTP1 10**	**GJP 53**	**GKP1 11**	**GD G8**	**GWD 75**	**GDG 10**	**GPT 28**	**GDP 29**
Major elements (wt.%)														
SiO_2	67.07	68.69	68.01	65.85	66.84	67.42	69.90	67.81	69.32	74.17	73.89	74.02	76.32	77.74
TiO_2	0.96	0.62	0.68	0.83	0.88	0.96	0.69	0.93	0.58	0.39	0.30	0.40	0.13	0.16
Al_2O_3	13.12	12.04	11.55	13.01	12.14	12.52	12.11	12.93	13.04	12.75	13.59	12.54	10.67	11.40
FeO*	6.53	8.39	7.65	7.74	7.59	5.48	5.03	6.96	5.57	5.06	2.72	3.62	1.10	2.44
MnO	0.24	0.13	0.30	0.14	0.17	0.19	0.17	0.18	0.08	0.07	0.17	0.09	0.01	0.01
MgO	0.12	0.36	0.31	0.24	0.20	0.24	0.12	0.27	0.63	0.02	0.18	0.05	0.19	0.16
CaO	0.85	0.35	1.02	0.67	1.15	1.40	1.58	0.78	1.46	0.59	0.68	0.80	0.71	0.78
Na_2O	4.80	3.99	4.54	4.35	4.66	5.09	4.46	4.30	4.20	3.29	3.35	3.64	4.10	3.66
K_2O	5.45	4.45	4.67	5.14	4.76	5.62	4.65	5.36	4.56	3.52	3.69	4.04	5.17	3.32
P_2O_5	0.18	0.01	0.18	0.12	0.17	0.22	0.45	0.14	0.35	0.01	0.01	0.01	0.01	0.01
H_2O	0.54	1.16	1.18	1.09	0.98	0.67	0.91	0.41	0.25	0.12	0.35	0.38	0.42	0.23
Total	**99.86**	**99.69**	**99.79**	**99.18**	**99.54**	**99.81**	**100.07**	**100.08**	**100.04**	**99.99**	**98.93**	**99.59**	**98.83**	**99.91**
Quartz	18.25	27.19	23.58	19.80	21.03	7.04	25.23	21.21	26.73	40.30	38.59	35.63	35.34	41.86
Orthoclase	32.21	26.30	27.60	30.37	28.13	33.21	27.48	31.67	26.95	20.80	21.81	23.87	30.55	19.62
Albite	37.14	33.76	33.41	36.81	35.94	33.11	36.40	36.39	35.54	27.84	28.35	30.80	26.10	30.97
Anorthite	--	1.67	--	0.79	--	--	--	0.15	3.26	2.86	3.31	3.90	--	3.80
Corundum	--	0.05	--	--	--	--	--	--	--	2.48	2.87	0.75	--	0.39
Acmite	3.06	--	4.41	--	3.07	8.77	1.18	--	--	--	--	--	3.18	--
Diopsite	0.50	--	1.67	--	1.07	1.29	0.64	0.21	--	--	--	--	1.02	--
Hyper-sthene	0.07	0.90	--	0.60	--	--	--	0.57	1.57	0.05	0.45	0.12	0.27	0.40
Wollas-tonite	--	--	0.73	--	0.34	0.52	0.97	--	--	--	--	--	0.72	--
Magnetite	--	--	0.46	--	--	--	--	--	--	--	--	--	--	--
Illmenite	0.51	0.06	0.34	0.30	0.36	0.41	0.36	0.39	0.17	0.15	0.36	0.19	0.02	0.02
Hematite	5.47	8.39	5.81	7.74	6.53	2.45	4.62	6.96	3.57	5.56	2.72	3.62	--	2.44
Apatite	0.42	0.02	0.42	0.28	0.39	0.51	1.04	0.32	0.81	0.02	0.02	0.02	0.02	0.02
Sphene	1.69	--	--	1.23	1.69	1.83	1.22	1.78	1.20	--	--	--	0.29	--
Rutite	--	0.11	--	0.22	--	--	--	--	--	0.40	0.14	0.38	--	0.19
DI	87.60	87.25	84.59	86.98	85.10	83.36	89.11	89.27	89.22	88.94	88.75	90.30	91.94	92.45
AI	1.05	0.95	1.08	0.98	1.06	1.07	1.02	0.99	0.91	0.72	0.69	0.83	1.15	0.84
(Na+K)	10.25	8.44	9.21	9.49	9.42	10.71	9.11	9.66	8.76	6.81	7.04	7.68	9.27	6.98
(Na/K)	0.88	0.89	0.97	0.85	0.98	0.91	0.95	0.80	0.91	0.93	0.90	0.90	0.79	1.10
KN/C	12.05	24.35	9.02	14.16	8.19	7.65	5.76	12.38	6.00	11.54	10.53	9.60	13.79	8.95
A/CNK	0.84	1.00	0.80	0.93	0.81	0.74	0.79	0.90	0.89	1.23	1.27	1.06	0.78	1.04
An/An+Ab	--	0.04	--	0.02	--	--	--	0.01	0.08	0.09	0.10	0.11	--	0.10

Table 1B. Trace and REE concentration of granites from Dhiran Area, Malani Igneous Suite Northwestern Peninsular India

	Pink Granite			Leucocratic Granite		
SAMPLE	GSP17	GTP109	GJP53	GWD75	GDG10	GDT28
Sc	4.499	5.94	4.86	3.603	1.591	1.693
V	4.246	2.509	10.518	7.324	4.129	3.829
Cr	1.07	1.335	2.289	50.308	2.061	3.203
Co	1.71	1.258	2.838	0.564	0.396	0.327
Ni	0.38	0.31	1.871	1.377	1.462	1.21
Cu	0.478	0.313	0.692	0.561	0.534	0.465
Zn	47.988	44.01	22.455	19.403	27.334	11.601
Ga	57.603	46.878	40.135	39.51	39.86	22.398
Rb	92.557	115.618	89.317	411.307	319.025	250.622
Sr	17.262	19.781	37.922	19.193	12.758	15.599
Y	259.235	217.849	236.226	542.545	365.974	164.131
Zr	1181.96	1138.81	3064.338	6568.279	4355.924	312.666
Nb	80.465	81.744	95.523	156.255	108.241	29.768
Cs	1.198	7.767	0.672	2.468	2.314	12.956
Ba	233.473	278.078	161.361	29.933	27.625	35.999
Hf	33.603	31.346	35.927	79.683	56.781	11.574
Ta	3.881	3.935	5.699	2.031	5.486	2.198
Pb	11.298	17.244	30.646	131.22	49.939	34.164
Th	11.925	11.381	18.123	67.623	51.145	31.286
U	3.603	3.16	4.75	13.829	12.249	3.475
La	106.598	110.455	140.097	261.698	226.782	128.431
Ce	281.117	262.634	344.405	690.733	488.914	147.259
Pr	35.407	33.381	42.594	66.802	59.642	32.815
Nd	157.301	145.115	186.342	270.023	242.028	139.736
Sm	37.423	32.399	41.793	62.493	52.559	31.709
Eu	4.816	3.696	3.095	2.492	2.066	0.492
Gd	32.961	28.569	34.171	53.611	44.287	25.387
Tb	6.331	5.443	6.252	10.851	8.335	4.404
Dy	44.781	38.031	43.901	81.941	61.49	29.691
Ho	5.262	4.388	4.802	9.479	7.033	3.252
Er	17.304	14.667	16.169	33.176	24.076	10.982
Tm	2.273	1.897	2.147	4.529	3.206	1.445

Table 1C. Radioelements, Heat Production and radioactive Heat Generation Unit data of granites from Dhiran area, Malani Igneous Suites, Northwestern Peninsular India

Sample No	U (ppm)	Th (ppm)	K (%)	Th/U	Ur	Heat Generation (HGU) due to			Total HGU	HP (μWm^{-3})
						U	Th	K		
GWD75	13.829	67.62	3.06	4.89	53.76	8.61	11.52	0.7	20.84	8.75
GDG10	12.25	51.15	3.65	4.18	45.12	7.63	8.71	0.84	17.18	7.22
GDT28	8.47	31.29	4.3	3.75	32.59	5.26	5.33	0.99	11.52	4.84
GSP17	3.603	11.93	4.52	3.13	18.61	2.24	2.03	1.04	5.32	2.23
GTP109	3.16	11.38	4.67	3.6	18.19	1.97	1.94	1.07	4.98	2.09
GJP53	4.75	18.12	4.44	3.82	22.69	2.96	3.09	1.02	7.07	2.97

Ur= Radioelement concentration; HP= Heat Production; HGU= Heat Generation Unit

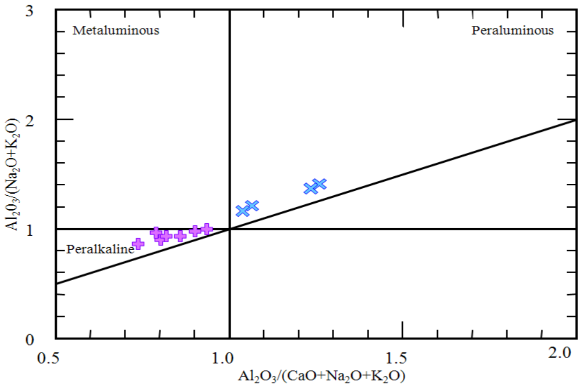

Figure 3. $Al_2O_3/(CaO+Na_2O+K_2O)$ vs $Al_2O_3/(Na_2O+K_2O)$ diagram[32] showing the fields of Dhiran granites

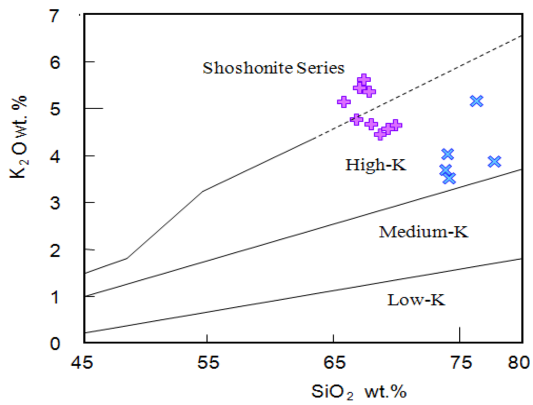

Figure 4. SiO_2 vs K_2O diagram with field after Rickwood[33]

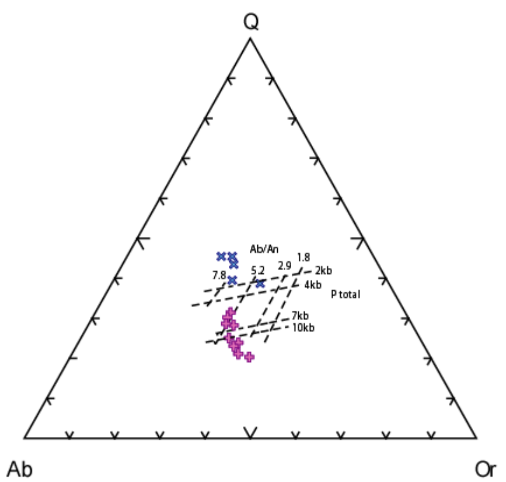

Figure 5. Normative Quartz – Albite – Orthoclase of Dhiran granites and composition to experimental minimum melt composition. Minimum melt experimental grid after Anderson,[6]

Projection of our samples on Frost et al.[37] modified alkali-lime index (Na_2O+K_2O-CaO) vs. SiO_2 diagram plot, the pink granites are in the alkalic field and leucocratic granites are in the alkali-calcic field (Fig. 8). Because of granitoids can contrast from corundum normative (Al_2O_3 oversaturated) to acmite normative (Al_2O_3 critically undersaturated), alumina saturation appears to be the most important criterion in classification of granitoids. Fig. 3 reveals that the studied A-type granites are peralkaline to peraluminous. Peralkaline samples are acmite and Na_2SiO_3 normative and have A/CNK values less than one. Peraluminous A-type granites are corundum normative and have A/CNK ratios greater than one. The major and trace elements geochemistry of igneous rocks bear a close relationship to their tectonic setting of formation.

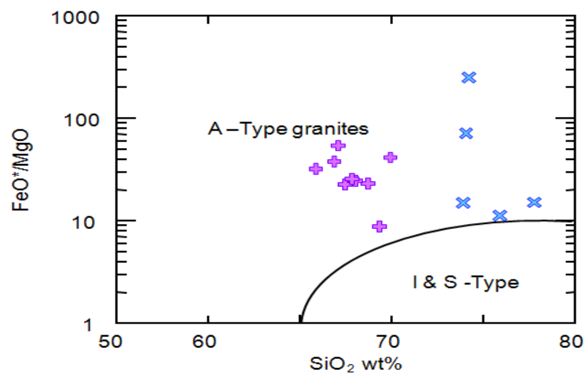

Figure 6. Plots of Dhiran granites on SiO_2 vs FeO*/MgO diagram[3]. Note that A-type granites are characterized by higher Fe*/MgO ratios compared with other granitoid types

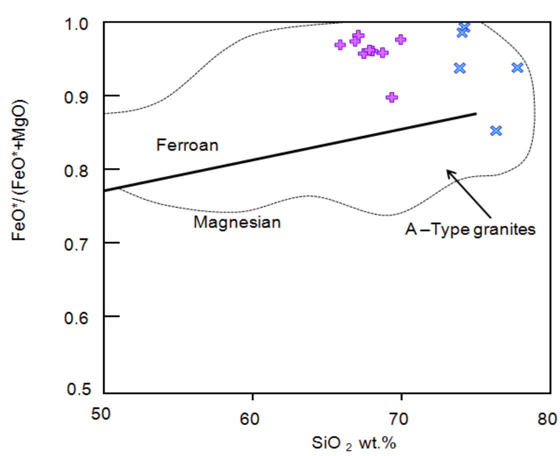

Figure 7. Chemical classification of Dhiran granites using FeO*/(FeO+MgO) vs SiO_2 diagram

According to Maniar and Piccoli's,[32] granitoids tectonic classification scheme based on major elements (SiO_2 vs Al_2O_3 diagram (Fig. 9), the studied A-type granitoid rocks are classified as anorogenic granites (CEUG and RRG). All the sample are assigned to a within-plate tectonic environment (Fig. 10). In the R1 – R2 diagram (Fig. 10) majority of the samples are also plotted in the anorogenic field, suggesting their emplacement in a within-plate tectonic setting. The prominent peralkaline and alkaline nature of the studied granitoids are consistent with their affiliation to extensional environments[38]. The Rb/Sr vs K/Rb diagram (Fig. 11) was found to be a useful discriminent between orogenic and anorogenic granites[39]. According to this diagram Dhiran granites are plots in the anorogenic field. Use of the popular Pearce et al.,[40] trace element discrimination diagrams (Fig. 12 and Fig. 13), for tectonic interpretation of granites rocks (Y vs Nb and Y+Nb vs Rb), all samples were plotted in both diagrams in WPG, as well in the field of A-type granites in the Y vs Nb diagram, delineated by Stern and Gottfried[41]. These granites are low in Mg# (Mg/Mg+Fe^t cation mole percent), MgO, FeO*, CaO, Sr and high SiO_2, Na_2O, K_2O, Fe/Mg, Y and show both the LREE and HREE enriched patterns with large negative Eu anomalies as common in A-type granitiods ([1,2,43]).

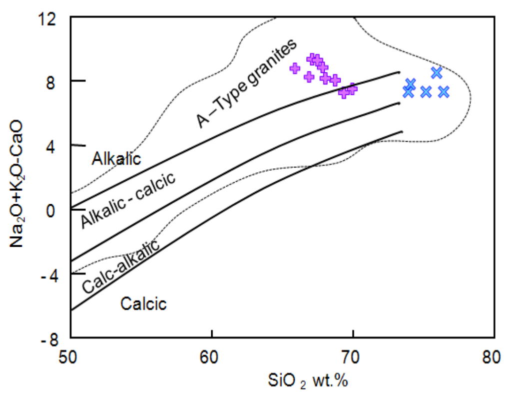

Figure 8. Chemical classification of Dhiran granites using Na_2O+K_2O-CaO vs SiO_2 diagram

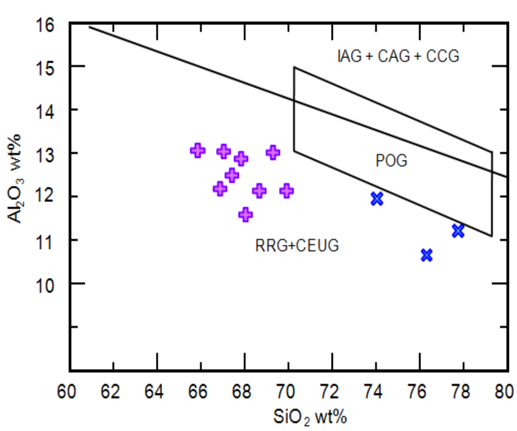

Figure 9. SiO_2 vs Al_2O_3 diagram[32]. Dhiran granites plots in the RRG+CEUG field. IAG= Island arc granitoids, CAG= Continental arc granitoids, CCG= Continental collision granitoids, POG= Post orogenic granitoids, RRG= Rift related granitoids and CEUG= Continental Epeirogenic uplift granitoids

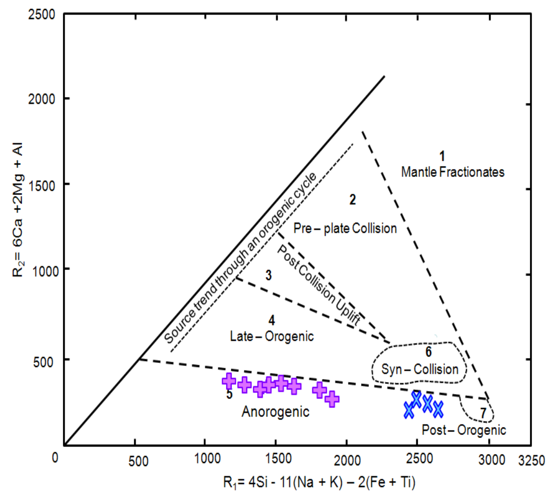

Figure 10. R_1-R_2[4Si - 11(Na + K) – 2(Fe + Ti) vs (6Ca + 2Mg + Al)] Diagram[42]

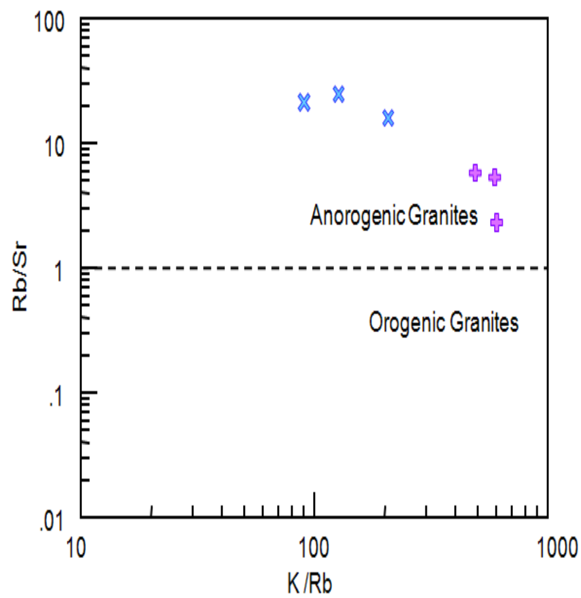

Figure 11. K/Rb vs. Rb/Sr diagram showing that all the data points of the present A-type granites exhibit Rb/Sr ratios higher than one similar to anorogenic granites, whereas the orogenic calc-alkaline granites are characterized by lower ratios[39]

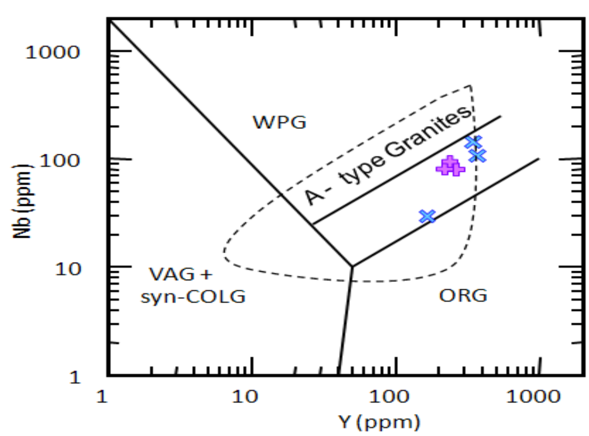

Figure 12. Plots of Dhiran granites on the tectonic discrimination diagram Nb vs Y of Pearce et al.,[40]. Field of A-type granites in the Nb vs Y diagram is after Stern and Gottfried,[41]

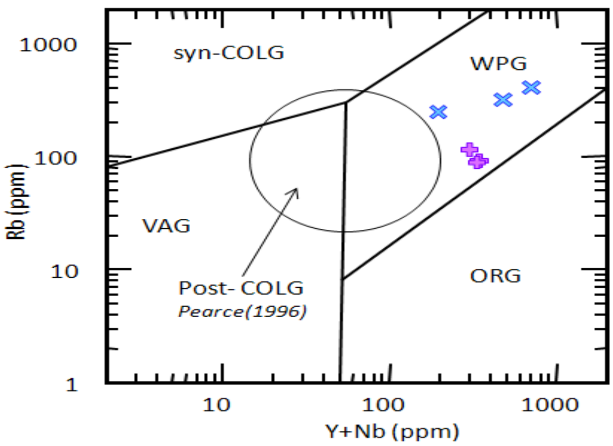

Figure 13. Plots of Dhiran granites on the tectonic discrimination diagram Rb vs (Y+Nb) of Pearce et al.,[40]. Field of post-COLG in the Rb vs (Y+Nb) diagram is adopted by Pearce ,[52]

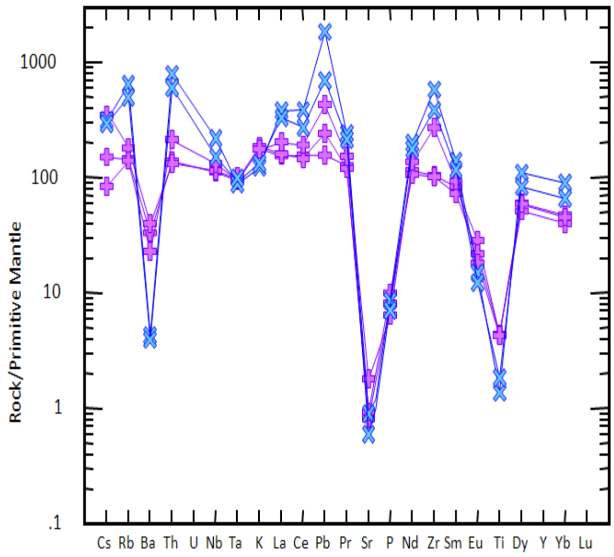

Figure 14. Primitive mantle-normalized multielement patterns for Dhiran granites. Normalization values are from Sun and McDonough,[53]

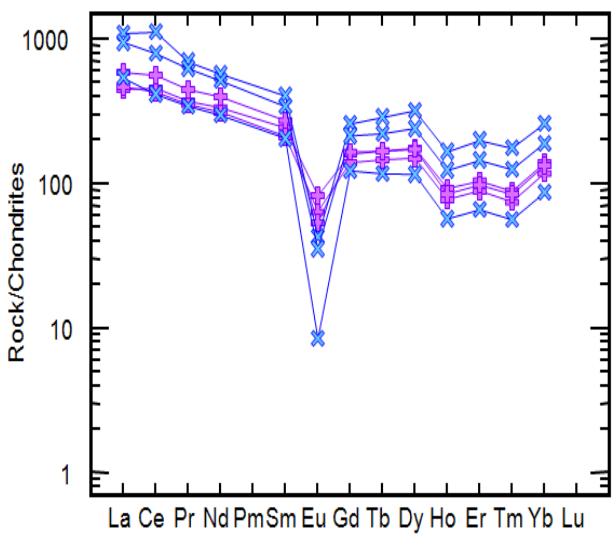

Figure 15. Condrite-normalized multielement patterns for Dhiran granites. Normalization values are from Sun and McDonough[53]

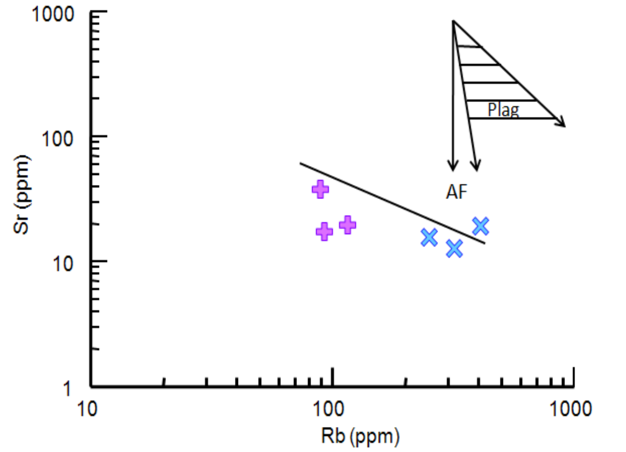

Figure 16. Rb vs Sr diagram. The fractional evolution of the plagioclase and alkali feldspar is after Arth,[54]

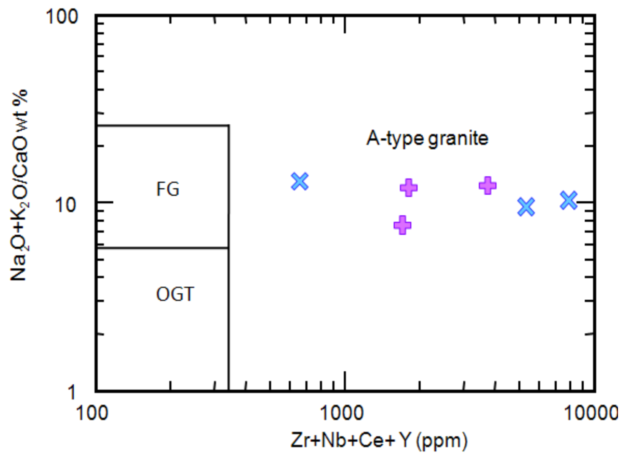

Figure 17. Zr+Nb+Ce+Y vs Na_2O +K_2O/CaO diagram[2]. FG= Field for fractionated I-type granitoids. OGT= Field for I, S and M- type granitoids

The trace element aboundances of granites are comparable to those of typical anorogenic granite. They are characterized by high concentration of Rb, Nb, Zr, Ga, Y, Hf, Th, U and prominent Eu anomalies with moderate LREE enrichment and flat HREE patterns (Fig. 14). Spidergrams show similar characteristics to those of pink granite and leucocratic granite with negative Ba, Sr, P and Ti anomalies, indicating either the retention of plagioclase and accessory minerals in the source during partial melting or their separation during fractionation (Fig. 15). However, these rocks show high Zr contents and have poor zircon yield, reflecting its high solubility in the alkaline magma ([44,45]). In the diagram Rb vs Sr (Fig. 16) and diagram indicates feldspar fractionation crystallization with minor plagioclase during the evolution of these rocks. The feldspar fractionated nature of the granitoids is indicated by the low Sr content and the negative Eu anomaly, suggesting plagioclase fractionation plays an important role in the evolution of A-type magmatism[46]. The granites are high in SiO_2, Fe_2O_3(t), Na_2O+K_2O, Zr, Hf, Th, U, Nb, Ta, Y, REE, HPU, Rb/Sr, Zr/Rb values and low in CaO, MgO, Ba, Sr, Sc, Ba/Rb, TiO_2/Ta values, suggesting their crustal origin ([19,20,47-50]). It also supported by their high Nb, Zr, Y and low Ti contents, characteristic of acid magmas generated within-plate tectonic environment[51].

Enrichment in the high field strength (HFS) elements is a characteristic feature of alkaline A-type granites in general. The high enrichment of these elements in the investigated granites confirm their A-type identity and exclude them from other granite type on the (Zr+Nb+Ce+Y) vs (Na_2O+K_2O)/CaO diagram (Fig. 17). All the granites samples lay away from Sr and arrange parallel to the Ba-Rb side in the Ba-Rb-Sr ternary diagram (Fig.18). The relation between Ba, Sr and Rb could be used in tracing differentiation trends in acid suites. Based on the distribution fields and evolution paths of El Bouseily and El Sokkary,[55], it is evident that all the studies samples plots in the strongly differentiated granites and normal granites field.

5. Mineralization and Radioactive Element Distribution

Presence of long lived isotopes of radioactive elements (U, Th, K) causes heat generation in the crust and their content are significant in understanding the nature of source magma and its mineralization. The radiogenic heat thus produced in the surface rocks play a significant role in the continental heat flow. Mineralization associated with A-type granite includes Sn, Mo, Ba, Nb, W, Ta, F, Be, Li, and REE ([1],[56]). The largest deposits of Nb, Ta, Zr, Hf, Sr, Al, P, REE etc. are associated with alkaline magmatism [57]. Biste,[58] described the mineralized granites as containing relatively higher Rb/Sr, Li x 10^{-3}/K and Ba/Sr ratios and Zr and lower values of K/Rb, Ba/Rb, Mg/Li and Zr/Sn. The granites of Dhiran area of MIS are enriched in Rb, Nb, Y, Zr, Ta, U, Th, Hf, Pb and REE and depleted in Sr, Ba and Ti. The enrichment of Zr, Nb and high Zr/Rb ratio in the rocks indicate Nb-Sn-W mineralization ([14],[59]). High Rb/Sr ratio and low Ba/Rb ratio in granitoids indicate post magmatic and Sn-Nb mineralization[60]. Leucocratic granite have more concentration of Y(164.13-542.55ppm), Zr (312.67-6568.28ppm), Nb (29.77-156.26ppm), Hf (11.57-79.68ppm), Pb (34.16-131.22ppm), Th (31.29-67.62ppm), U (3.47-13.83), La (128.43-261.70ppm), Ce (147.26-690.73ppm), and Nd (139.74-270.02ppm) than Pink granites: Y (217.85-259.23ppm), Zr (1138.81- 3064.34ppm), Nb (80.47-95.52ppm), Hf (31.34-35.93ppm), Pb (11.30-30.65ppm), Th (11.93-18.12ppm), U (3.16-4.75ppm), La (106.60-140.09ppm), Ce (262.63-344.41ppm) and Nd (145.12-186.34ppm). High contents of Ba, Pb, Th, U, LREE and Zr in the leucocratic granite are possibly due to its notable contents of radioactive minerals such as Zircon, apatite and monazite. The concentration of Y in leucocratic granites (164.13-542.55ppm) and pink granites (217.85-259.23ppm) is much higher than the quoted average value of 40ppm for normal granites[61]. Anomalous Zr content is found in both the granites, 312.67-6568.28ppm for leucocratic granites and 1138.81-3064.34ppm, for pink granites. The Zr enrichment trend is accompanied by enhance U and Nd associated with Nd-Sn-W mineralization[62-64] have reported variable amount of Zr (20 and 300ppm) in the Sr-W-Mo-Cu related granitoids of the Australia and range granitoids of Malaysia respectively. Ga concentration is more in the pink granites (40.14-57.60ppm) than leucocratic granites (22.39-39.86ppm). The concentration of Pb in both the granites (34.16-131.22ppm and 11.30-30.65ppm) are much higher than the quoted average abundance of 20ppm Pb for normal granites[61]. Sn- bearing or productive granitoids contains Pb>15ppm whereas the Sn-barren or non productive granitoids has Pb<5ppm. A-type anorogenic granites that are emplaced along rift zones or major lineaments characterized by high contents of Ga, Y, REE and Nb, with notable depletion of Ba, Ti, P[65].

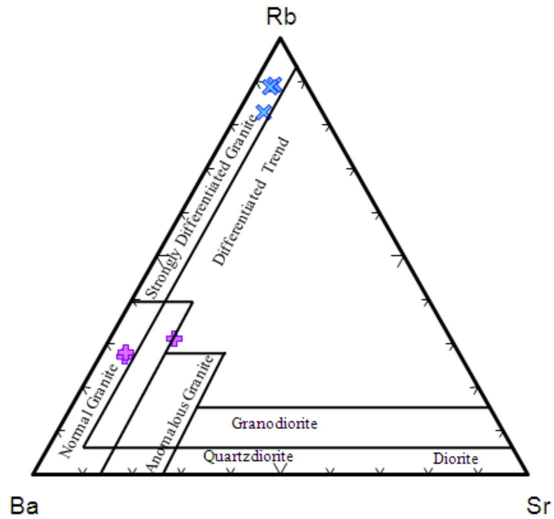

Figure 18. Ba-Rb-Sr ternary diagram for studied granites. Compositional fields and differentiation trends are after El Bouseily and El Sokkary,[55]

In these Granites viz. leucocratic granite generate higher value of Ur= 32.59-53.76; HP= 4.84-8.75 μWm^{-3}; HGU= 11.52-20.84 than pink granite (Ur= 18.19-22.69; HP= 2.09-2.976 μWm^{-3}; HGU= 4.98-7.07). The average concentration of U and Th of the granites of the Dhiran area significantly higher (upto 3 times than the world concentration of 4ppm for U and 18ppm for Th in granite[66] and high upto 8 times than upper continental crust[67].

The concentration of U and Th of the both granites are shown in the Th-U diagram (Fig. 19). It exhibits positive correlation and both shows greater mobility. The distribution of U and Th are much higher in leucocratic granite than Pink granite (Fig. 19). Granites in the upper parts of the continental crust usually have 3-4 ppm of U and 10-15ppm of Th with a Th/U ratio of 3.7[68]. The granites of the Dhiran area of MIS shows higher concentration of U and Th as compared to A-type granite & rhyolite of Northwestern Ontario[69] and A-type rhyolite of St. Francois Mountains, Missouri[70] (Fig. 19). The enrichment of U in granites appears to be due to fractional differentiation and that is indicates by the increase of K content of these granites. The Th/U ratios of the granites are comparable and are fairly close to the upper crustal estimate of 3.8[67] (Fig. 20). The most Th and U enriched rocks sample have lower ratio of Th/U. Low Th/U ratios in few sample may suggest fractionation of phase like Th-orthosilicate and Zircon[71]. In the K-U-Th diagram

(Fig. 21) granites plot near the Th-apex, indicating high content of Th (11.38-67.62ppm) in the samples, and hence the heat generation of Th (2.03-11.52 HGU) is much higher than U (1.97-8.61 HGU) and K (0.70-1.07 HGU). The average total heat generation value of 16.51 HGU for leucocratic granites, 5.79 HGU for pink granites is much higher than average value of 3.8 HGU for continental crust[72] and the value of 8.3 HGU obtained for the Peninsular India[73]. Since the heat generation value of 7 HGU is taken as the boundary between the 'hot crust' and 'cold crust' the Dhiran granites (Leucocratic granite) data (>7 HGU) support that granites belongs to the 'hot crust' category. Both the granites show comparable heat production and heat generation value. The HP–Ur diagram (Fig. 22), shows good correlation of HP and Ur concentrations. The fields of the rhyolite of Jhunjhunu, MIS[74] and rhyolite of Mokalsar, MIS[14] is shown for comparison. The present studies samples are well comparable with Mokalsar Rhyolite.

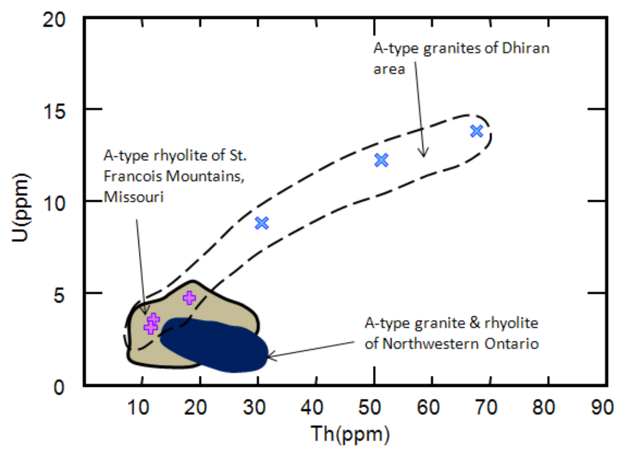

Figure 19. Plots of Th vs U. Fields of A-type rhyolite of St. Francois Mountains, Missouri[70] and A-type granite and rhyolite of Northwestern Ontario[69] are shown for comparison

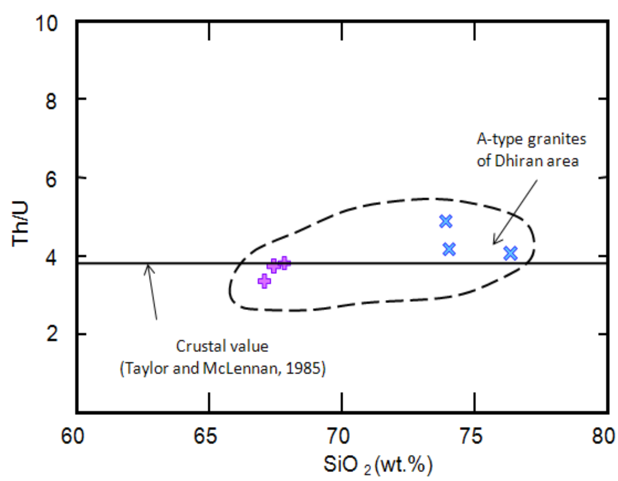

Figure 20. Plots SiO_2 vs Th/U. Showing the boundary of Crustal value[67]

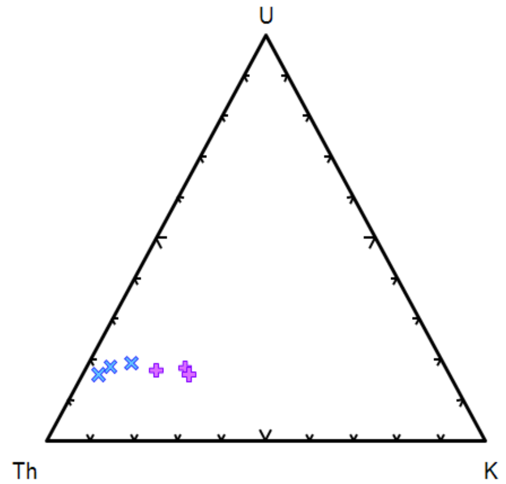

Figure 21. Plots of K-U-Th ternary diagram showing the concentration of K, U and Th of the Dhiran granites

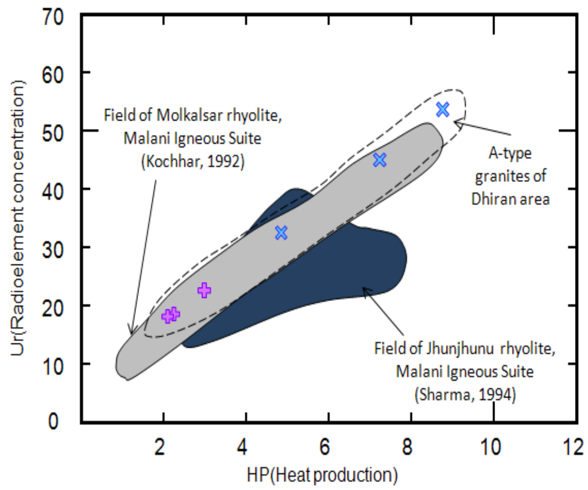

Figure 22. HP vs Ur diagram showing comparison of Jhunjhunu rhyolite, Malani Igneous Suite[74] and Molkalsar rhyolite Malani igneous Suites[14]

6. Petrogenesis

A number of petrogenetic models have been proposed for the origin of A-type granites, including high fractional crystallization of mantle-derived mafic magmas, with or without crustal assimilation ([75],[76]) and partial melting of pre-existing crustal materials ([4],[77]). Possibly, A-type magma does not represent a particular geologic setting, but rather similar end-products derived through different processes ([8],[78]). The obtained geochemical data indicates that the partial melting hypothesis is more applicable for the Dhiran granites according to the following reasons: The presence of a compositional gap in the major and trace elements, as well as the irregularity in REE distributions among the studied granites indicate a different magma source. The fractionation of basaltic melts, which is dominated by plagioclase, pyroxene and olivine in the lower to middle crust, would produce magmas with very large negative europium anomalies[79]. Both the granites show very large negative europium anomalies. Eby,[8] divided the A-type granitoids into A1 and A2 chemical groups, based on tectonic affiliation (A1 = truly anorogenic rifting, A2 = postcolisional) and the Y/Nb ratios to differentiate between mantle (Y/Nb< 1.2) and crustal (Y/Nb>1.2) origin. A-type granitoids have Y/Nb ratios (2.4-5.5) greater than 1.2 and they plot clearly in the A2 granite field in the Y/Nb – Rb/Nb binary diagram (Fig. 23). Accordingly, these chemically defined A–type granites correspond to magmas derived from a crustal source. In the Y-Nb variation diagram (Fig. 24), the Y and Nb increase systematically along well defined positive trends as shown by the distinct lineup of data points (Fig. 24) also, Y is typically concentrated in accessory minerals, commonly zircon, as Y replaces Zr[80]. As expected, a negative correlation between Ba and Rb is observed in Fig. 25, which shows a gradual decrease in Ba with increasing Rb. This is possibly the result of fractional crystallization of the alkali feldspar (perthite). It should be noted that these granitoid indicates control by crystal-melt equilibrium[81] and the magmatic processes control the evolution of this granitoid, were crystal-liquid equilibrium processes with minimal involvement of post-magmatic aqueous fluid phase interactions. Dhiran granites produce a well–defined negative trend showing gradual decrease in the Rb/Sr ratios linearly with increasing concentration of Sr. It should be noted that the depletion in Sr and Ba, which is typically associated with enrichment in Rb in alkaline felsic melts (Fig. 26) is interpreted to have been caused by internal differentiation of the parent granitic magma. Sr and Ba are typically removed with the fractionation of the feldspars, whereas Rb (a highly incompatible element) is gradually being enriched in late stage residual melts. Spider diagrams (Fig. 14) have pronounced Ba, Sr, and Ti troughs and ales obvious Nb trough. The Ba, Sr, and Ti depletion could be related to fractionation of plagioclase and ilmenite. The Nb trough is a strong indicator of continental crust involvement in magma processes ([82],[83]), as they are very characteristic feature of rocks formed of granites derived from a crustal source. The deep negative Ti anomaly or depletion may be linked with crustal contamination phenomena and/or involvement of continental materials ([84],[85]). However, the strong depletion and very low abundances of Ba, Sr, Eu and Ti, which sometime drop below those of primitive mantle, require an advanced fractionation of feldspars and ilmenite or titanomagnetite in upper crustal conditions. All of the REE patterns have strong negative Eu anomalies and exhibit concave upward shapes of obvious negative slopes due to light REE enrichment relative to middle and heavy REE. The heavy REE are not greatly depleted, but in turn are comparable or even sometimes slightly enriched relative to middle REE, suggesting absence of garnet in the source, since heavy REE are highly compatible in garnet[82]. This further indicate that, if mantle participation is assumed in the source material, a shallow mantle is preferred rather than deep one where spinal stability is favored rather than garnet[86]. The fraction of the heavy rare earth element (HREE) is considerable pronounced with significantly high $(Gd/Yb)_N$ ratios ranging between 1.25 and 1.78, suggesting that more HREE-bearing minerals, such as hornblende and pyroxene, might have been fractionated during the formation of these granites. The similarities between Arabian-Nubian Shield (ANS) and Malani supercontinent in respect of age, ring structure, tectonic environment and element compositions which provide a new approach for the search of economic mineralization[87].

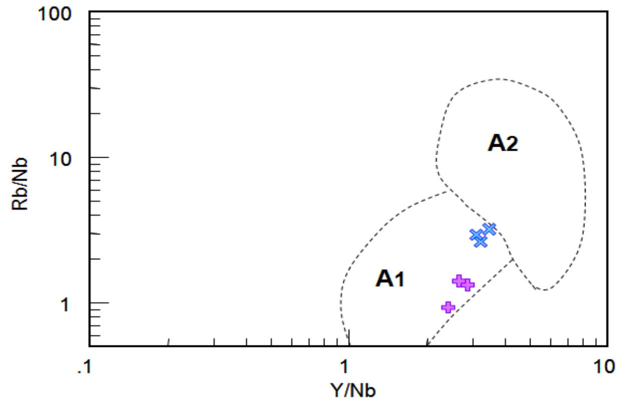

Figure 23. Plots of the studies A-type granites on Rb/Nb vs. Y/Nb binary diagram[8] A1 and A2 granitoids (A1=Truly anorogenic rifting, A2= Postcollisional)

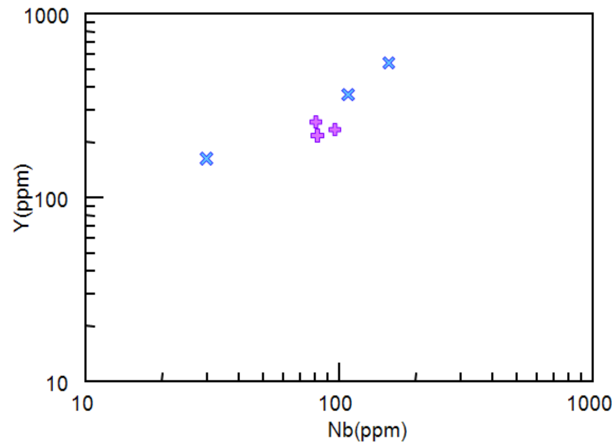

Figure 24. Nb vs Y variation diagram showing a well-defined trend, which displays the systematic increase in both elements

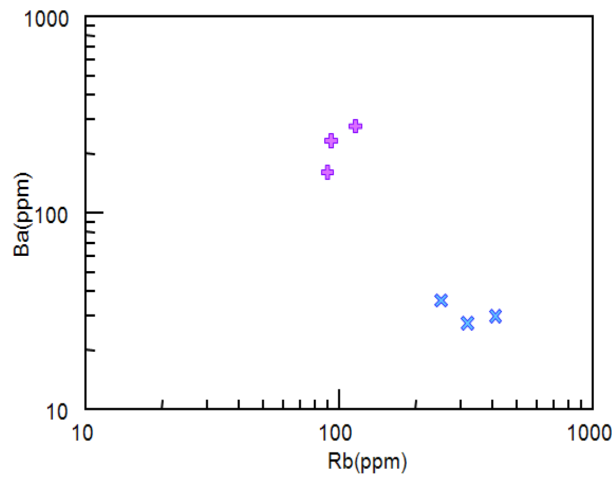

Figure 25. Rb vs Ba variation diagram showing a well-defined trend, which displays the systematic increase of Rb with decrease of Ba

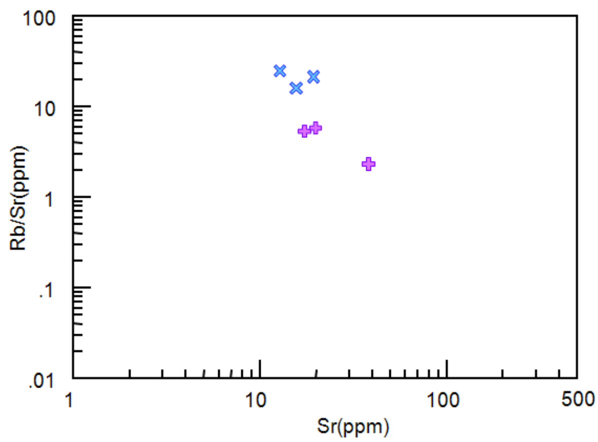

Figure 26. Rb/Sr vs Sr diagram showing that the Rb/Sr ratios increase with decreasing Sr contents

According to Bonin,[88], A-type magma move up and pass through the crust. Their levels of emplacement from the mantle-crust boundary to the surface are controlled mainly by the mechanical discontinuities with solid rocks, favoring propagation of buoyant magmas and by wall rock density and strength, tending to arrest them, and then crust operates as a density filter for migrating magmas.

7. Conclusions

Anorogenic A-type granitoids of the Dhiran area of MIS, Western Peninsular India are classified chemically as ferroan, alkaline, peralkaline and peraluminous, A-type granites. This A-type granites are highly evolved in composition (65.85-77.74 wt% SiO_2 and DI values of 83.36-92.45) and display the typical geochemical characteristics of A-type granites with high SiO_2, Na_2O+K_2O, FeO*/MgO, Ga/Al, Zr, Nb, Ga, Y, Ce, and REE and low CaO, MgO, Ba, Sr, they exhibit significantly high Rb/Sr ratios and negative Eu anomalies. Their trace and REE characteristics indicate predominant formation by partial melting of continental crust. Although these A-type granites display almost all the conventional typical characteristic of anorogenic within plate magmas, comprehensive integrated investigations revealed that they are corresponding to magmas derived from a crustal source that has gone through a hot-spot tectonics. The extremely high Rb/Sr ratios combined with the obvious Sr, Ba, P, Ti, and Eu depletions clearly indicates that these A-type granites were highly evolved and require advanced fractional crystallization in upper crustal conditions and argue against its formation by fractional crystallization of a parental mafic magma.

High to medium content of radioactive element (U, Th, K) heat generation of anorogenic, A-type granites of Dhiran Area, MIS, has been reported. These granites are classified as high to medium Heat Production (HP). Leucocratic granites and pink granites of the Dhiran area shows higher average value of total Heat Generation Unit than the average value of 3.8 HGU for the continental crust. The high Heat Generation Unit values of the Dhiran granite indicates 'hot crust' category and a possible linear relationship between the surface heat flow and crustal heat generation in the MIS. Since, the HHP acidic rocks are associated with rare metal mineralization and based on the characteristic of U, Th, Nb, Zr, Zn, Pb and REE, it is suggested that the granitoids of Dhiran of MIS have the potential for rare metal and rare earth elements mineralization.

Dhiran A-type magma move up and pass through the continental crust. Their levels of emplacement from the mantle-crust boundary to the surface are controlled mainly by the mechanical discontinuities with solid rocks, favoring propagation of buoyant magmas and by wall rock density and strength, tending to arrest them, then crust operates as a density filter for migrating magmas. Hence, the magmatism of the granites of Dhiran area, MIS are related to intraplate, crust mantle interaction, anorogenic, within plate, A-type, subvolcanic setting and emplaced in the extensional tectonic regime.

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