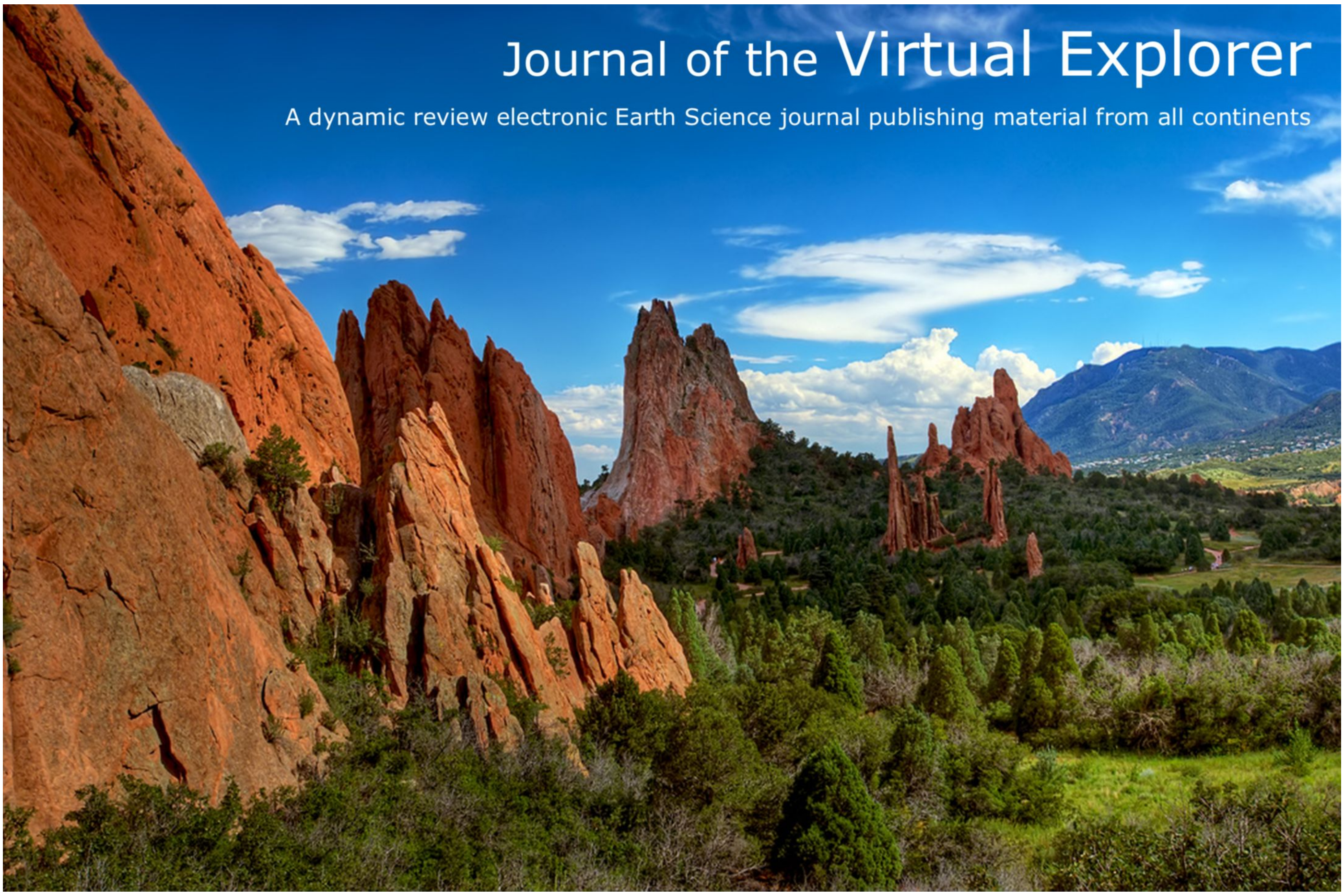


The Precambrian granitic magmatism in the NE Himalaya: implications for ancient tectonics

Shaik A. Rashid

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **32**, paper 5
In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri,
Geological Anatomy of India and the Middle East, 2009.

The Precambrian granitic magmatism in the NE Himalaya: implications for ancient tectonics

Shaik A. Rashid

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **32**, paper 5
In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri,
Geological Anatomy of India and the Middle East, 2009.

Abstract: The Paleoproterozoic Bomdila granites emplaced close to Main Central Thrust in the amphibolite-grade metasedimentary rocks in the Arunachal Pradesh, North East Lesser Himalaya. On the basis of field and petrological studies, two principle types of granites have been distinguished: porphyritic biotite-muscovite (two-mica) granites and tourmaline-bearing leucogranites. Both the types are subalkaline, strongly peraluminous (A/CNK > 1.1) and have >70% SiO_2, $Na_2O + K_2O = 5.5 – 8.5\%$, $K_2O/Na_2O = 0.8 – 2.9$. The two-mica granites show relatively more abundance of Rare Earth Elements (REE) concentrations (up to 294 ppm) when compared to the tourmaline granites, which have a lesser amount of REE contents (up to 67 ppm). However, both the types exhibit similar LREE enriched and HREE depleted patterns with consistent moderate Eu negative anomalies (Eu/Eu* = 0.3 – 0.6). Comparison with experimental data and Q-Ab-Or-H_2O phase relations in the haplogranite system indicate the magmas for two-mica suite were generated by dehydration melting of biotite under water-undersaturated conditions at temperatures of > 8000C and pressures less than 5 kbar, with tourmaline-bearing samples representing near minimum melt compositions formed under low-extent dehydration melting of muscovite. The Bomdila granites with peraluminous geochemical characteristics and the presence of pelitic enclaves, probably exhibit the features of S-type granites, and thus it is proposed that the granites may have been derived by dehydration partial melting of the upper crust. Having high Rb contents and low Y + Nb abundances the granites plot mostly within the Syn-Collision field, indicating that the granites in Bomdila formed in a continental collision tectonic setting. These results support the hypothesis that the peraluminous S-type granites are generally derived from partial melting of pelitic protoliths and further document a regional late Paleoproterozoic collisional tectonic event, which is probably related to the welding of two ancient continental blocks

Citation: Rashid, S. 2009. The Precambrian granitic magmatism in the NE Himalaya: implications for ancient tectonics. In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri, *Journal of the Virtual Explorer*, volume **32**, paper 5, doi: 10.3809/jvirtex.2009.00244

Introduction

The study of granitic magmatism in any area is significant because any attempt to model the evolution of the continental crust needs a detailed knowledge of the granite-forming events. All along the Lesser Himalaya, large areas of Proterozoic and Paleozoic granitic rocks are exposed and have been investigated in detail. More recently, petrological, geochronological and isotopic data have been instrumental for the understanding of their role in the tectonic evolution of the Lesser Himalaya (Sharma, 1983: Singh and Jain, 2003; Islam *et al.*, 2005). These granitic bodies reveal the presence of early to middle Proterozoic and Paleozoic basement rocks in the whole Lesser Himalaya. The ubiquitous character of the granites is their Peraluminous, collision-related, S-type nature and the association with amphibolite-grade metasediments.

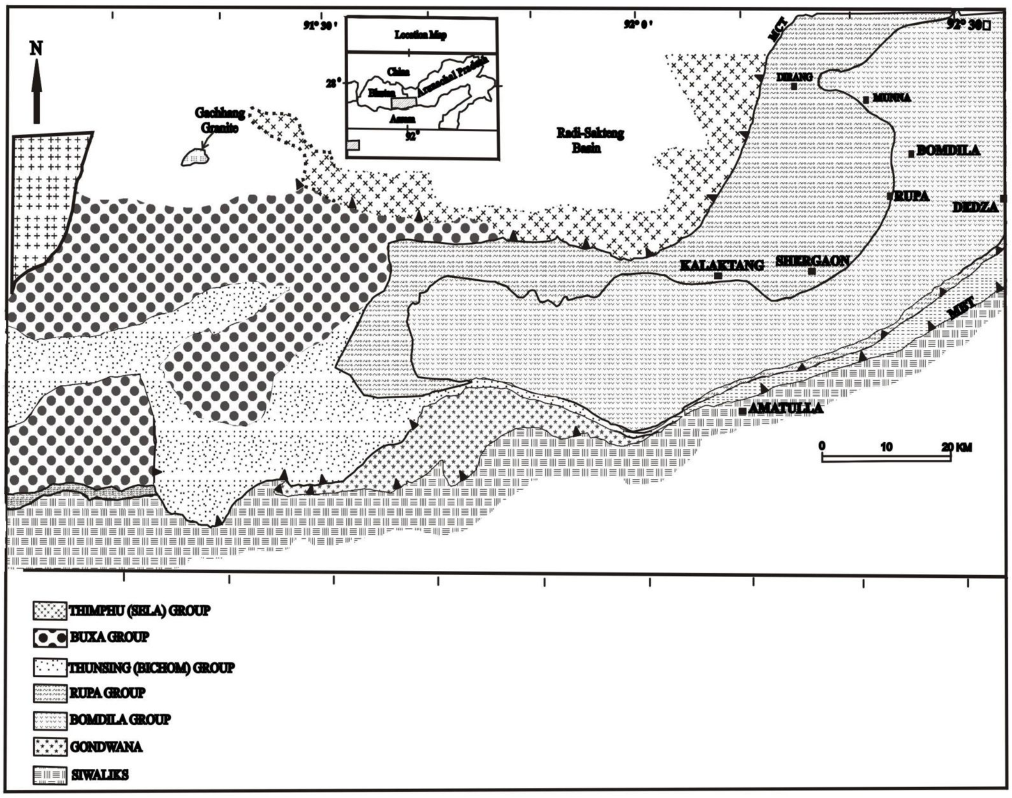
Peraluminous leucogranites, thought to have been derived by melting of the continental crust, provide important information toward understanding the evolution of the continental crust. The obvious reason is that mantle involvement in the generation of leucogranites is almost negligible. The radiogenic and stable isotope studies of different plutons (France-Lanord *et al.*, 1988; Nablek *et al.*, 1992; Castelli and Lombardo, 1988; Inger and Harris, 1993; Friend *et al.*, 2009) indicate that many are generated from heterogeneous sources. Negative ε_{Nd} values and very high $^{87}Sr/^{86}Sr$ ratios for most of the leucogranites suggest that the sources had long crustal histories (Vidal *et al.*, 1982; France-Lanord and LeFort, 1988).

Remarkable contributions on the study of basement granites from the northwest Himalaya are available but much less attention has been paid in the northeast Himalaya. Early research was concentrated only on geological and stratigraphical aspects of the region. In particular, geochemical work appears scarce. The Paleoproterozoic Bomdila granite body, associated with the extensive development of Proterozoic granitoids along a 2000 km linear belt in the Lesser Himalaya, was chosen for the present study. The granite has been examined thoroughly with a view toward understanding its petrogenesis, the regional implications of the Proterozoic granitic magmatism and its contribution in the evolution of the continental crust in the Himalaya.

Geological Setting

Bomdila orthogneisses occurs in the Arunachal Himalaya, Arunachal Pradesh, which is the northeastern most state of India. The study area, situated in the Lesser Himalaya, West Kameng district of Arunachal Pradesh, is bounded by many important thrust faults on either side (Fig. 1). Although many workers have studied the area and proposed different stratigraphic names (Acharya et al., 1975, Verma and Tandon, 1976, Kumar, 1997), recently, on the basis of lithostratigraphy, grade of regional metamorphism and associated igneous intrusives, the Proterozoic rocks of Arunachal Himalaya have been grouped into three major tectono-stratigraphic units by Srinivasan (2001).They are the Sela Group, Rupa Group and the Bomdila Group. The Sela Group, which is considered to be the youngest sequence (late Proterozoic) among the three, is best exposed around Se La pass along Bomdila-Tawang road in western Arunachal Pradesh close to Bhutan border. It consists of calc-silicates, marble, kyanite-sillimanite ± staurolite polyphase deformed schists, migmatites, high-grade ortho-augen gneisses and amphibolites, etc. with younger intrusions of hornblende granite (481 ±23 Ma, Dikshitulu *et al.*, 1995), tourmaline granite (29 ±7 Ma, Bhalla and Bishui, 1989), pegmatites and aplites.

Figure 1. Geological map



Geological map of the Arunachal Pradesh (after Srinivasan, 2001) showing different lithostratigraphic units including Bomdila orthgneisses.

The Rupa Group of rocks belong to Mesoproterozoic which unconformably overlies the Bomdila Group in the Lesser Himalaya. The Rupa Group constitutes a thick sequence of low- to medium-grade garnetiferous biotite-muscovite schists, phyllites, sericite quartzites, calc-silicates and tremolite-actinolite marbles. Main Crystalline Thrust (MCT) separates the Sela group from Rupa group of rocks and thus the former group belongs to the Higher Himalayas. The Bomdila Group comprises essentially of low- to mediumgrade metasedimentary rocks (mainly phyllites, garnetiferous mica schists and quartzites) intruded by Paleoproterozoic Bomdila augen gneisses and mafic metavolcanics.

The Bomdila gneiss, which has been characterized as orthogneiss on the basis of textural properties, is a batholithic dimension body occupying ~500km^2 area in the western Arunachal Pradesh, India. It is characterized by medium- to coarse-grained, well-defined porphyritic augen gneisses wherein the quartz/albite augens, measuring 1-10 cm, are wrapped with biotite and muscovite. The augen gneisses exposed around Bomdila town have been dated as 1914 ±23 by Rb/Sr technique by Dikshitulu *et al.* (1995) and hence are considered to be Paleoproterozoic in age. Mafic metavolcanics (amphibolite sills and dykes) occur within the gneisses. The discordant field relations and reaction zones noticed at number of places with the gneisses clearly demonstrate that the metavolcanics are younger than the gneisses and might have intruded into the basement rocks.

A weakly foliated tourmaline-bearing leucogranite is well exposed along Bomdila-Rupa road section. This granite shows an intrusive relationship with the augen gneisses, which further indicates that the leucogranites are younger than augen gneisses. In places, the tourmaline granites are associated with pegmatites and numbers of aplite along with quartz veins. Metasedimentary (pelitic schist) enclaves of different sizes have been found in the augen gneisses, which is in agreement with the already established hypothesis that the collision-related, S-type granites contain metasedimentary enclaves. This in turn suggests that the metasediments might have had a significant role in the petrogenesis of these granites. Efforts were made to collect fresh and unweathered samples of the gneisses and granites mainly from road cuttings in and around Bomdila town.

Petrography

In general, the Bomdila Orthogneisses are foliated, augen-bearing, medium to coarse grained, leucocratic and consists of quartz, plagioclase (albite to oligoclase), microcline, biotite and muscovite as essential minerals. The substantial amount of felsic mineralogy strongly suggests that they are leucogranite magmas, in agreement with the common occurrence of other such leucogranites in the Himalaya. On the basis of mineralogy (and field observations), two principle types of granites are identified. They are tourmaline-free biotite-muscovite (here after referred to as two mica) granites, which constitutes major part of the batholith and tourmaline-bearing granites (here after referred to as tourmaline granites). The only mineralogical difference between the two types is in the nature of the ferromagnesian phase, biotite in two-mica granites and tourmaline in tourmaline granites.

The gneissose structures with perfect alternate bands of mica and quartzo-fedspathic minerals are preserved in the two mica granites in which the augens are of quartz and sodic plagioclase. They show porphyritic texture with the development of K-feldspar and plagioclase phenocrysts set in a groundmass of quartz, biotite and muscovite. In addition to perthite, myrmekite and graphic, intergrowth textures were also developed in the two-mica granites. Inclusional relationships and crystal morphologies have been used to constrain the crystallization sequence, which is very similar for both types. Plagioclase showing tabular habit was perhaps the earliest mineral to crystallize, whereas anhedral K-feldspar phenocrysts, which contain abundant inclusions of other phases, occurred later. Biotite is usually interstitial and commonly intergrown with muscovite. However, albitic plagioclase (An_{12}) phenocrysts with occurrence of abundant euhedral biotite and muscovite inclusions (along cleavage planes) suggest that the latter minerals began to crystallize early. The quartz is generally interstitial but also commonly occurs as rounded inclusions in plagioclase, K-feldspar, biotite and muscovite, thus indicating an early crystallization. Some samples, particularly those from the marginal part of the main pluton, show fine- to medium-grained cataclastic textures with abundant tectonic-related features. For example, occurrence of ribbon quartz with undulating extinction, bending in biotite, bending and cracks in plagioclase which are invaded by plastically mobilized quartz, *etc.* are some of the features indicative of ductile shearing of the rocks at the contact zone. In addition to these features, the two mica granites also exhibit mylonitization characteristics at the contact zone along with the development of tectonically fractured garnets where muscovite and quartz squeezed plastically into cracks of the brittle garnets. Among the accessory minerals, iron oxides occur along with apatite, zircon and garnet.

The tourmaline granite consists of predominantly quartz, K-feldspar, plagioclase, muscovite and tourmaline. Biotite is either absent or very rarely found in the thin sections. Tourmaline is euhedral to subhedral, slightly broken and contains abundant inclusions of quartz, muscovite and, in some cases, of apatite. Tourmaline is also found as inclusions in euhedral plagioclases and anhedral quartz. The occurrence of penetrative relation between tourmaline and muscovite suggest a magmatic origin for these two minerals. Foliation is completely absent in this granite, however few thin sections show weak foliation. Textures are mainly equigranular, with occasional plagioclase or K-feldspar megacrysts up to 4mm in length. Quartz recrystallization along cleavage planes of perthitic feldspar suggests that it has been subjected to metamorphism during Tertiary Himalayan orogeny and hence is considered to be older than Tertiary age. Zircon and tourmaline occur as common accessory minerals.

Analytical notes

The major and trace element analyses, after appropriate crushing, splitting, pulverization and homogenization procedures, have been carried out by X-ray fluoresence

(XRF) spectrophotometer (SIEMENS SRS 3000) on pressed pellets at the Wadia Institute of Himalayan Geology, Dehradun and by ICP-MS at the National Geophysical Research Institute (NGRI), Hyderabad, respectively. The quality of the analyses was monitored by the simultaneous analysis of some in-house (DG-H) and international standards (GSP-1, G-2, JG-2). The analytical precision, obtained on the basis of replicate analysis, is well within 5-10% for trace elements and ~5% for major oxides. Accuracy for most of the elements that were analysed was good (<5 % for major elements and <12 % for trace elements).

Geochemistry

The major and trace element geochemical data of the Bomdila Orthogneisses is presented in Table 1. The silica content of the samples varies from 70-76 wt.%. Total alkali concentrations are generally variable and range from 5.5 to 8.5 wt.%, which are mainly controlled by K_2O abundance. However, the tourmaline granites show slightly higher total alkalies when compared to the two-mica granites; this may be because the former are enriched in both K and Na contents. All the Bomdila samples are peraluminous with aluminium saturation index [ASI, molecular Al_2O_3/CaO+Na_2O+K_2O] of more than 1.1 and also contain abundant normative corundum. These characteristics and high Al_2O_3 (>13 wt.%) contents indicate that they correspond to S-type granites of Lachlan Fold Belt (Chappell and White, 1974). The pertinent major and trace element compositions of the granites are represented in Harker variation diagram for ease of interpretation and comparison with data from the literature. Large variation in both the suites and intra- and inter-suite variations in some of the elements can be observed (Fig. 2) emphasizing the heterogeneity of the granites. Moreover there are no discernible trends of the major elements (with silica) which could potentially indicate fractional crystallization. However, Al_2O_3, Fe_2O_3 and MgO exhibit poor decreasing linear trends with increasing silica, which may indicate fractionation of early formed aluminous and ferromagnesian phases from the magma. It is noteworthy that two-mica granites have low silica content and high FeO+MgO content (up to 6 wt.%) when compared to tourmaline granites, where the latter is characterized by relatively high silica and low FeO + MgO (up to 2 wt.%), TiO_2 and CaO abundances. Tourmaline granites are enriched in K_2O and hence in normative Or/Ab in contrast to the other tourmaline bearing granites. For example, in the Himalayan Badrinath-Gangotri and Manaslu plutons, tourmaline is generally confined to the most sodic granites (Scaillet *et al.*, 1990; France-Lanord and LeFort, 1988).

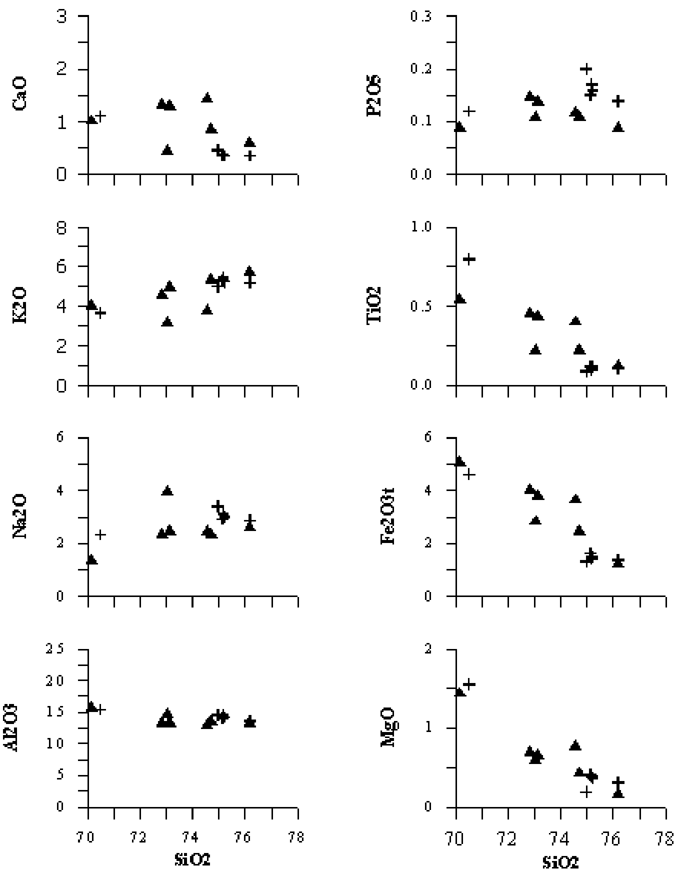
Table 1. Major and trace element concentrations of Bomdila orthogneisses, Arunachal Pradesh, NE Lesser Himalaya

	Two-mica granites									Tourmaline granites			
	BG-2	BG-3	BG-4	BG-6	BG-8	BG-28	BG-10	BG-20	BG-33	BG-33A	BG-34	BG-35	BG-36
SiO_2	73.13	72.84	76.17	74.55	74.71	73.03	70.16	70.49	74.97	75.21	75.16	75.11	76.18
TiO_2	0.44	0.46	0.13	0.41	0.23	0.23	0.55	0.8	0.09	0.12	0.1	0.12	0.11
Al_2O_3	13.4	13.5	13.45	13.16	13.79	14.97	16.02	15.46	14.61	14.24	14.58	14.11	13.61
Fe_2O_3	3.85	4.08	1.27	3.71	2.5	2.89	5.16	4.62	1.34	1.48	1.45	1.64	1.37
MgO	0.67	0.72	0.18	0.78	0.45	0.61	1.46	1.55	0.19	0.37	0.39	0.42	0.31
CaO	1.32	1.34	0.63	1.47	0.89	0.48	1.04	1.11	0.47	0.36	0.38	0.36	0.36
Na_2O	2.51	2.41	2.66	2.53	2.41	4.01	1.42	2.34	3.44	3.01	3.11	2.93	2.87
K_2O	5.05	4.66	5.83	3.86	5.38	3.23	4.1	3.7	5.02	5.25	5.43	5.29	5.19
P_2O_5	0.14	0.15	0.09	0.12	0.11	0.11	0.09	0.12	0.2	0.16	0.17	0.15	0.14
MnO	0.04	0.05	0.01	0.05	0.03	0.03	0.02	0.05	0.02	0.02	0.02	0.02	0.02
Trace elements (ppm)													

	Two-mica granites									Tourmaline granites			
Sc	5.76	5.92	2.33	5.48	3.91	3.44	7.41	6.92	4.48	4.16	3.73	4.66	4.17
Rb	278.68	308.26	290.27	273.36	367.28	177.59	178.55	156.43	555.61	465.57	426.03	459.68	436.14
Sr	79.76	57.74	38.77	52.67	42.48	31.39	90.61	109.02	20.21	21.14	23.05	19.76	20.90
Y	42.22	46.55	17.69	36.94	48.65	36.30	26.37	28.67	18.81	19.24	18.21	28.45	21.47
Zr	3.60	2.32	3.10	3.01	2.47	19.15	2.90	6.40	3.27	3.10	3.62	2.73	3.27
Nb	11.75	12.18	8.64	10.37	9.39	13.64	10.51	13.59	14.37	12.57	8.96	11.70	10.27
Ba	696.31	470.61	211.90	332.50	374.33	290.90	663.46	599.20	115.42	128.89	171.05	118.90	125.41
Hf	0.19	0.15	0.12	0.17	0.15	1.06	0.12	0.23	0.13	0.14	0.14	0.12	0.15
Ta	1.63	2.35	1.65	1.82	1.56	2.86	1.28	1.68	3.69	2.54	3.24	3.85	2.24
Pb	26.01	25.88	31.63	21.94	26.01	14.97	21.61	23.74	16.30	15.25	15.87	14.22	16.59
Th	27.81	28.18	13.57	26.19	23.37	21.19	15.44	23.35	6.68	9.27	8.31	9.89	9.79
U	5.91	6.60	3.00	7.73	6.39	4.49	2.65	4.55	8.06	7.35	17.72	30.15	9.14
La	54.13	55.00	24.77	46.80	35.10	33.11	49.93	63.56	8.30	11.07	12.61	13.75	12.35
Ce	113.02	113.98	52.94	97.40	74.05	69.04	97.73	130.31	17.74	23.48	25.57	26.09	26.24
Pr	11.96	12.15	5.73	10.25	7.85	7.30	9.98	13.46	1.81	2.41	2.76	2.95	2.67
Nd	45.45	46.04	21.18	37.93	29.01	27.22	36.62	51.02	6.91	8.77	10.25	10.87	9.63
Sm	8.70	9.01	4.84	7.32	6.14	5.58	6.07	8.28	1.68	1.79	2.20	2.42	1.98
Eu	1.11	1.05	0.54	0.83	0.62	0.62	1.02	1.41	0.19	0.21	0.27	0.25	0.20
Gd	7.39	7.65	3.75	5.96	5.43	4.77	4.64	6.33	1.55	1.64	1.81	2.22	1.70
Tb	1.18	1.26	0.60	1.00	1.05	0.87	0.68	0.86	0.35	0.35	0.38	0.50	0.39
Dy	7.38	8.14	3.38	6.45	7.49	6.03	4.24	4.96	2.75	2.88	2.82	4.03	3.04
Ho	0.78	0.88	0.31	0.67	0.88	0.66	0.47	0.53	0.32	0.34	0.32	0.47	0.37
Er	2.47	2.75	0.88	2.05	2.85	2.11	1.62	1.73	1.12	1.23	1.08	1.59	1.32
Tm	0.30	0.34	0.10	0.24	0.36	0.25	0.21	0.20	0.17	0.19	0.15	0.22	0.19
Yb	2.86	3.29	0.81	2.27	3.39	2.28	2.18	2.00	1.88	1.97	1.56	2.20	2.08
Lu	0.45	0.53	0.12	0.35	0.51	0.32	0.36	0.30	0.29	0.30	0.22	0.32	0.31
Eu/Eu*	0.42	0.39	0.39	0.38	0.33	0.37	0.59	0.60	0.35	0.37	0.41	0.33	0.33
CIPW norms													
Quartz	0.50	0.53	0.47	0.56	0.51	0.49	0.65	0.55	0.45	0.47	0.46	0.48	0.49
Ortho-clase	0.43	0.39	0.49	0.33	0.45	0.28	0.35	0.52	0.42	0.44	0.46	0.45	0.44

	Two-mica granites									Tourmaline granites			
Albite	0.32	0.31	0.34	0.32	0.31	0.52	0.18	0.13	0.44	0.39	0.40	0.38	0.37
Anorthite	0.09	0.10	0.04	0.10	0.06	0.03	0.07	0.05	0.03	0.03	0.03	0.03	0.03

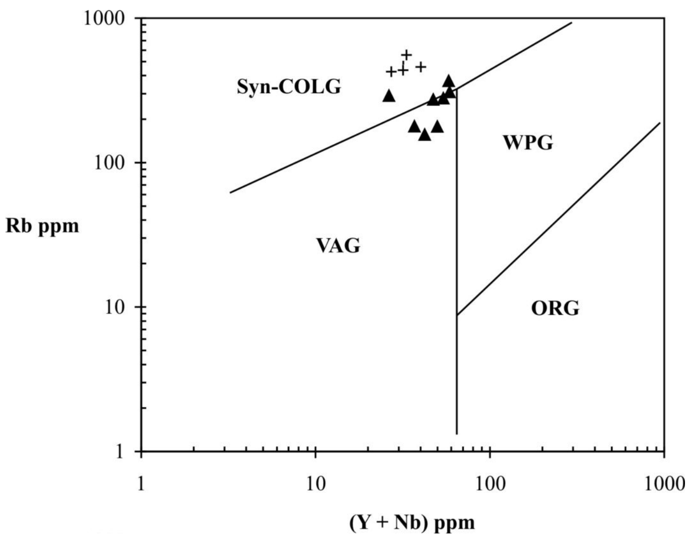
Figure 2. Harker variation diagram (major elements vs. silica)



Harker variation diagram (major elements vs. silica) for Bomdila orthogneisses. Solid triangles = two-mica granites and Cross hair symbol = tourmaline-bearing leucogranite.

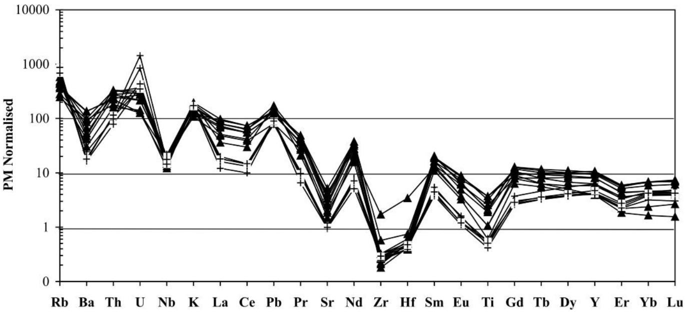
The Bomdila orthogneisses are enriched in incompatible elements such as Rb, Ba, K and Th, and depleted in high field strength elements (HFSE) like Zr, Hf, Ta, Y and Nb (Table 1). The enrichment of the Bomdila samples in the incompatible elements and the depletion in the HFSE strongly supports their postulated crustal source. Both the granite suites are characterized by high incompatible elements/HFSE ratios, which is in agreement with many intra-crustally derived granites. Tourmaline granites are clearly distinguished by their low Sr and Ba contents compared with the two-mica granites and are generally depleted in Sc, Y and Nb (Table 1). The discriminant Rb vs. (Nb + Y) diagram (Fig. 3) shows that the tourmaline granite generally lies within the syn-collision field (as do other Himalayan leucogranites), whereas the two-mica granites straddles the field boundary between collision granite and volcanic-arc granite. The extensive studies on Himalayan leucogranites by Harris *et al.* (1986), suggest that the granites that form in the syn-collision zones are generally peraluminous leucogranites and may be derived from the hydrated bases of continental thrust sheets. Primitive mantle normalized spidergrams for the Bomdila rocks are presented in Fig. 4. Like most crustal granitoids, they show negative Ti, Sr and Nb anomalies, reflecting the influence of some accessory phases such as rutile as a residual phase in high pressure melting during the event that formed juvenile sialic crust (Gill, 1981).

Figure 3. Tectonic discrimination diagram



Tectonic discrimination diagram of Pearce et al. (1984). Syn-COLG – syn-collision granites, WPG-within-plate granites, VAG-volcanic arc granites. Symbols as in figure 2.

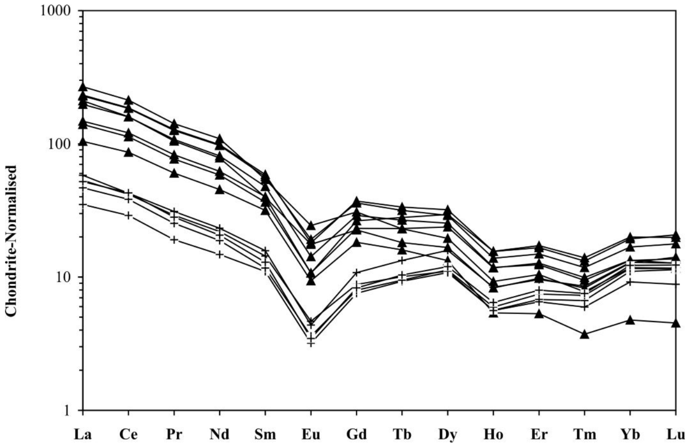
Figure 4. Primitive mantle normalized trace element spider diagram



Primitive mantle normalized trace element spider diagram of Bomdila orthogneisses. Normalising values after Sun and McDonough, 1989.

In contrast with other Himalayan leucogranites which are generally characterized by unusually low REE contents, the Bomdila rocks show higher concentrations of all REEs than published averages from other such leucogranites (Vidal *et al.*, 1982; Scaillet *et al.*, 1990). The two-mica granites show higher total REE concentrations (up to 294 ppm) than the tourmaline granites (sum = 67 ppm). The REE contents of two suites indicate light REE (LREE) enrichment over heavy REE (HREE) and have variable LREE/HREE ratios [$(La/Yb)_N$ = 3–23]. The patterns show steeply inclined LREEs with flatter and little-fractionated HREEs resulting in overall concave patterns (Fig. 5). The REE abundances of the Bomdila granites coincide with typically crustally derived granites (*i.e.* La = 20-100X chondrite, Yb = 0.5–8X chondrite, Holtz, 1989) and show consistent fractionation patterns within the LREE group [$(La/Sm)_N$ = 3–5]. Negative Eu anomalies are pronounced in both the suites and reveal a very narrow range of difference (Eu/Eu* = 0.35–4) indicating that plagioclase fractionation has been essential in their petrogenesis.

Figure 5. Chondrite-normalised REE patterns of Bomdila orthogneisses.

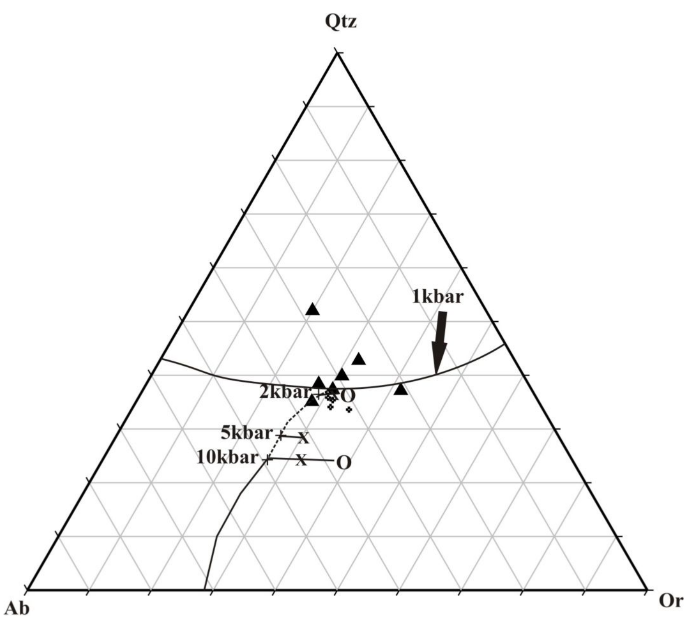


Chondrite-normalised REE patterns of Bomdila orthogneisses. Normalising values after Sun and McDonough, 1989. Symbols as in figure 2.

Petrogenesis and Discussion

Although experimental studies suggest that leucogranites can be generated by a variety of processes, both the major and trace element characteristics of the Bomdila leucogranites are better explained by varying degrees of partial melting and fractionation. An overlap in the wide concentration ranges of oxides, such as SiO_2, CaO, MgO, $Fe_2O_3^t$ and Sr (Table 1) of the two-mica and tourmaline granite suites, with no discernable differentiation trends on Harker variation diagram, precludes the derivation of one suite from the other by differentiation following emplacement. This, in turn, suggests that both suites may have been derived from different sources. In order to determine the phase equilibria conditions of the Bomdila granites, the samples were projected onto the Q-Ab-Or phase diagram (Fig. 6) which also contains 2 and 5 kbar minima and eutectics of the haplogranite system with varying aH_2O in the melt (Holtz *et al.*, 1991). It can be noticed in the diagram that the two-mica granites do not cluster about a minimum-melt composition characteristic of water-saturated haplogranite phase relations (Tuttle & Bowen, 1958). Instead, they form a spread of compositions with a trend defined by variable quartz/orthoclase and orthoclase/albite ratios. Experimental work by Johannes & Holtz (1990) has demonstrated that quartz/orthoclase ratios increase as pressure decreases in water-undersaturated melts. Further studies on granite indicated that orthoclase/albite ratios of granite minimum melt compositions are greatly increased at decreased water activities (Ebadi & Johannes, 1991). Experimental studies on crystallization of leucogranite magmas (Scaillet *et al.*, 1995) suggest that two-mica granites and tourmaline granites can be generated at low (between 5 and 7.5 wt%) and high (>7 wt.%) initial water contents, respectively. Therefore, the Bomdila two-mica granites with quartz-rich compositions and plotting at decreased pressures (<5 kbars) and low water activities in the diagram, suggest their derivation from an alumina-saturated source under water-undersaturated condition at temperatures >800°C. Whereas the tourmaline granite samples cluster around a composition corresponding to minimum melt at ~3 kbar, aH_2O ≈0.5. These values are consistent with thermobarometric studies of the many well-studied leucogranites from the Himalaya such as Manaslu (Guillot *et al.*, 1991), Langtang (Inger and Harris, 1993), *etc.*

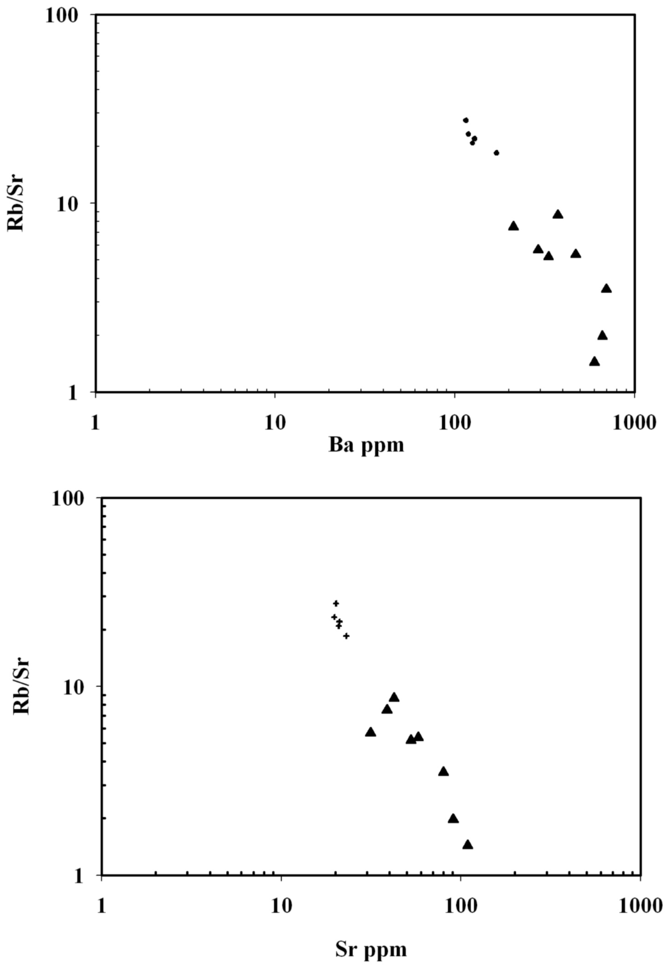
Figure 6. Phase relations and minimum-melt compositions



Phase relations and minimum-melt compositions in the system Quartz-Albite-Orthoclase ±H_2O. Minimum-melt compositions are from Winkler (1979) and Ebadi and Johannes (1991)., aH_2O=1; O, aH_2O=0.5; Δ, aH_2O=0.3. Qtz= Quartz, Ab= Albite, Or= Orthoclase. Symbols as in figure 2.

Therefore the phase-equilibria considerations and geochemical variation of the two suites of Bomdila gneisses suggest that the dominant petrogenetic process was partial melting rather than large scale post-emplacement differentiation. Further, the peraluminous geochemistry, S-type character, negative Ti, Sr and Nb anomalies of the rocks in primitive mantle normalized diagram and the presence of metasedimentary enclaves strongly support a crustal source, possibly a pelitic protolith for these granites. Harris & Inger (1992) tried to evaluate the melt reactions involved in the generation of granitic melts from pelitic rocks and have given different models such as: 1) fluid-saturated muscovite melting, 2) fluid-absent muscovite melting, and 3) fluid-absent biotite melting. For these models, trace elements such as Rb, Sr and Ba and their corresponding ratios may act as diagnostic. A linear negative trend can be observed in the diagram (Fig. 7), particularly in the Rb/Sr vs. Sr plot and show systematic variation between tourmaline-free and tourmaline-bearing samples. The negative trend clearly corresponds to removal of K-feldspar. The higher concentrations of Ba (up to 952 ppm) in two-mica granites are consistent with biotite melting in the source. The Kd (biotite/melt) value (~6, Hanson, 1978) implies that if more than ~20% biotite is in the residue, most of the Ba from the source will remain in the residue. According to McDermott's *et al.* (1996) model, biotite dehydration melting is mainly controlled by the presence of plagioclase or biotite minerals in the source. If the abundance of plagioclase in pelite-dominated sources limits the maximum degree of partial melting, then the melt is enriched in Sr relative to both Rb and Ba. Any increase in the proportion of the greywacke end-member in the source would lower the melt fraction because melting is then limited by the availability of biotite. The melt then becomes enriched in Rb and Ba relative to Sr resulting in high Rb/Sr and Ba/Sr ratios. Thus, it can be inferred from the above discussion that biotite-limited, vapour-absent biotite dehydration melting is the probable mechanism which can best explain the combination of high Rb/Sr, Ba/Sr and Fe_2O_3 + MgO (up to 11 wt.%) contents of the two-mica granites.

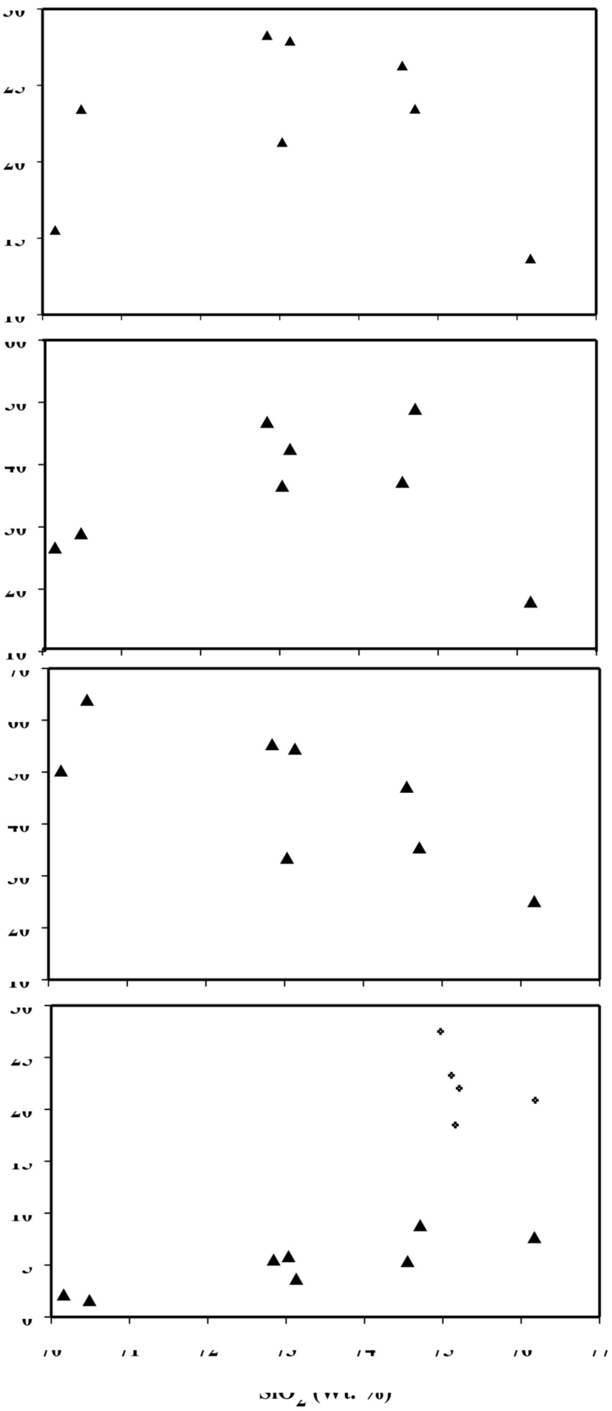
Figure 7. Rb/Sr vs. Sr and Ba plot for Bomdila orthogneisses.



Rb/Sr vs. Sr and Ba plot for Bomdila orthogneisses. Symbols as in figure 2.

In addition to partial melting, fractional crystallization may also have played an essential role in the generation of two-mica granites as evident from fractionation trends displayed by the granites. For example, decreasing Fe_2O_3t and MgO (Fig. 2) and increasing Rb/Sr ratios with increase in SiO_2 (Fig. 8) exhibited by the granites substantiate the above inference. On the contrary, it is prominently seen that tourmaline granite suite with almost negligible silica range (75–76 wt.%), shows vertical variation in these diagrams, suggesting the insignificant role of fractional crystallization during their formation. The P_2O_5 abundance will be increased progressively with fractional crystallization in the S-type granites because apatite is soluble in strongly peraluminous and felsic melts (London, 1992). Other elements that occur in phosphate accessory minerals, such as Th, La and Y, decrease in abundance with continuing fractional crystallisation of S-type melts (Chappell 1999), because of the low solubility of monazite. The progressive increasing trend of P_2O_5 (Fig. 2) and decreasing trend of Th, La and Y shown by the two-mica granites (Fig. 8) further confirms the role of fractional crystallization.

Figure 8. SiO_2 vs. Rb/Sr, La, Y and Th plot

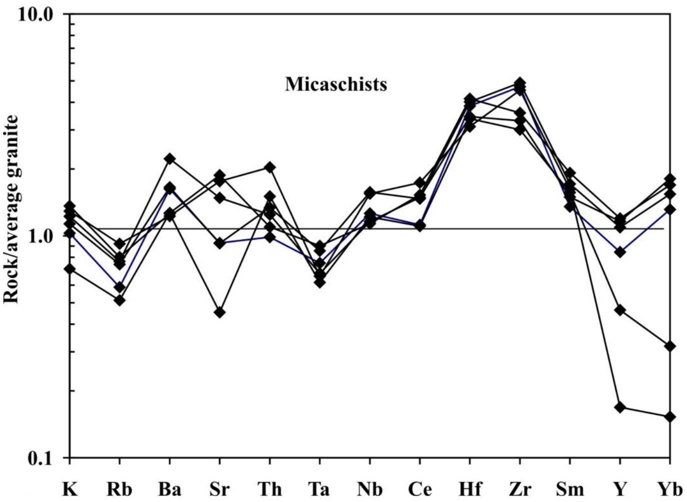


SiO_2 vs. Rb/Sr, La, Y and Th plot for Bomdila orthogneisses. Symbols as in figure 2. Note the prominent Rb/Sr positive correlation and negative correlation of La, Y and Th with SiO_2 of two-mica granites.

The phase equilibria and geochemistry of the tourmaline granites represent melting conditions of ≥700°C low water activity (Fig. 6) and possibly pressures <5 kbar. The low concentrations of TiO_2 (~0.1 wt.%) and Ba in the tourmaline granites suggest a lack of extensive melting of biotite. On the other hand, the high K_2O (>5 wt. %), Rb and low CaO (~0.4 wt.%), total iron (~1.5 wt.%), MgO (≤0.5 wt.%) and Sr contents indicate that melts were derived from the incongruent dehydration melting of muscovite (Harris *et al.*, 1993). Various mineral analyses have shown that after tourmaline, muscovite is the most important site for boron in granitic rocks (Rockhold *et al.*, 1987). Dehydration melting of muscovite in pelites is likely to lead to B-rich melts and it has been estimated that 10% fusion of a pelitic schist with 100ppm B will lead to ~1000ppm boron in the melt, enough to produce approximately 3.5% tourmaline (Nablek *et al.* 1992). This in turn indicates that the petrogenetic process proposed for Bomdila tourmaline granites is consistent with many such other leucogranites from the Himalaya. The ascent of the hot melts of two-mica granites may have triggered low extent muscovite dehydration melting of pelites (most probably schists) higher in the crust producing the boron-rich low-Ti melts (Nabelek *et al.*, 1992) similar to Bomdila tourmaline leucogranites.

From the above discussion, it an be convincingly argued that the two suites of the peraluminous Bomdila orthogneiss were predominantly formed by partial melting and fractional crystallization (in the case of two-mica granites) of pelitic rocks from the upper crust. Presence of metasedimentary enclaves (pelitic schists) in the two-mica granites and the crystallization of magmatic tourmaline in tourmaline granites are also consistent with a metasedimentary source (Bernard *et al.*, 1985). An attempt is made in this paper to explore the possible source rocks for these granites. In this perspective, the mica schists with whom the granites are associated offer potential source lithologies. A striking similarity between the composition of proposed source lithology and the average Bomdila orthogneiss is clearly evident in the diagram (Fig. 9), supporting the assumption that metasedimentary rock (similar to the micaschists) exposed along with granites are the most likely source for the Bomdila orthogneisses.

Figure 9. Trace element abundances in mica schists



Trace element abundances in mica schists, normalized against average Bomdila leucogranites.

Implications for ancient tectonics in the Himalaya

The Paleoproterozoic (1900 ±200 Ma) granitic magmatism has been reported from all along the 2000km Lesser Himalayan belt staring from the Besham gneiss in the Lower Swat Valley, NW Himalaya to the Bomdila gneiss in the NE Himalaya (Sharma, 1998). The extensive studies of these granites (Sharma, 1983; Gupta *et al.*, 1994; Prabha and Rawat, 1999; Sharma and Rashid, 2001) indicate that they have unequivocal similarities in terms of their geological setting, tectonic setting and geochemistry. All of these studies show that the granites are formed during syn-collisional tectonic environment, suggesting that collision of two continental blocks might have occurred during Proterozoic period along this linear belt, similar to the already established Paleozoic Lesser Himalayan granitoid belt (Le Fort *et al.*, 1986) related to Pan-African orogeny. This further implies an episode of significant Proterozoic orogenic events in the Lesser Himalaya: and, possibly the later tectonics exposed these granites to weathering and provided detritus to the then formed large Proterozoic sedimentary basins in the Lesser Himalaya. This deduction is in strong agreement with the inference drawn by many researchers who, on the basis of textural and geochemical investigations of the Proterozoic sediments from the Lesser Himalaya (Rashid, 2002, 2005), suggested that the sediments were derived exclusively from felsic (leuco-, S-type-granitic) sources occurring in close proximity or adjacent to the basins. This argument rules out the hypothesis that the relatively mafic, I-type-granitic plutons from the Peninsular India, such as Bundelkhand granite and granites from Aravalli region, may have contributed sediments to the Lesser Himalayan sedimentary basins.

Conclusions

The Paleoproterozoic Bomdila orthogneisses exposed in the Arunachal Pradesh, NE Lesser Himalaya are medium- to coarse-grained pelite-derived leucogranites emplaced in the amphibolite-facies schistose rocks. The main pluton consists of two suites, *i.e.* two-mica granite and tourmaline-bearing granite. The chemical compositions are similar to those of other Himalayan leucogranites, being typical for melts generated through anatexis of upper crustal material. Trace element composition and the presence of pelitic enclaves suggest that Bomdila leucogranites formed by vapour-absent anatexis of metapelites (mica schists) similar to those exposed in the Bomdila area. Phase equilibria considerations and comparisons with experimental data indicate that the magmas for two-mica suite were generated by dehydration melting of biotite under water-undersaturated conditions at temperatures of >800°C and pressures less than 5 kbar, with tourmaline-bearing samples representing near minimum melt compositions formed under low-extent dehydration melting of muscovite. The high Rb and low Y+Nb concentrations of the granites are consistent with syn-collisional tectonic setting, which might have resulted in the emplacement of leucogranites during periods of crustal thickening. Thus the indicated syn-collisional tectonic setting of the granites has noteworthy implications by documenting a strong evidence for the existence of a Proterozoic orogenic event in the Lesser Himalaya.

Acknowledgements

The author thanks the Chairman, Department of Geology, AMU, Aligarh for providing necessary facilities. Dr. V. Balaram, NGRI, Hyderabad and Dr. N. K. Saini, WIHG, Dehradun are thankfully acknowledged for the geochemical analyses. I am also thankful to the DST, New Delhi for sanctioning me the project under the HIMPROBE programme.The author is also thankful to Drs. Rafiqul Islam and D.V. Subba Rao for their constructive reviews.

References

Acharya, S. K., Ghosh, S.C., Ghosh, R.N. and Shah, S.C., 1975. The continental Gondwana Group and associated marine sequences of Arunachal Pradesh (NEFA), Eastern Himalayas. Himalayan Geology, 60-82.

Bernard, F., Moutou, P. and Pichavant, M., 1985. Phase relations of tourmaline leucogranites and the significance of tourmaline in silicic magmas, Jour. Geol. 93, 271-291.10.1086/628952

Bhalla, J.K. and Bishui, P.K., 1989. Geochronology and geochemistry of granite emplacement and metamorphism in northeastern Himalaya. Records of Geological Survey of India 122, 18-20.

Chappell, B.W. and White, A.J.R., 1974. Two contrasting granitoid types. Pacific Geology 8, 173-174.

Chappell, B. W., 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. Lithos 46, 535–551.10.1016/S0024-4937(98)00086-3

Castelli, D. and Lombardo, B., 1988. The Gophu La and western Lunana granites: Miocene muscovite leucogranites of the Bhutan Himalaya. Lithos 21, 211-225.10.1016/0024-4937(88)90010-2

Dikshitulu, G.R., Pandey, B.K., Krishna, V. and Dhanaraju, R., 1995. Rb-Sr systematics of granitoids of central gneissic complex, Arunachal Himalaya: implications on tectonism, stratigraphy and source. Jour. Geol. Soc. India, 45, 51-56.

Ebadi, A. and Johannes, W., 1991. Beginning of melting and composition of first melts in the system Qz-Ab-Or-H2O-CO2. Contributions to Mineralogy and Petrology 106, 286-295.10.1007/BF00324558

France-Lanord, C.and Le Fort, P., 1988. Crustal melting and granite genesis during Himalayan collision orogenesis. Trans. Royal. Soc. Edinburg 79, 183-195.

France-Lanord, C., Sheppard, S.M.F. and Le Fort, P., 1988. Hydrogen and oxygen isotope variations in the High Himalayan peraluminous Manaslu leucogranite: evidence for heterogeneous sedimentary source. Geochim. et Cosmochim. Acta 52, 513-526.10.1016/0016-7037(88)90107-X

Friend, C.R.L., Allen P., Nutman, Halfdan Baadsgaard, M. John M. and Duke, C., 2009. The whole rock Sm–Nd 'age' for the 2825 Ma Ikkattoq gneisses (Greenland) is 800 Ma too young: Insights into Archaean TTG petrogenesis. Chemical Geology 261, 62-76.10.1016/j.chemgeo.2008.09.019

Gill, J.B., 1981. Orogenic andesites and plate tectonics. Springer-Verlag, Berlin. 358 pp.

Gupta, L.N., Ghildiyal, H. and Chawla, H.S., 1994. Petrochemistry and tectonic environment of granitoids and porphyries of Amritpur-Ramgarh area, Lesser Himalaya, Uttar Pradesh. Jour. Him. Geol.5, 103-116.

Guillot, S., Le Fort, P. and Pecher A., 1991. Contact metamorphism of the Manaslu leucogranite: an emplacement within a thickened upper crust. Geol. Alp. Mem. H.s. 16, .47.

Hanson, G.N., 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. Earth and Planetary Science Letters 38, 26-43.10.1016/0012-821X(78)90124-3

Harris,N.B.W., Pearce, T.A. and Tindle, A.G., 1986. Geochemical characteristics of collision zone magmatism; in: Coward, M.P. and Ries, A.C. (eds.), Collision Tectonics. Geol. Soc. London Spl. Pub.19, 67-81.

Harris, N.B.W. and Inger, S., 1992. Trace element modeling of pelite derived granitoids. Contrib. Mineral. Petrol. 110, 46-56.10.1007/BF00310881

Harris, N.B.W., Inger, S. and Massey, J., 1993. The role of fluids in the formation of High Himalayan leucogranites. Himalayan Tectonics, Treloar, P.J., Searle, M.P. (Eds.). Geol. Soc. Spl. Pub. 74, 391-400.

Holtz, F., 1989. Importance of melt fraction and source rock composition in crustal genesis- the example of two granitic suites of northern Portugal. Lithos 24, 21-35.10.1016/0024-4937(89)90013-3

Holtz, F., Johannes, W. and Pichavant, M., 1991. Effects of excess alumina on phase relations and composition of granitic melts. Terra abst., 3, 29.

Inger, S. and Harris, N.B.W., 1993. Geochemical constraints on leucogranite magmatism in the Langtang Valley, Nepal Himalaya. Jour. Petrol. 34, 345-368.

Islam, R., Ahmad, T. and Khanna, P.P., 2005. An overview on the granitoids of the NW Himalaya. Him. Geol., 49-60.

Johannes, W. and Holtz, F., 1990. Formation and composition of H2O under-saturated granitic melts. In: Ashworth, J.R. and Brown, M. (eds.), High temperature metamorphism and crustal anatexis. Unwin Hyman, .87-104.

Kumar, G., 1997. Geology of Arunachal Pradesh., Geol. Soc. India., 217pp.

Le Fort, P., Debon, F., Pecher, A., Sonet, J. and Vidal, P., 1986. The 500 Ma magmatic event in Alpine Southern Asia, a thermal episode at Gondwana scale. Sciences de la Terre, Memoire 47, 191-209.

London, D., 1992. Phosphorus in S-type magmas: the P2O5 content of feldspars from peraluminous granites, pegmatites, and rhyolites. American Mineralogist 77, 126–145.

McDermott, F., Harris, N.B.W. and Hawkesworth, C.J. 1996. Geochemical constraints on crustal anatexis: a case study from the Pan-African Damara granitoids of Namibia. Contrib. Mineral. Petrol. .123, 406-423.10.1007/s004100050165

Nabelek, P.I., Nabelek, C.R. and Denison, J.R., 1992. The generation and crystallization conditions of the proterozoic Harney Peak leucogranite, Black Hills, South Dakota, USA: petrologic and geochemical constraints. Contrib. Mineral. Petrol.110, 173-191.10.1007/BF00310737

Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Jour. Petrol. .25, 956-983.

Prabha, P. and Rawat, R.S., 1999. Geochemistry and tectonic setting of the Amritpur granite series, Kumaun Lesser Himalaya, India. Jour. Geol. Soc. India 54, 83-90.

Rashid, S.A., 2002. Geochemical Characteristics of Mesoproterozoic Clastic Sedimentary rocks from the Chakrata Formation, Lesser Himalaya: implications for crustal evolution and weathering history in the Himalaya. Journal of Asian Earth Sciences 21, 285-295.10.1016/S1367-9120(02)00071-8

Rashid, S. A., 2005. The Geochemistry of Mesoproterozoic clastic sedimentary rocks from the Rautgara Formation, Kumaun Lesser Himalaya: implications for provenance, mineralogical control and weathering. Current Science. 88, 1832-1836.

Rockhold, J.R., Nabelek, P.I. and Glascock, M.D., 1987. Origin of rhythmic layering in the calamity peak satellite pluton of the Harney Peak granite. South Dakota: the role of boron. Geochim. Cosmochim. Acta. .51, 487-496.10.1016/0016-7037(87)90063-9

Scaillet, B., France-Lanord, C.and Le Fort, P., 1990. Badrinath-Gangotri plutons (Garhwal, India): petrological and geochemical evidence for fractionation processes in a High Himalayan leucogranite. Jour. Volcano. Geotherm. Res. 44, 163-188.10.1016/0377-0273(90)90017-A

Scaillet, B., Pichavant, M. and Roux, J., 1995. Experimental crystallization of leucogranite magmas. Jour. Petrol. 36, 663-705.

Sharma, K.K., 1983. Granitoid belts of the Himalayas. In: Shams, F.A. (ed.), Granitoids of Himalayas, Karakorum and Hindukhush. 11-37.

Sharma, K.K., 1998. Evidence of Paleoproterozoic orogeny (deformation, metamorphism and magmatism) from Sutlej valley, NW Himalaya. Abstract volume, 13th HKT International Workshop, Peshawar. 31, 181-182.

Sharma, K.K. and Rashid, S.A., 2001. Geochemical evolution of peraluminous paleoproterozoic bandal orthogneisses, NW Lesser Himalaya, Himachal Pradesh, India: implications for the ancient crustal growth in the Himalaya. Jour. Asian. Earth. Sci., 19, 413-428.10.1016/S1367-9120(00)00052-3

Singh, S. and Jain, A.K., 2003. Himalayan Granitoids. In: Singh, S. (ed.), Granitoids of the Himalayan Collisional Belt. Jour. Virtual Explorer, 1-20.

Srinivasan, V., 2001. Stratigraphy and structure of low grade metasedimentaries in eastern Bhutan and western Arunachal Pradesh. Him. Geol., 83-98.

Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Magmatism in the ocean basins, Saunder, A.D., Norry, M.J. (Eds.). Geol. Soc. London Spl. Pub. 42, 313-345.

Tuttle, P.F. and Bowen, N.L., 1958. Origin of granite in the light of experimental studies in the system NaAlSi3O8-KAlSi3O8-H2O. Mem. Geol. Soc. Am. 74, 45.

Verma, P.K. and Tandon, S.K., 1976. Geologic observations in a part of the Kameng District, Arunachal Pradesh (NEFA). Him. Geol., 259-286.

Vidal, P., Cocherie, A. and Le Fort, P., 1982. Geochemical investigations of the origin of the Manaslu leucogranite (Nepal Himalaya). Geochim. et Cosmochim. Acta 46, 2279-2292.10.1016/0016-7037(82)90201-0

Winker, H.C.F., 1979. Petrogenesis of metamorphic rocks, 2nd edition. Spinger-Verlag.