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Geochemistry and petrogenesis of Narnaul Pegmatites in Delhi Supergroup rocks, Narnaul area, southern Haryana, India

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ABSTRACT

Metasedimentary rocks of Delhi Supergroup (900-1600 Ma; latitude 28˚2´- 28˚7N´ and longitude 76˚3´- 76˚7´E) are exposed in the Aravalli Mountain (South of Haryana State). The metasedimentary rocks are mainly quartzite with lesser amount of schist, granitic gneiss, basic rocks, calc rocks, phyllite, slate, granite, pegmatite and veins of quartz. Most of the pegmatites of the study area intruded into the quartzite. Pegmatites occur as irregular masses, dyke swarms, branching dykes, criss-cross veins and elongated lenses. They strike in NNE direction with low dip angle. Their dimensions are variable (0.5 m - 250 m length and 0.5 - 100 m width). Narnaul pegmatites are very coarse grained and consist of quartz (smoky, milky, yellowish brown, buff), orthoclase, albite, biotite, muscovite, tourmaline, calcite, beryl, garnet, hornblende and natrolite in the decreasing order of abundance. Pegmatitic, hypidiomorphic and granophyric textures are observed in them. Model analyses data of the pegmatites is plotted mainly in the field of granite, alkali granite and quartz rich granitoid fields of QAP diagram. The studied granitoids belong to calc-alkaline-granodiorite series which were generated by crustal fusion process. Geochemically, the pegmatites are high in SiO_2, Al_2O_3, K_2O, Rb, Zr, Cs, Ta, Pb, P and Y and low in CaO, K, U,Th, Ti, Ba, Sr, Nb and Nd. These characters attest them as peraluminous, I-type and they are formed in post-orogenic tectonic settings. Petrogenetic modeling studies indicate that these pegmatites could have been derived by 30% partial melting of crustal source rock occurring in the region.

Keywords: Pegmatites; Geochemistry; Partial melting; Narnaul; Haryana.

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INTRODUCTION

In southern part of Haryana State, metasedimentary rocks of Delhi Supergroup (between 900 and 1600 Ma according to Crawford, 1970) are exposed in the Aravalli mountain range. Gopalan et al. (1979) dated 1480 ± 40 Ma for the granites of Dosi, Maroli, and Dhanota areas, southern Haryana which are trending at NNE –SSW direction in northeastern continuity of Khetri granite in Rajasthan. Pant et al. (2008) has reported 945 ±14 Ma of the age of metamorphism of Delhi Supergroup rocks exposed in the southern Haryana. The reported age is based on the determination of Th, corrected U & Pb dating of monazites from the subcalcic Fe-Mg amphibole rocks in the Bayal area of Mahendragarh District in southern Haryana. Kaur et al. (2011) have provided ca. 1.70 - 1.72 Ga for late Paleoprotorozoic igneous-metamorphic complex in Khetriregion of NE Rajasthan. Valdiya (2010) has considered that the tectonic movement that gave rise to Delhi Mobile Belt occurred at 1600±100 Ma. Several workers in recent time have undertaken on various geological aspects of northern part of Delhi Supergroup of rocks exposed in Khetri and Narnaul regions *viz.* Bhola and Varadarajan (1981); Bhola et al. (1983); Saxena et al. (1984); Chaudhary et al. (1984); Chakraborti and Gupta (1992); Gupta et al. (1998); Kaur and Mehta (2004); Kaur et al. (2006); Qazi and Sukhchain (2006); Thussu (2006); Pant et al. (2008).

GEOLOGY OF THE STUDY AREA

The present study area consists mainly of quartzite with sub ordinate amount of schist, granitic gneiss, basic rocks, calc rocks, phyllite, slate, granite, pegmatite and veins of quartz (Fig.1). Most of the pegmatites of the study area intruded into the quartzite, but also occur within the granitic gneiss, granite, schist, basic rock, calc rock, slate and phyllite. Pegmatite occurs as irregular mass, dyke swarm, branching dyke, criss-cross vein and elongated lenses. Pegmatites are orientating in NNE strike direction with low dip angle and their dimensions are variable (0.5 m - 250 m length and 0.5 - 100 m width). These pegmatites show sharp contact with the host rocks in the region (Fig. 2a and c). Sharp contact with the quartzite (Fig. 2a) and granitic gneiss (Fig. 2b) are exposed at Azimpur and Raghunathpura, respectively. Pegmatite contact with basic rock is seen at Raghunathpura(Fig. 2c). Blurred contact between granite and pegmatite at Narnaul is also observed (Fig. 2d). These contacts are strong proofs of Aravalli orogenic movement in the geological past.

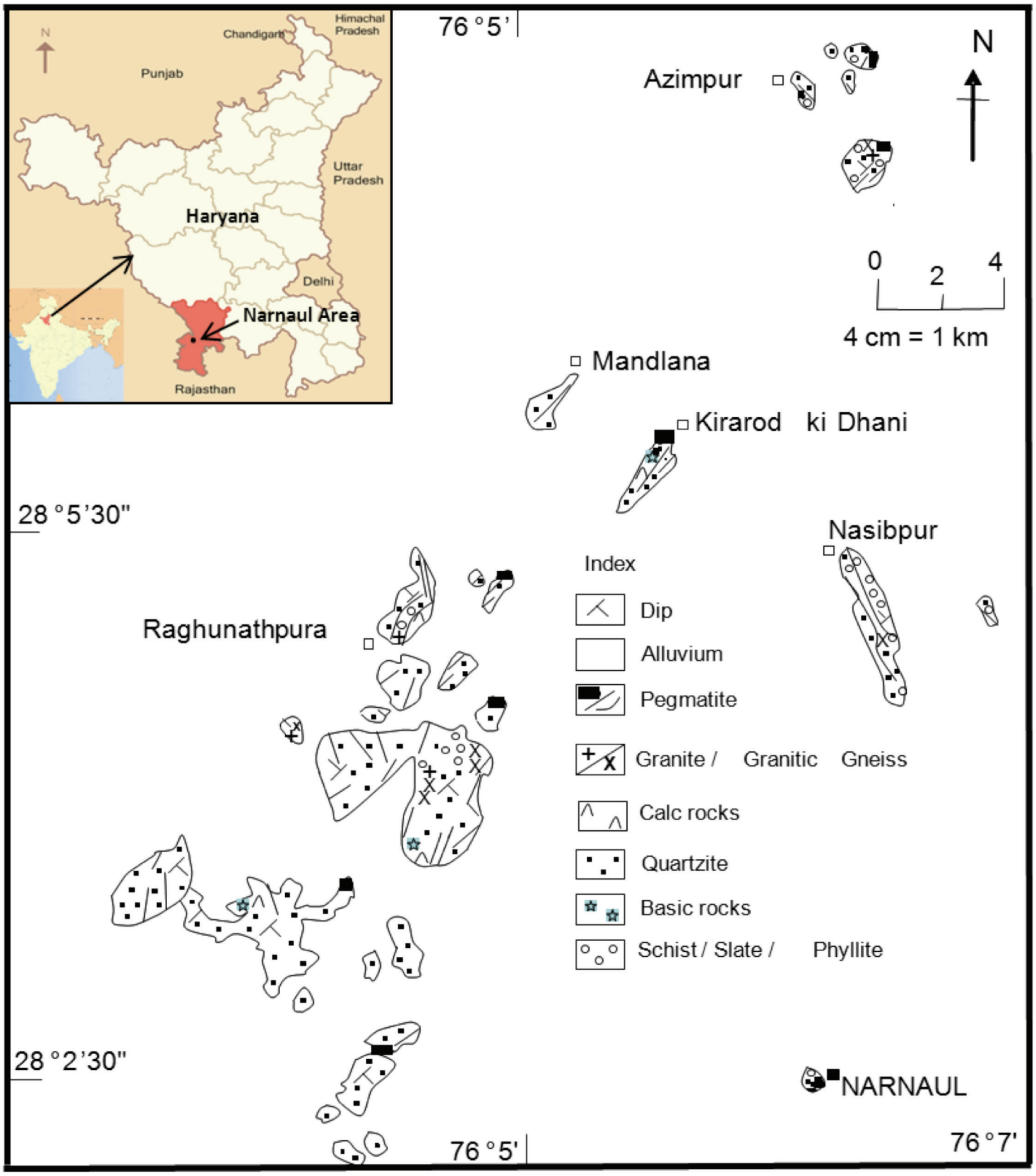

Fig. 1: The geological sketch map of the Narnaul area, District Mahendragarh, Haryana.

Narnaul pegmatites consist of quartz (smoky, milky, yellowish brown, buff), orthoclase, albite, biotite, muscovite, tourmaline, calcite, beryl, garnet, hornblende and natrolite in the decreasing order of abundance among various types & locations. The presence of garnet and natrolite in the different types of pegmatite of present study areas indicate the presence of regional as well as contact metamorphic conditions in their formation. The presence of calcite minerals may indicate the source of magma close to uppermost mantle besides the crust or calcareous source rocks in curst.

Based on detailed studies on their occurrence, association, structure, texture, and mineralogy, pegmatites are classified into groups and sub groups. Detailed historical reviews on the classifications of the pegmatite are provided in (Babu, 1993). Adopting the field criteria i.e., mode of occurrence, association, mineralogy and geochemistry, pegmatites of present study area are classified into simple or undifferentiated and complex or differentiated types. The complex type are further classified as subtypes such as partly complex (contains either

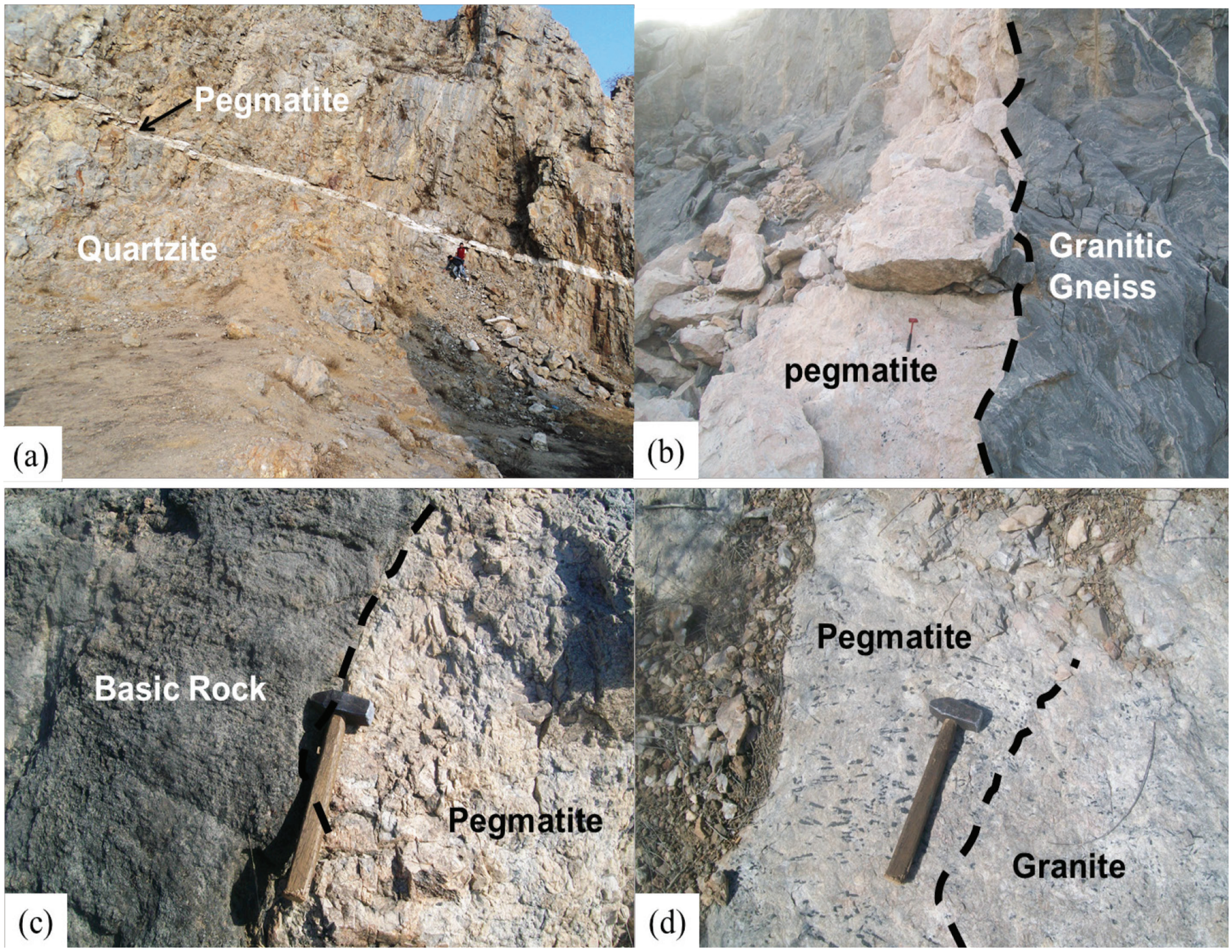

Fig. 2: Field photographs showing (a) sharp contact between quartzite and pegmatite at Azimpur (b) Sharp contact of pegmatite with granitic gneiss at Raghunathpura (c) Pegmatite contact with basic rock is seen at Raghunathpura (d) Blurred contact between granite and pegmatite at Narnaul is also observed.

acicular or prismatic tourmaline), fully complex (contains both type of tourmalines), replacements & completely zoned and incompletely zoned. Partly complex type has quartz, orthoclase, muscovite and acicular or prismatic tourmaline. Fully complex type has both acicular & prismatic tourmaline, ± beryl / calcite crystals / transparent or crystals of quartz / malachite in addition to minerals in partly Complex type. Complex pegmatites are predominantly exposed as compared to simple pegmatites in the study area.

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PETROGRAPHY

Pegmatites are very coarse-grained and show pegmatitic, hypidiomorphic, granophyric, equigranular and graphic textures. They contain quartz, K-feldspar (orthoclase, perthite, microcline), albite, biotite, muscovite as essential minerals and the accessory minerals are garnet, apatite, magnetite, and ilmenite. Quartz shows wavy extinction and occurs as microgranophyric intergrowth in the groundmass. Orthoclase is medium grained, subhedral and shows carlsbad twinning. Perthites are characterized by cloudy, patchy, incoherent and extensive coarsening nature due to feldspar-fluid interaction at subsolidus temperature (Yund and Ackermand, 1979; Parson, 1980) 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 places, minute mica flakes are also observable along the margins of perthite as post magmatic phases due to accumulation of residual fluid. They also contains phenocryst of quartz, perthite, microcline in quartzofeldspathic groundmass (Fig. 3a), muscovite, dark brown garnet phenocrysts with quartz & biotite inclusions (Fig. 3b), dark blue & light brown prismatic tourmaline and quartz (Fig. 3c) and rhombic calcite crystals are in association with biotite (Fig. 3d). Zoning in tourmaline, luxullianization, kaolinization of orthoclase and sericitation of albite are observed. The modal composition of (volume %) pegmatites of the study area are plotting mainly in the field of granite, also in alkali granite and quartz rich granitoid fields of QAP diagram (Fig. 4) (Streckeisen, 1973). They are also plotting in the fields (Lameyre and Bowden, 1982) of calc-alkaline-granodiorite series & granitoid generated by crustal fusion process.

GEOCHEMISTRY

In this study we have analyzed a total of 15 pegmatites samples from Narnaul area. Major elements concentration was determined using XRF Bruker S8 TIGER on powder pellets at National Geophysical Research Institute (NGRI), Hyderabad. Trace elements and Rare earth elements (REE) were analyzed on ICP-MS (Perkin Elmer Sciex ELAN DRC- II) at National Geophysical Research Institute (NGRI), Hyderabad. Sample preparation for ICP-MS was carried out under open acid digestion method and other analytical precision were provided in Roy et al. (2007). An amount of 0.05 g of whole rock powder was dissolved with acid mixture (7:3:1 HF-HNO_3-$HClO_4$) under fume hood and added 5ml of 1ppm ^{103}Rh solution to act as an internal standard and diluted it into 250ml for ICP-MS analysis. The whole rock geochemical data of the investigating pegmatites is shown in tables 1-3.

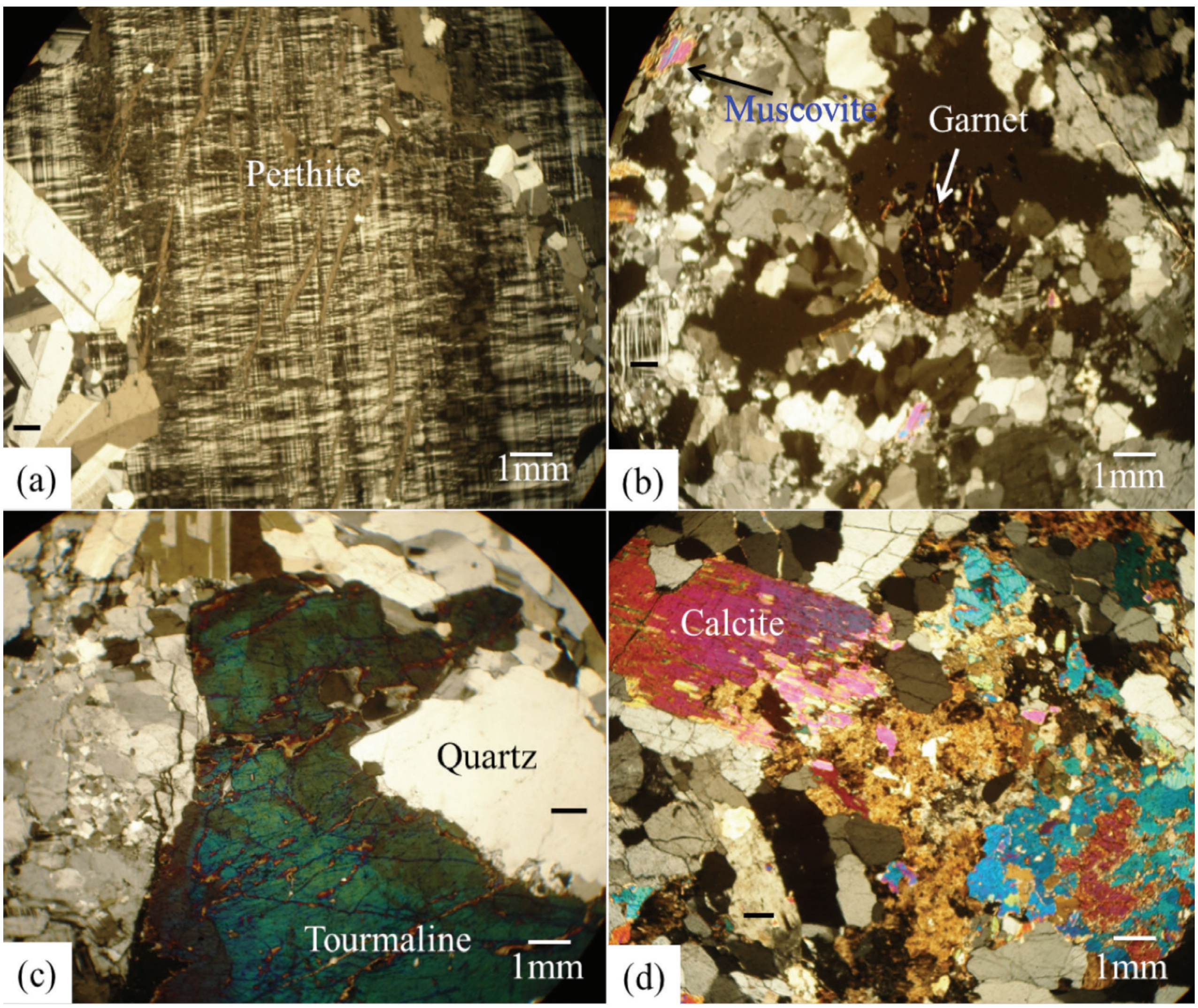

Fig. 3: Photomicrographs show (a) Pegmatite consists phenocryst of quartz, perthite, microcline in quartofeldspathic groundmass (b) Muscovite, dark brown garnet phenocrysts with quartz &biotite inclusions (c) Dark blue, light brown colour prismatic tourmaline and quartz (d) Rhombic calcite crystals in association with biotite.

Table 1: Major elements (wt %) and CIPW norms of pegmatites from Narnaul area of Delhi Supergroup, southern Haryana.

Sample no.	A2	A4	A7	DDN1	F2	K2	K3	M1	N2	R10	R18	R2	R5
SiO_2	73.72	74.81	73.6	76.81	74.71	76.23	75.66	74.91	75.95	73.89	75.95	75.94	75.71
TiO_2	0.01	0.05	0.02	0.01	0.03	0.02	0.02	0.01	0.01	0.02	0.03	0.01	0.02
Al_2O_3	16.92	15.9	15.99	14.81	15.58	14.74	13.87	13.6	14.89	16.03	14.87	14.85	14.94
Fe_2O_3	2.77	1.78	2.64	2.32	1.59	2.23	2.32	6.21	2.13	1.57	1.93	1.85	1.87
MnO	0.02	0.08	0.04	0.03	0.02	0.03	0.04	0.08	0.03	0.02	0.02	0.03	0.03
MgO	0.06	0.03	0.03	0.07	0.03	0.03	0.07	0.04	0.08	0.03	0.05	0.01	0.02
CaO	0.18	0.47	0.2	0.39	0.2	0.2	1.41	0.15	0.44	0.29	0.25	0.2	0.24
Na_2O	2.6	3.07	3.07	3.29	2.79	2.86	2.85	2.69	3.26	2.68	3.48	3.13	3.32
K_2O	2.29	2	2.51	0.86	3.34	2.2	2.64	0.75	1.27	3.71	2.26	1.97	2.69
P_2O_5	0.01	0.05	0.07	0.04	0.04	0.03	0.09	0.01	0.03	0.05	0.09	0.05	0.05
Total	98.58	98.24	98.17	98.63	98.33	98.57	98.97	98.45	98.09	98.29	98.93	98.04	98.89
CIPW Norms													
Quartz	47.44	47.44	44	51.92	44.23	49.01	44.47	51.65	49.65	42.48	47.36	48.58	44.38
Orthoclase	13.53	11.82	14.83	5.08	19.74	13.24	15.6	4.43	7.5	21.92	13.36	11.64	15.9
Albite	22	25.98	25.98	27.84	23.61	24.2	24.12	22.76	27.59	22.68	29.45	26.49	28.09
Anorthite	0.83	2.01	0.53	1.67	0.73	0.8	6.41	0.68	1.99	1.11	0.65	6.7	0.86
Corundum	9.86	7.95	8.03	7.85	7.11	7.32	3.98	8.11	7.42	7.2	6.46	7.32	6.25
Hypersthene	4.4	2.85	4.15	3.75	2.49	3.63	3.76	9.72	3.48	2.47	3.05	2.89	2.93
Illmenite	0.02	0.09	0.04	0.02	0.04	0.04	0.02	0.02	0.02	0.04	0.04	0.02	0.04
Magnatite	0.2	0.13	0.18	0.17	0.11	0.17	0.17	0.44	0.15	0.11	0.14	0.13	0.13
Apatite	0.02	0.12	0.16	0.09	0.09	0.07	0.21	0.02	0.07	0.12	0.21	0.11	0.12
DI	83.8	86.9	85.3	88.3	86.5	87.3	90.6	79.5	86.7	88.2	88.8	87.4	89.3
AI	0.4	0.46	0.49	0.43	0.53	0.49	0.55	0.39	0.46	0.53	0.55	0.49	0.64
Na+K	3.82	3.93	4.36	3.15	4.84	3.98	4.3	2.61	3.47	5.06	4.45	3.95	4.69
Na/K	1.01	1.37	1.09	3.41	0.74	1.14	0.96	3.2	2.29	0.64	1.37	1.41	1.1
KN/C	20.94	8.57	21.68	9.12	22.85	19.9	2.98	19.57	8.57	16.17	18.26	20.35	19.47
A/CNK	2.35	1.94	1.93	2.06	1.79	1.93	1.35	2.42	1.94	1.77	1.69	1.91	1.46
An/(An+Ab)	0.03	0.07	0.01	0.02	0.56	0.03	0.2	0.02	0.06	0.04	0.02	0.02	0.02
Density(g/cc)	2.77	2.74	2.74	2.71	2.75	2.73	2.71	2.84	2.74	2.71	2.72	2.73	2.71
Viscosity(pas/sec)	1.19	1.25	1.17	1.23	1.35	1.3	1.22	1.28	1.32	1.19	1.25	1.32	1.24
Estimated liqidusT°c	756	732	752	735	699	711	725	721	708	750	720	708	724

Table 2: Trace element data and their calculations of Narnaul Pegmatites.

Sample	A2	A4	A7	DDN1	F2	K2	K3	M1	N2	R10	R18	R2	R5
Sc	1.71	1.04	1.24	0.84	0.86	0.82	0.85	2.69	1.48	0.91	1.14	0.89	0.8
V	8.73	9.59	8.14	4.1	9.17	5.54	6.79	5.6	7.64	7.03	5.35	6.58	5.24
Cr	61.55	55.25	46.79	47.91	57.38	53.76	51.69	45.45	51.41	39.95	48.89	38.63	46.74
Co	1.86	1.47	1.19	1.6	1.88	1.82	4.4	3.43	2.09	2.63	1.16	1.59	1.08

Table 2 continued

Sample	A2	A4	A7	DDN1	F2	K2	K3	M1	N2	R10	R18	R2	R5
Ni	10.55	7.34	4.24	5.08	11.31	7.12	6.1	6.31	4.83	5.71	4.51	5.81	4.83
Cu	2.32	1.94	2.36	1.89	2.15	2.58	2.03	1.79	1.67	1.62	1.65	2.04	1.54
Zn	3.1	3.01	5.14	2.26	5.47	2.68	3.27	13.16	2.33	1.42	1.87	1.54	2.38
Ga	10.44	11.58	20.33	8.9	9.79	13.99	16.28	45.77	12.06	17.92	14.62	27.48	26.64
Rb	72.94	162.48	603.45	25.81	288.46	387.33	377.7	12.17	66.76	246.17	131.02	321.24	250.06
Sr	13.08	74.01	3.68	15.55	84.96	14.44	22.72	7.34	43.97	80.72	4.13	12.21	6.92
Y	3.39	15.78	1.82	5.34	5.74	2.17	2.58	0.81	1.48	1.3	2.1	2.35	4.15
Zr	19.91	21.06	27.93	57.25	10.44	14.46	24.57	12.96	12.5	17.59	42.89	29.52	13.01
Nb	6.74	2.68	1.49	1.6	2.24	2.08	1.62	1.69	1.15	4.15	0.3	5.26	8.3
Cs	1.43	26.47	35.39	1.04	3.9	5.28	27.76	0.4	0.95	8.25	6.4	4.58	5.23
Ba	92.24	336.06	40.5	32.53	808.88	107.67	411.26	46.92	238.17	807.57	25.37	145.27	51.82
Ta	0.37	0.35	0.34	0.24	0.2	0.47	0.38	0.93	0.72	0.51	0.05	0.57	0.91
Pb	18.27	62.42	48.69	22.63	51.06	34.81	53.3	7.56	16.08	64.57	30.8	23.86	21.27
Th	0.37	1.74	0.63	0.99	0.71	5.1	1.98	0.32	0.9	0.68	2.1	0.81	0.71
U	0.64	1.31	2.6	4.25	1.17	2.02	1.74	0.54	1.02	2.88	2.63	1.69	1.38
Al	8.95	8.41	8.46	7.83	8.24	7.8	7.34	7.19	7.87	8.48	7.86	7.85	7.9
K	1.9	1.66	2.08	0.71	2.77	1.85	2.19	0.62	1.05	3.07	1.87	1.63	2.23
K/Rb	0.03	0.01	0	0.03	0.01	0	0.01	0.05	0.02	0.01	0.01	0.01	0.01
Ba/Rb	1.26	2.07	0.07	1.26	2.8	0.28	1.09	3.86	3.57	3.28	0.19	0.45	0.21
Rb/Sr	5.58	2.2	163.85	1.66	3.4	26.82	16.62	1.66	1.52	3.05	31.76	26.31	36.13
Ba/Sr	7.05	4.54	11	2.09	9.52	7.46	18.1	6.4	5.42	10	6.15	11.9	7.49
Th/U	0.58	1.34	0.24	0.23	0.61	2.52	1.14	0.59	0.88	0.23	0.8	0.48	0.52
Y/Nb	0.5	5.89	1.23	3.35	2.57	1.05	1.59	0.48	1.28	0.31	6.97	0.45	0.5
Rb/Ba	0.79	0.48	14.9	0.79	0.36	3.6	0.92	0.26	0.28	0.3	5.16	2.21	4.83
Sr/Y	3.86	4.69	2.02	2.91	14.79	6.64	8.82	9.11	29.81	62.09	1.96	5.19	1.67
Rb/Zr	3.66	7.72	21.61	0.45	27.62	26.78	15.37	0.94	5.34	14	3.05	10.88	19.22
Zr/Nb	2.96	7.86	18.77	35.89	4.67	6.97	15.19	7.66	10.86	4.24	142.02	5.61	1.57
Ga/Al	1.17	1.38	2.4	1.14	1.19	1.79	2.22	6.37	1.53	2.11	1.86	3.5	3.37
Zr/Rb	0.27	0.13	0.05	2.22	0.04	0.04	0.07	1.07	0.19	0.07	0.33	0.09	0.05
Nb/Y	1.99	0.17	0.82	0.3	0.39	0.95	0.63	2.1	0.78	3.19	0.14	2.24	2
Zr/Y	5.88	1.33	15.31	10.71	1.82	6.65	9.54	16.1	8.48	13.53	20.39	12.55	3.14

Table 3: REE data and their calculations of Narnaul Pegmatites.

Sample	A2	A4	A7	DDN1	F2	K2	K3	M1	N2	R10	R18	R2	R5
La	1.43	2.14	0.95	1.1	1.3	1.96	1.54	0.61	0.85	3.45	0.92	0.96	0.9
Ce	2.75	4.64	1.71	1.75	2.23	3.37	2.64	1.04	1.08	6.84	1.43	1.72	1.72
Pr	0.31	0.48	0.17	0.15	0.25	0.33	0.25	0.12	0.15	0.68	0.11	0.16	0.17
Nd	1.22	1.9	0.63	0.42	1	1.09	0.86	0.46	0.55	2.56	0.29	0.51	0.53
Sm	0.27	0.68	0.13	0.09	0.35	0.29	0.16	0.09	0.12	0.44	0.08	0.13	0.28
Eu	0.15	0.92	0.03	0.1	0.85	0.1	0.1	0.04	0.27	0.77	0.02	0.06	0.03
Gd	0.28	0.74	0.14	0.13	0.4	0.26	0.19	0.09	0.11	0.39	0.09	0.12	0.25
Tb	0.06	0.23	0.03	0.04	0.12	0.06	0.04	0.02	0.03	0.04	0.02	0.03	0.08

Table 3 continued

Sample	A2	A4	A7	DDN1	F2	K2	K3	M1	N2	R10	R18	R2	R5
Dy	0.46	2.18	0.23	0.42	0.95	0.37	0.31	0.12	0.2	0.19	0.2	0.26	0.59
Ho	0.06	0.28	0.03	0.07	0.1	0.04	0.03	0.01	0.02	0.02	0.02	0.03	0.05
Er	0.22	1.07	0.1	0.41	0.32	0.13	0.13	0.05	0.07	0.06	0.09	0.11	0.17
Tm	0.03	0.17	0.02	0.08	0.05	0.03	0.02	0.01	0.01	0.01	0.02	0.03	0.03
Yb	0.35	2.06	0.22	1.26	0.52	0.36	0.26	0.08	0.12	0.09	0.25	0.36	0.41
Lu	0.06	0.33	0.03	0.25	0.08	0.06	0.04	0.01	0.02	0.02	0.04	0.06	0.07
Hf	0.7	1	1.89	2.18	0.37	0.97	1.45	0.81	0.55	1.07	2.42	2.64	0.85
REE∑	8.36	18.8	6.28	8.44	8.89	9.41	8.03	3.54	4.14	16.61	5.99	7.19	6.13
HREE∑	5.99	9.83	3.58	3.5	5.14	7.03	5.46	2.31	2.75	13.96	2.83	3.49	3.61
LREE∑	2.22	8.05	2.67	4.84	2.9	2.28	2.48	1.19	1.12	1.88	3.14	3.64	2.5
*Eu/Eu	0.15	0.99	0.03	0.15	0.96	0.09	0.11	0.04	0.24	0.68	0.02	0.06	0.03
Ce/Yb	7.78	2.25	7.9	1.39	4.32	9.24	10.28	13.27	9.03	77.73	5.63	4.82	4.15
La/Yb	4.04	1.04	4.38	0.87	2.52	5.38	6.01	7.76	7.08	39.23	3.62	2.68	2.17
Sm/Nd	0.22	0.36	0.2	0.21	0.35	0.27	0.19	0.2	0.23	0.17	0.28	0.26	0.53
Eu/Sm	0.55	1.35	0.23	1.13	2.41	0.36	0.59	0.44	2.15	1.76	0.24	0.46	0.1
La/Nb	0.21	0.8	0.64	0.69	0.58	0.94	0.95	0.36	0.74	0.83	3.04	0.18	0.11
Th/Yb	1.06	0.85	2.93	0.78	1.38	14.01	7.68	4.09	7.46	7.67	8.3	2.27	1.71
La/Gd	5.12	2.91	6.75	8.37	3.26	7.47	8	6.95	7.59	8.94	10.79	7.75	3.65
Ce/Nd	2.25	2.44	2.7	4.15	2.24	3.09	3.08	2.25	1.98	2.68	4.85	3.37	3.25
Ce/Sm	10.12	6.78	13.22	19.4	6.33	11.6	16.11	11.01	8.73	15.69	17.38	12.96	6.08
Gd/Yb	0.79	0.36	0.65	0.1	0.77	0.72	0.75	1.12	0.93	4.39	0.34	0.35	0.59

The pegmatites (15 representative samples) show (in wt %) SiO_2 (73.6 – 76.81), Al_2O_3 (13.09 – 16.92), Na_2O (2.6 – 3.48), K_2O (0.75 – 3.71), Fe_2O_3 (1.57 – 6.21), TiO_2 0.01 – 0.05), CaO (0.15 – 1.41), MnO (0.02 – 0.08), MgO (0.01 – 0.08) and P_2O_5 (0.01-0.09). Average values of SiO2, Al_2O_3, Na_2O, K_2O, Fe_2O_3, TiO_2, CaO, MgO, MnO and P_2O_5 (in wt %) are 75.22, 15.15, 3.0, 2.19, 2.40, 0.02, 0.35, 0.04, 0.03 and 0.04, respectively. DI (Differentiation Index) ranges from 79.9 to 90.6 and AI (Agpaiitic Index) ranges from 0.38 to 0.56 for all samples of pegmatites. In the CIPW normative mineralogy, quartz and orthoclase vary from 45.70 to 56.04 (Avg. 48.79) and 5.08 to 21.92 (Avg. 12.96), respectively. Albite ranges from 22.0 to 29.45 (Avg. 25.44) and Anorthite vary from 0.8 to 6.7 (Avg. 1.92). An/(An+Ab) varies from 0.01 to 0.5(Avg. 0.09) which is less than 1. Density and viscosity ranges from 2.71 – 2.84 and from 1.19 – 1.35, respectively. The average values of density and viscosity are 2.73 and 1.25, respectively. In CIPW normative An-Ab-Or ternary plot (Fig.5) (after Barker, 1979), the Narnaul pegmatites (15 samples) are mainly lie in the field of granite, trondhjenite and tonalite field, respectively.

Narnaul pegmatites lie in the field of peraluminous (Fig.6) in the diagram proposed by (Maniar and Piccoli, 1989). They owe their high Al_2O_3/CaO+Na_2O+K_2O (A/CNK) ratio to a combination of source, magmatic and fluid effects. In the tectonic discrimination R_1 - R_2 diagram (Batchelor and Bowden, 1985), the Narnaul pegmatites fall in the field of post- orogenic (Fig.7). Commonly, the intrusion of post- orogenic felsic magma into upper crust follows a cycle of compressive tectonic activity and generates orogenicmovements. Therefore, Aravalli orogeny was suitable for rock-metamorphic conditions. The clustering of the pegmatites in the post- orogenic field indicates the limited melting of a crustal source (after Bachelor and Bowden, 1985). In the Harker variation diagram, Narnaul pegmatites are plotted in the SiO_2vs. oxides and show two distinct trend i.e., (i) Ca rich pegmatites – poor in silica ranges 45-65 % and (ii) Ca poor pegmatites – rich in silica ranges 73-77 %. The Ca rich pegmatites show the constant trend of the K_2O, TiO_2, Al_2O_3, Na_2O, P_2O_5 against silica and increasing trend of the MgO, total iron against silica and decreasing trend against CaO. The Ca poor pegmatites are showing the constant trend of silica against the TiO_2, P_2O_5, CaO, MgO and increasing trend of silica against Na_2O, total iron and decreasing trend against K_2O, Al_2O_3. In CaO/(MgO+FeO^t) vs. Al_2O_3/(MgO+ FeO^t) plot, these pegmatites plot in the region of par

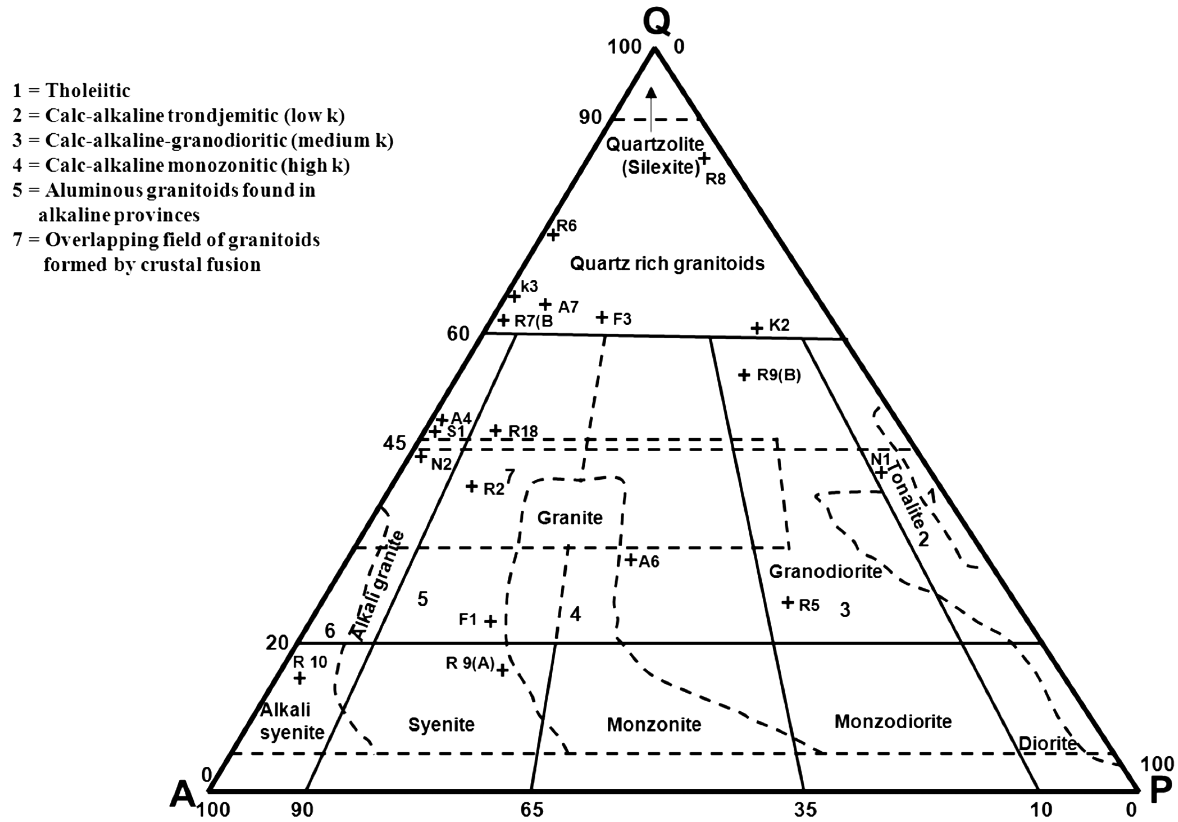

Fig. 4: QAP diagram (Streckeisen, 1973) shows the compositional field of Narnaul pegmatites (+). They are plotting in the fields (Lameyre and Bowden, 1982) of calc-alkaline-granodiorite series & granitoid generated by crustal fusion process.

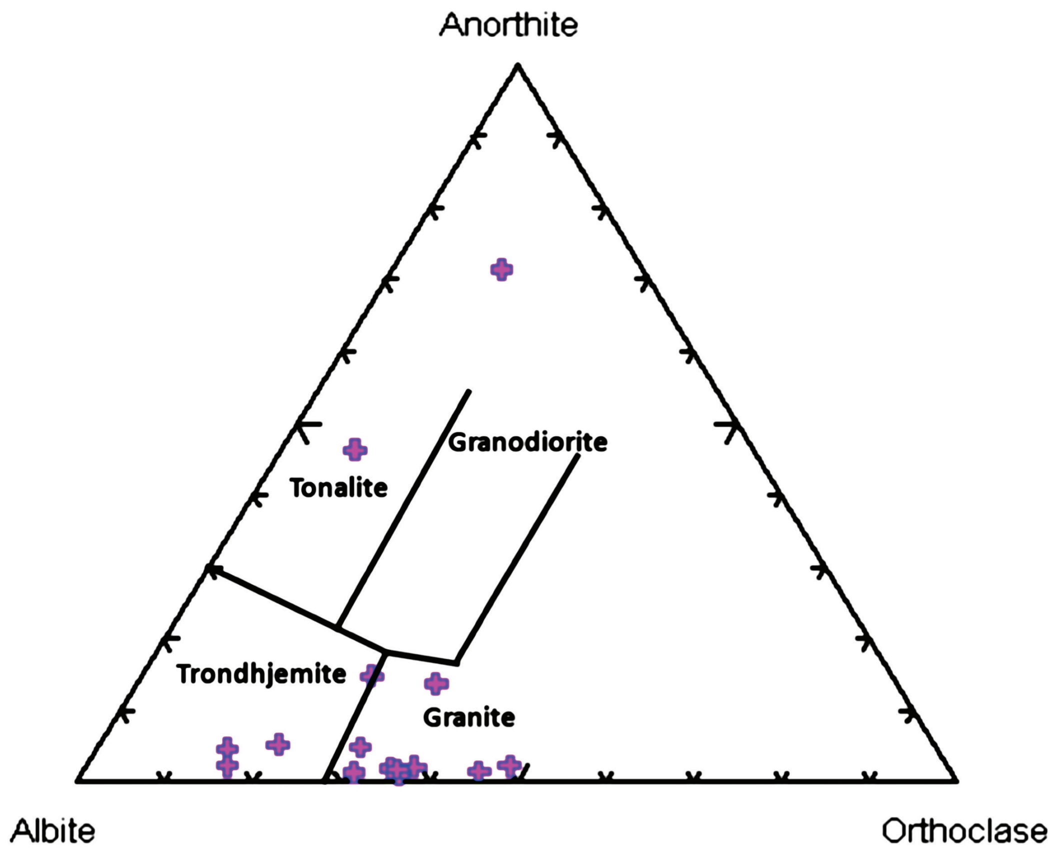

Fig. 5: Classification and nomenclature of the Narnaul pegmatites according to the Normative An-Ab-Or ternary plot (after Barker, 1979).

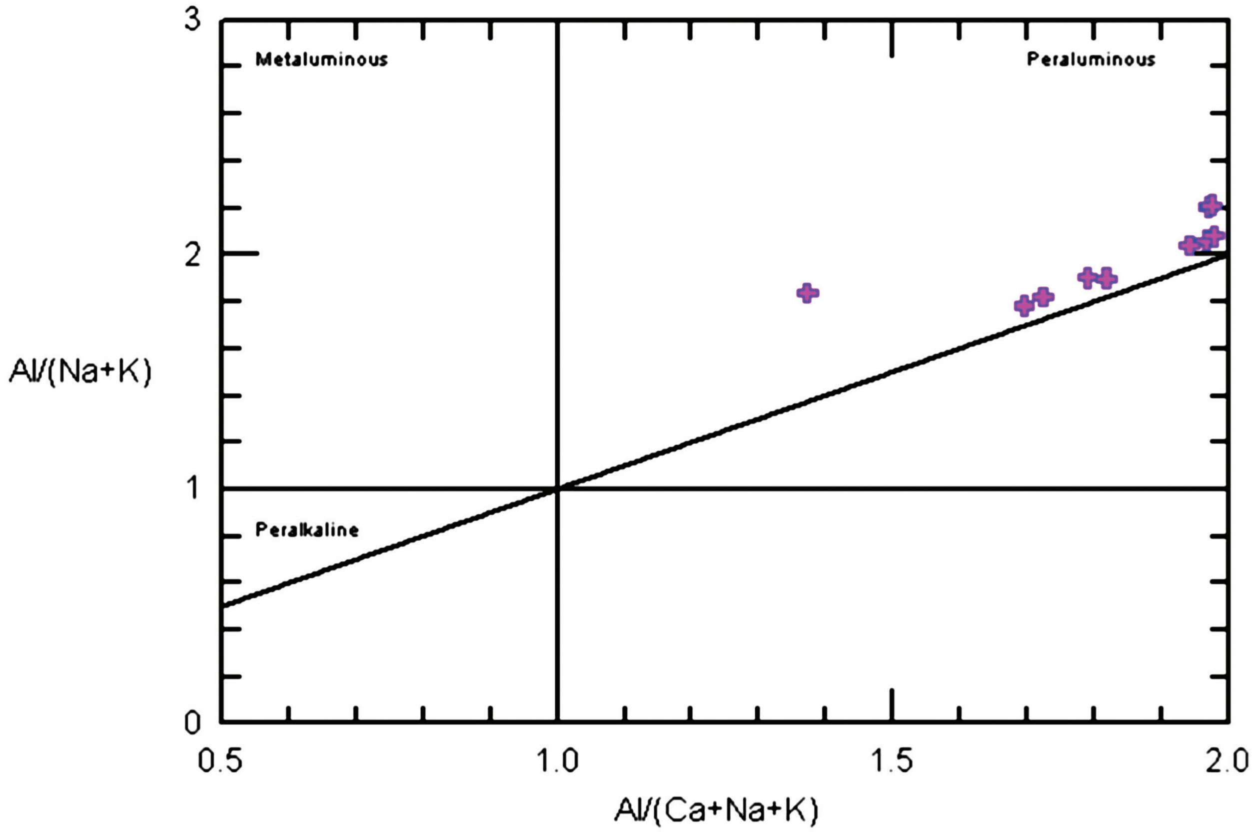

Fig. 6: Al/ (Ca+ Na+ K) versus Al/ (Na+ K) diagram (fields after Maniar and Piccoli, 1989) showing Narnaul Pegmatites lie in the field of peraluminous.

tial melting from metapelitic source (Fig. 8) (Altherr et al., 2000). In addition, the depth of source magma and orogenic tectonic activities could be important factors in their calcium content (Ca poor/Ca rich). The classification proposed by White (1979) is also used for pegmatites in which the S-type (AI ≥ 1.1) granite contains peraluminous mafic minerals and belongs to source of metasedimentary sequences. The I-type (AI < 1.1) granite shows the presence of hornblende and is associated with igneous materials from deep crustal levels. In the K_2O vs. Na_2O diagram (after Misra and Sarkar, 1991), the Narnaul pegmatites are falling in the field of I -types (Fig. 9). Anderson (1983) prepared a grid pattern by using the existing minimum melt compositions over a range of pressures and Ab/An ratios. In the ternary diagram of normative Qz–Ab–Or, the Narnaul pegmatites show departure of the projection points of early-stage melts from the relevant cotectic line hence they are accountable to the gaseous phase which is composed essentially of water including other components viz. chlorine, fluorine, etc. In Al_2O_3 vs. SiO_2, content of the Narnaul pegmatites with the experimentally generated melt compositions of different water contents (Waight et al., 1998), all the samples of Narnaul area plot near the field for more than 10% H_2O content (Fig. 10), suggesting hydrated and water saturation condition for the pegmatites. Finally, the normative Q- Ab-Or parameters (Fig. 11) of Narnaul pegmatites have been ploted in the field of more than 870^0 C (Holtz et al., 1992).

The pegmatites (15 samples) are analyzed in ICP-MS from NGRI, Hyderabad for trace and rare earth elements (35 elements). The concentration of these elements in ppm is showing variations in different samples. The pegmatites show values of Sc(0.8-2.694), V(4.098-68.595), Cr (31.067-61.548), Co(1.08-11.184), Ni(4.243-13.42), Cu(1.35-2.357), Zn(1.418-13.157), Ga(2.633-45.772), Rb(2.03-387.33), Sr(3.683-84.957), Y(0.805-107.697), Zr(5.284-57.246), Nb(1.151-8.301), Cs(0.125-35.388), Ba(25.371-808.882), La(0.605-61.48), Ce(1.035-129.759), Pr(0.112-13.338), Nd(0.421-49.618), Sm(0.082-7.739), Eu(0.03-0.971), Gd(0.085-8.799), Tb(0.019-1.443), Dy(0.118-11.242), Ho(0.13-1.642), Er(0.047-6.834), Tm(0.006-1.06), Yb(0.078-12.466), Lu(0.013-2.436), Hf(0.373-2.638), Ta(0.053-0.925), Pb(7.561-64.574), Th(0.319-5.1) and U(0.335-4.253). The average values in corresponding order are 1.236, 12.134, 48.262, 2.70, 6.956, 1.883, 3.670, 16.095, 196.661, 30.288, 10.713, 21.544, 2.734, 8.500, 212.586, 5.373, 11.070, 1.138, 4.236, 0.753, 0.3, 0.826, 0.154, 1.221, 0.164, 0.664, 0.106, 1.280, 0.239, 1.173, 0.411, 31.652, 1.233, and 1.647. The Sr-Rb binary plot (fields after Condie, 1997) suggested that

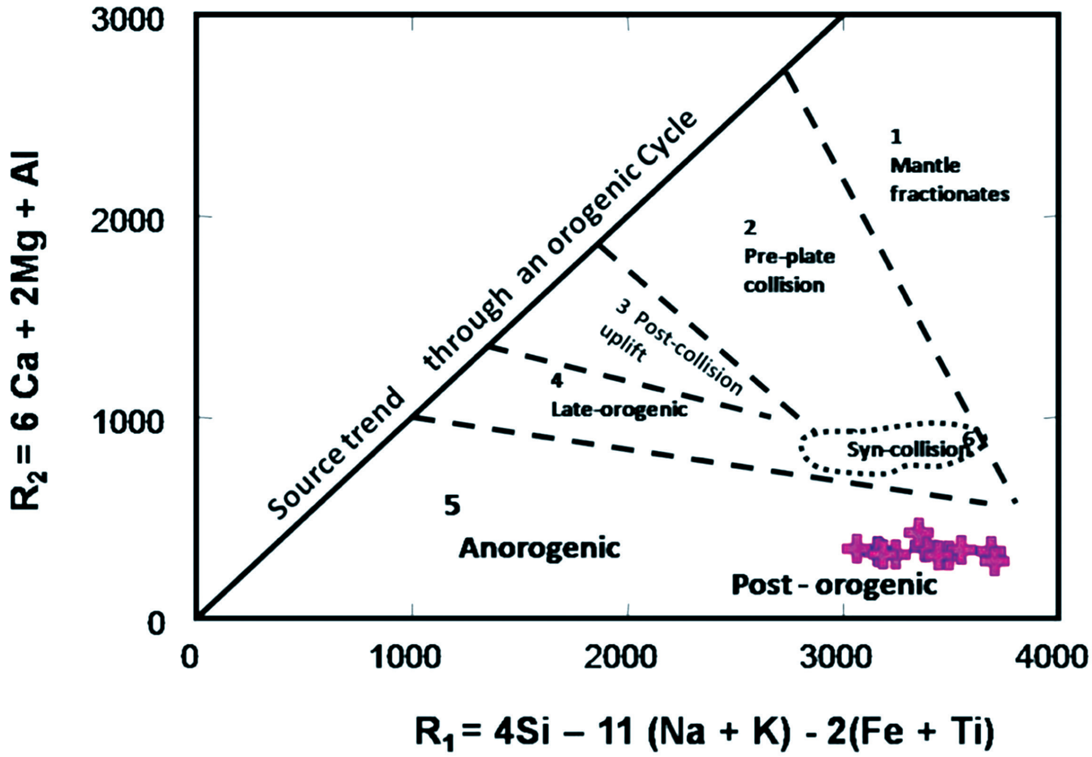

Fig. 7: R_1 - R_2 diagram showing various tectonic fields (after Batchelor& Bowden, 1985) plotted for Narnaul pegmatites.

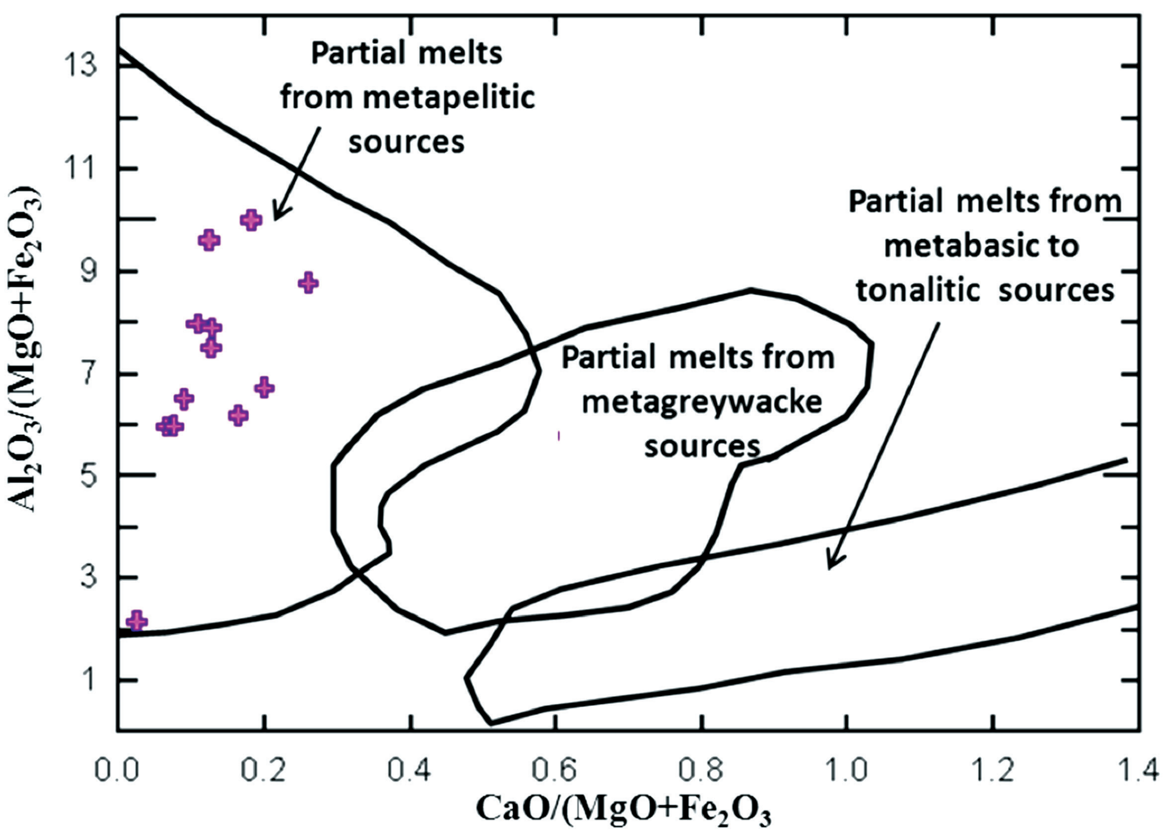

Fig. 8: Mol. CaO/(MgO+FeOt) versus mol Al_2O_3/(MgO+ FeOt) plot showing pegmatites plot in the region of partial melting from metapelitic source(fields after Altherr et al., 2000).

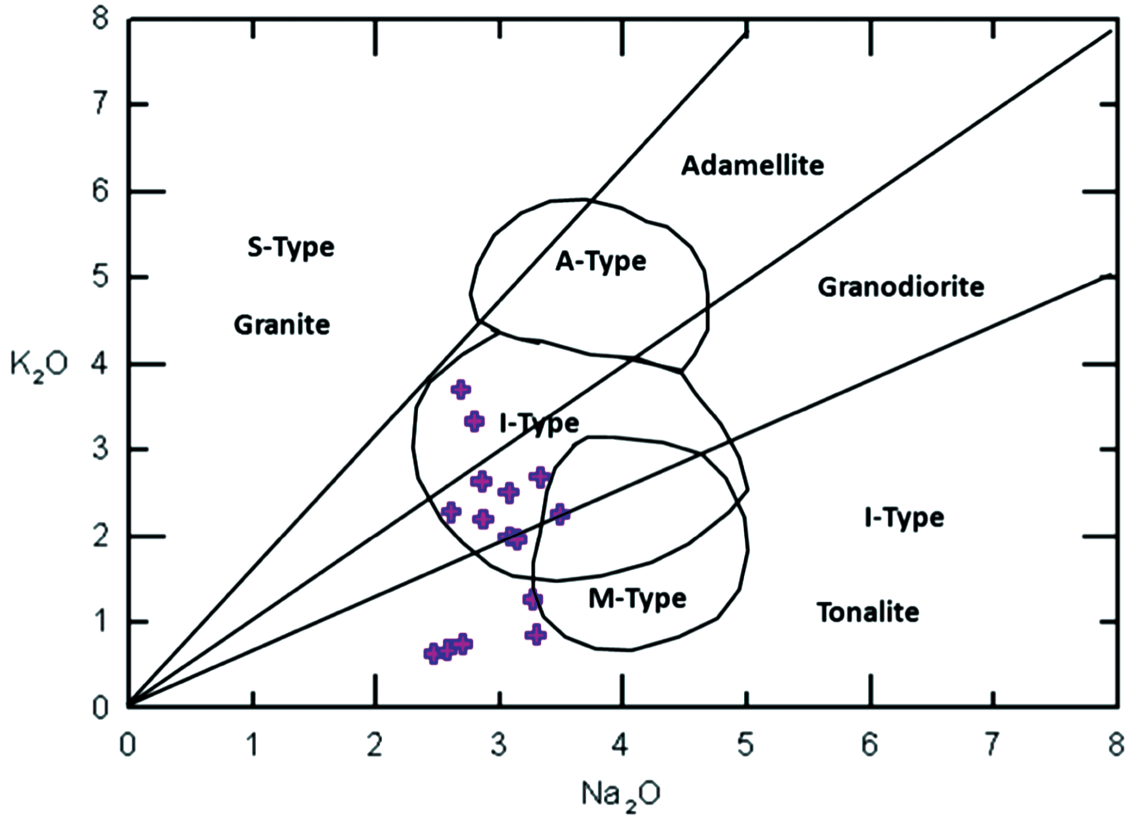

Fig. 9: K_2O versus Na_2O binary plot of Narnaul pegmatites with fields of M-, I-, S-, and A-type granite marked in it (after Misra and Sarkar, 1991).

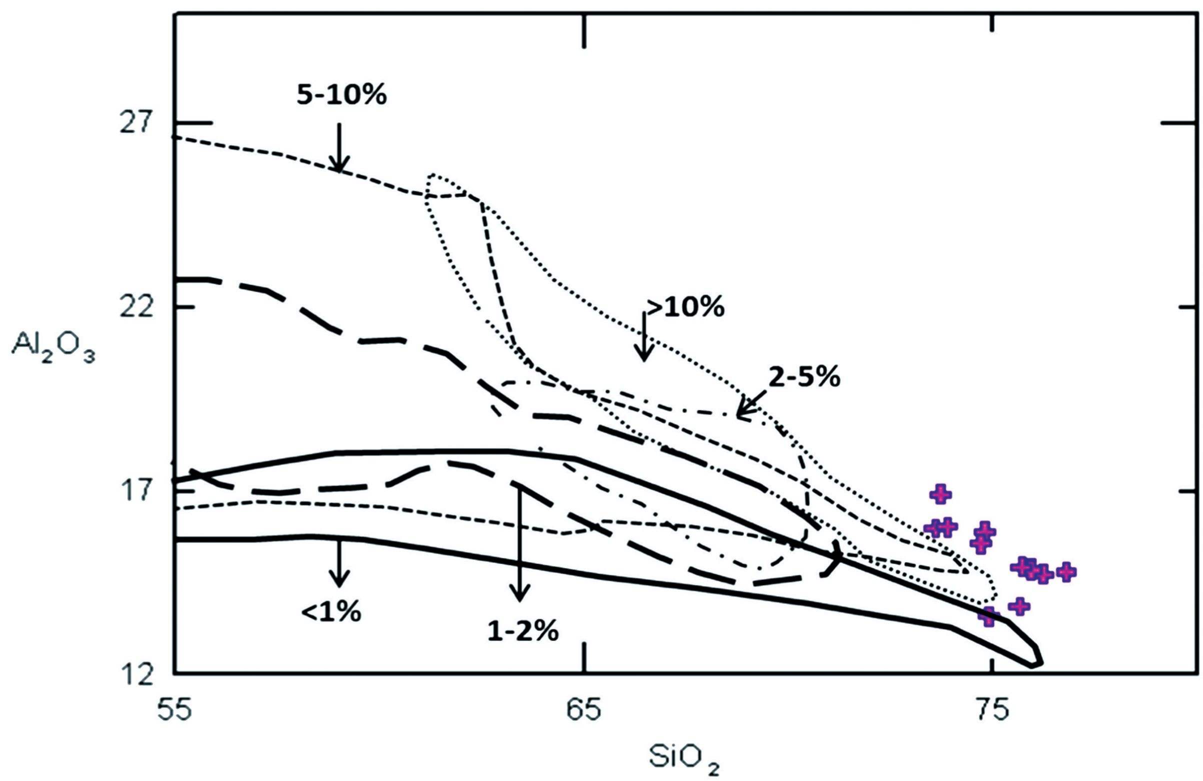

Fig. 10: Al_2O_3versus SiO_2 bivariate plot with experimentally generated melt compositions at different water contents (after Waight et al., 1998).

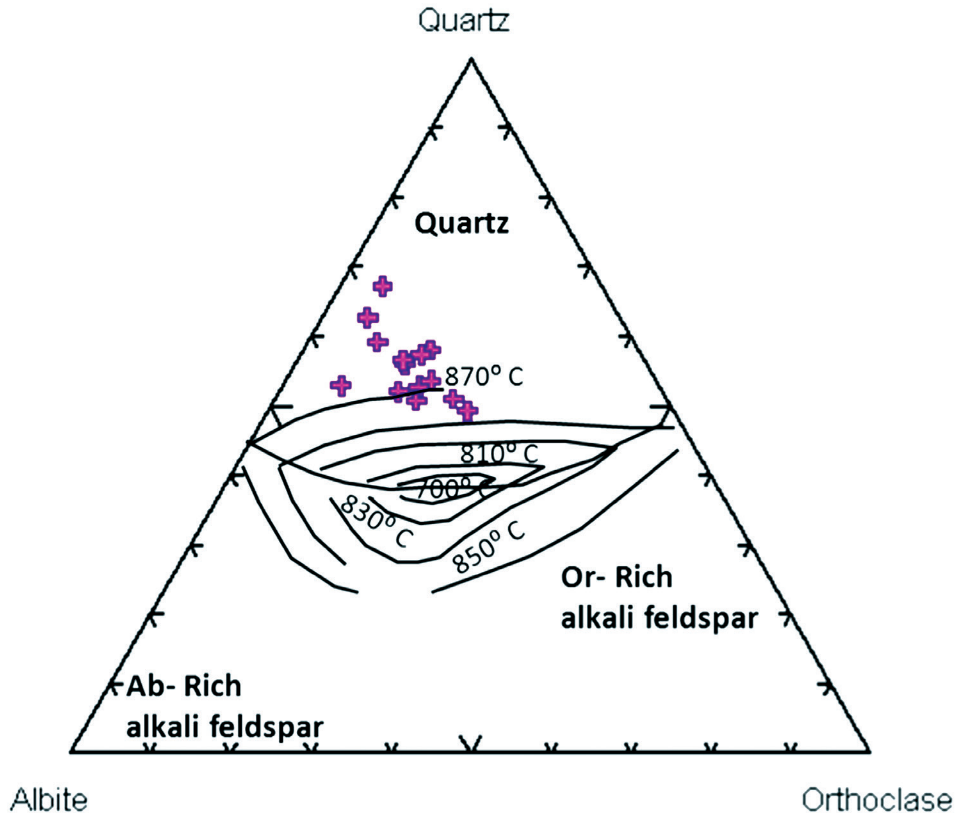

Fig. 11: Normative Q- Ab-Or ternary parameters (after Holtz et al., 1992) for Narnaul pegmatites.

Narnaul pegmatites are formed at the depth of ~30 km (Fig.12). In the Rb-(Y+Nb) and Y-Nb bivariate plot (after Pearce et al., 1984), the samples of Narnaul pegmatites plot in VAG-Syn-COLG fields (Fig. 13a & 13b). The primitive mantle (PRIMA)-normalized spider pattern (Fig.14) of Narnaul pegmatites which are characterized by negative Ba, Nb, K, Nd, and Ti and Cs, Rb, Ta, Pb, P and Zr are characterized by positive. In chondrite normalized REE diagram (Fig. 15) (Sun and McDonough, 1989), the pattern of the Narnaul pegmatites are shown in have very low total REE contents, sub parallel and fractionated patterns.

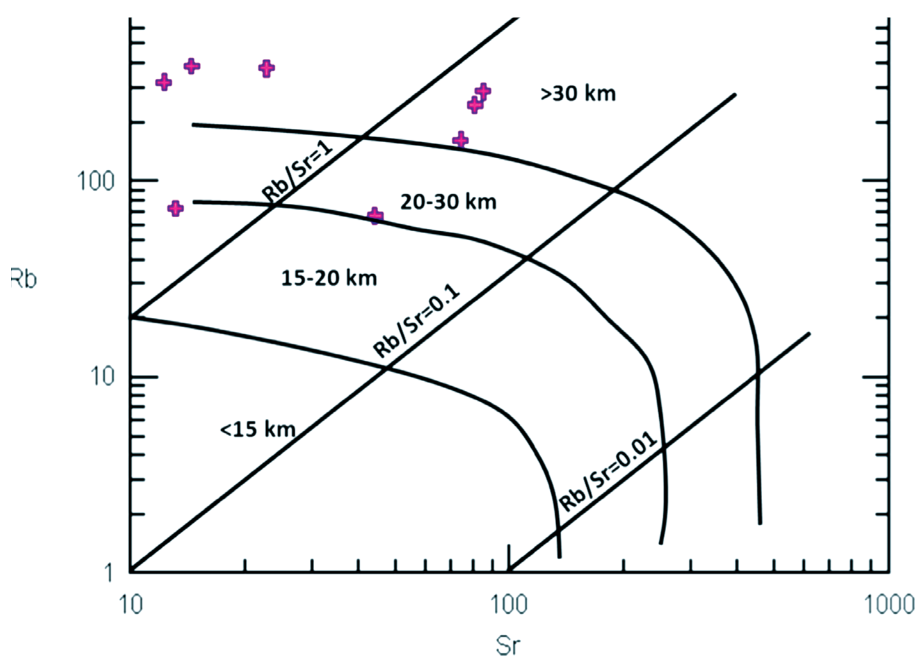

Fig. 12: Sr-Rb binary plot of Narnaul pegmetites (fields after Condie, 1997).

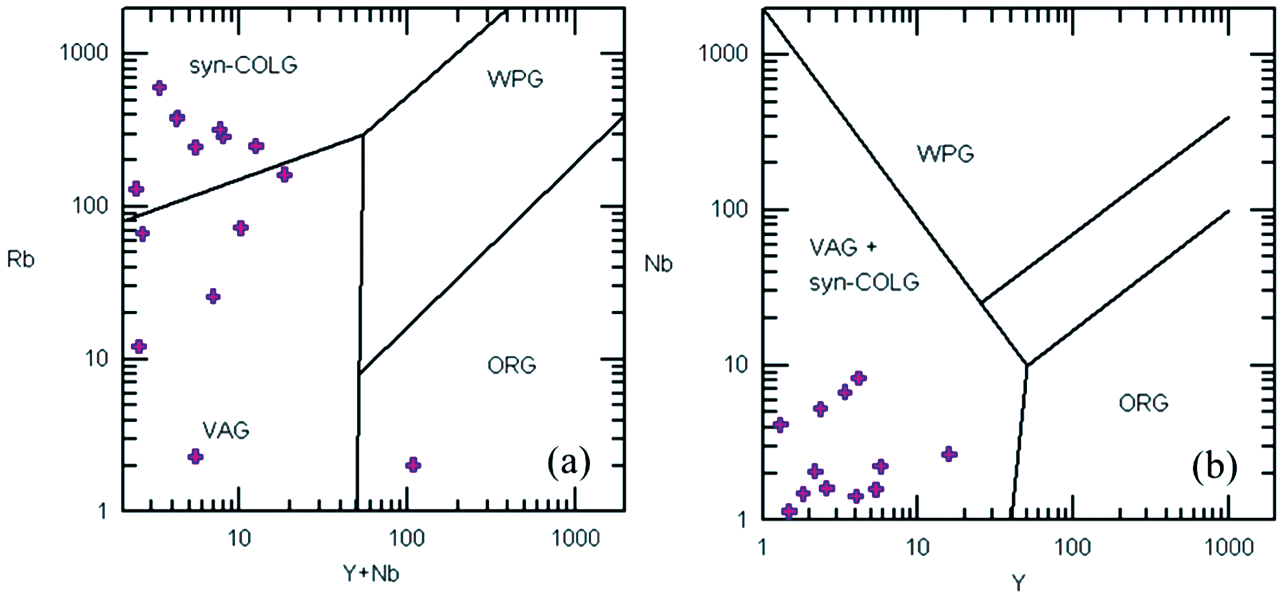

Fig. 13: In (a) Rb versus (Y+Nb) and (b) Nb versus Y discrimination diagrams (after Pearce et al., 1984) for the Narnaul pegmatites. ORG- Ocean ridge granites, WPG- Within plate granites, VAG-volcanic arc granite and Syn-COLG- Syn- collision granites.

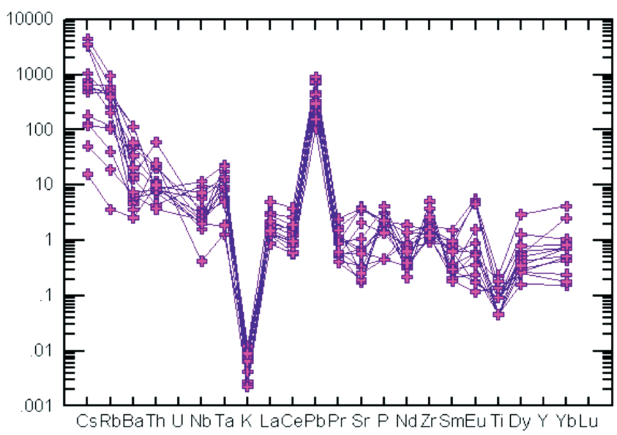

Fig. 14: Primitive mantle normalized elements pattern for the Narnaul pegmatites (Primitive mantle values are after Sun and McDonough, 1989).

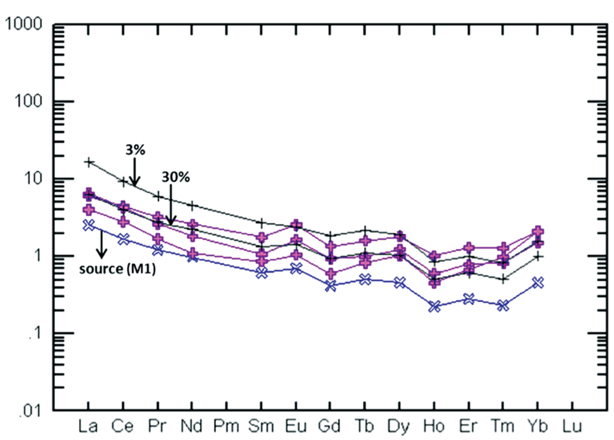

Fig. 15: The calculated REE pattern of the Narnaul pegmatites. Narnaul pegmatite sample number M1 has been selected as source rocks. Note 30% partial melt pattern of M1broadly coincide.

PETROGENESIS

Some hypotheses on the genesis of pegmatites are as below:-

Crystal growth rates in pegmatite must be incredibly fast to allow gigantic crystals to grow within the confines and pressures of the Earth's crust. For this reason, the consensus on pegmatitic growth mechanisms involves a combination of the following processes:

1. Low rates of nucleation of crystals coupled with high diffusivity to force growth of a few large crystals instead of many smaller crystals?

2. High vapor and water pressure, to assist in the enhancement of conditions of diffusivity?

3. High concentrations of fluxing elements such as boron and lithium which lower the temperature of solidification within the magma or vapor?

4. Despite this consensus on likely chemical, thermal and compositional conditions required to promote pegmatite growth, there are three main theories behind pegmatite formation. They are:

(i) Metamorphic: pegmatite fluids are created by devolatilisation (dewatering) of metamorphic rocks, particularly felsic gneiss, to liberate the right constituents and water, at the right temperature?

(ii) Magmatic pegmatites tend to occur in the aureoles of granites in most cases, and are usually granitic in character, often closely matching the compositions of nearby granites. Pegmatites thus represent exsolved granitic material which crystallizes in the country rocks?

(iii) Metasomatic: pegmatite, in a few cases, could be explained by the action of hot alteration fluids upon a rock mass, with bulk chemical and textural change?

Narnaul pegmatites have high SiO_2, Na_2O, K_2O and Y relatively low Mg number, low amount of MgO, Fe_2O_3, CaO & Sr and very low total REE. They have both the LREE and HREE elevated pattern with small positive Eu anomalies & depleted MREE. These features of Narnaul pegmatites suggest crustal origin. Very low total REE concentration in Narnaul Pegmatites are very close to the REE values of average of value chondrites (Evensen et al., 1978) and value of primordial mantle (Taylor and McLennan, 1985). The large negative Nb values of these rocks are characterized by continental crust and indicator of crustal involvement in magma processes. Here for the petrogenetic modeling of Narnaul Pegmatites, Batch melting equation (Schilling, 1966) is used which enables to calculate the trace element composition in the melt. CL/C0=1/D(1-F)F, where CL and C0 are the concentrations of a given trace element in melt and in original source, respectively. F is the melt proportion (degree of partial melt) and D (D=∑Kdi Xi) is the bulk distribution coefficient of the element in residue, where Kdiis the single element distribution coefficient for the mineral i and Xi is the weight proportion of the mineral i in the residual phases.The bulk distribution coefficient is calculated based on the reported Kd's for REE for different minerals from Hanson (1980).

The origin of Narnaul pegmatites are constrained using numerous possible source rock composition viz. Jasarpura granite, Jasrapura granitoids and Dosi pluton, average of value chondrites (Evensen et al., 1978) and value of primordial mantle (Taylor and McLennan, 1985). Jasrapura granite, Jasrapura granitoids and Dosi pluton are intruded within metasediments of Delhi Super Group of rocks and located ~ 40 km and 10 km NW, respectively of Narnaul area. Jasrapura granite and Jasrapura granitoid (Kaur and Mehta, 2007) are characterized by negative Nb and Ti anomalies and Rb, K enrichment. The Dosi pluton (Kaur et al. 2011) (sample DS-4) is represented by (2 km×1.4 km) an oval-shaped outcrop amidst Quaternary sand and alluvium and is essentially composed of albitised granite in association with minor unaltered granite. The analysed sample has undergone moderate albitisation and minor silicification. It is pink coloured, medium grained, foliated rock with largely hypidiomorphic granular texture. The rock is an amphibole-bearing albite-microcline granite and is characterized by the occurrence of virtually pure albite (An2.0±1.5, n=10) along with microcline (Or 94.1±0.7, n=17; Kaur et al., 2011).The calculated melt patterns (1 to 30%) of above source are not compatible with the REE patterns of the Narnaul pegmatites and are lying above the REE pattern of Narnaul.

Finally, the Narnaul pegmatite sample number no. M1 has been selected as an alternate source rocks (Fig.15) for Narnaul pegmatites. Pegmatite sample M1,consists quartz, microcline, orthoclase, perthite, albite, muscovite as essential minerals. It is geochemically characterized as high silica, alumina, potash, and low in iron, calcium, magnesium, phosphorous, titanium and elevated in LREE, HREE with a small positive Eu anomaly & low in MREE as compared to other pegmatite of Narnaul area. Hence, it is assumed that Narnaul pegmatites are possibly derived from a similar source having the characteristics as sample number M1 (Narnaul pegmatite rock-sample). The melt REE pattern was generated by 3%, 15%, 30% batch partial melting of sample no M1 leaving a residue consisting of 39% alkali feldspar, 40% quartz, 20% plagioclase and 1% clinopyroxene. The calculated REE pattern which is derived from 30% of the partial melting of sample number M1 is overlapping / compatible (Fig.15) with the REE pattern of Narnaul pegmatite. From above calculation using sample number M1 as a possible source rock for Narnaul pegmatites, it is advocated that a source similar to M1 sample is appearing more suitable source than Jasrapura granite, Jasrapura granitoid and Dosi pluton. Hence, Narnaul pegmatites could have been derived by 30% partial melting of a source rock similar to the composition of sample number M1 which composed of quartz, microcline, orthoclase, perthite, albite and muscovite mineralogy. The role of upper mantle cannot be neglected in the formation of Paleoproterozoic magmatism.

DISCUSSION AND CONCLUSIONS

Narnaul area consists mainly of quartzite with sub ordinate amount of schist, granitic gneiss, basic rocks, calc rocks, phyllite, slate, granite, pegmatite and veins of quartz. The rocks are included in the Delhi Supergroup. Most of the pegmatites of the study area intruded into the quartzite. These pegmatites show sharp contact with the host rocks (mainly quartzite, also schist, gneiss, basic rocks) and blurred contact with granite. Based on petromineralogical studies, pegmatites of present study area are classified into simple or undifferentiated and complex or differentiated types. The latter type is predominately exposed. Pegmatites are very coarse grained and show pegmatitic, hypidiomorphic and granophyric textures. They contain quartz, K-feldspar (perthite, microcline), albite, biotite, muscovite as essential minerals and the accessory minerals are garnet, apatite, magnetite, and ilmenite. Occurrence of large sized tourmaline, calcite, quartz, orthoclase crystals in pegmatites suggest the low rate of nucleation of crystals coupled with high diffusivity of melt due to high vapour content which induced the rapid cooling than crystallization. The presence of garnet and natrolite in the different types of pegmatite of present study areas indicate the presence of regional as well as contact metamorphic conditions in their formation. The magmatic and metamorphic reactions were operated by compressive tectonic activities during the Aravalli-Orogeny. Occurrence of beryl and tourmaline in the present pegmatite indicate the high concentration of flux elements such as boron, and beryllium which lower the temperature of the solidification of the pegmatitic melt. Their modal compositions are plotted in the field of granite, also in alkali granite and quartz rich granitoid fields of QAP diagram (Streckeisen, 1973). Narnaul pegmatites have high SiO_2, Na_2O, K_2O, low MgO, Fe_2O_3, CaO, Sr, Mg no. and very low total REE. They have both the LREE and HREE elevated pattern with small positive Eu anomalies & depleted MREE. The geochemical data show that they are I-type, peraluminous and post-orogenic characters. Detailed petromineralogical and geochemical characters of the pegmatites in Narnaul area suggested that the pegmatite fluids are generated due to the partial melting of metasediments occurring in the area and subsequently undergone replacement process which are evidenced by the presence of complex pegmatite type. Petrogenetic modeling calculation also supports that these pegmatites could have been derived by 30% partial melting of crustal source rock occurring in the region possibly during the terminal phase of Delhi orogeny.

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AUTHOR'S CONTRIBUTIONS

The geological field-work data and geochemical data were collected by N. K. Kanyan under the guidance and supervision of N. K. Sagwal and A. R. Chaudhri. The manuscript is drafted by N. K. Kanyan and N. K. Nain. All authors reviewed and approved the final manuscript.

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