Mineralogy and geochemistry of granitoids from Kinnaur region, Himachal Higher Himalaya, India: Implication on the nature of felsic magmatism in the collision tectonics

BRAJESH SINGH¹, SANTOSH KUMAR^{1,*}, MASAO BAN² and KAZUO NAKASHIMA²

¹Department of Geology, Kumaun University, Nainital 263 002, Uttarakhand, India.

²Department of Earth and Environmental Sciences, Yamagata University, 990 8560, Yamagata, Japan.

*Corresponding author. e-mail: skyadavan@yahoo.com

Felsic magmatism in the southern part of Himachal Higher Himalaya is constituted by Neoproterozoic granite gneiss (GGn), Early Palaeozoic granitoids (EPG) and Tertiary tourmaline-bearing leucogranite (TLg). Magnetic susceptibility values ($<3 \times 10^{-3}$ SI), molar $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ (≥ 1.1), mineral assemblage (bt-ms-pl-kf-qtz $\pm$ tur $\pm$ ap), and the presence of normative corundum relate these granitoids to peraluminous S-type, ilmenite series (reduced type) granites formed in a syncollisional tectonic setting. Plagioclase from GGn (An_{10} – An_{31}) and EPG (An_{15} – An_{33}) represents oligoclase to andesine and TLg (An_2 – An_{15}) represents albite to oligoclase, whereas compositional ranges of K-feldspar are more-or-less similar (Or_{88} to Or_{95} in GGn, Or_{86} to Or_{97} in EPG and Or_{87} to Or_{94} in TLg). Biotites in GGn ($\text{Mg}/\text{Mg}+\text{Fe}^t = 0.34$ – 0.45), EPG ($\text{Mg}/\text{Mg}+\text{Fe}^t = 0.27$ – 0.47), and TLg ($\text{Mg}/\text{Mg}+\text{Fe}^t = 0.25$ – 0.30) are *ferribiotites* enriched in siderophyllite, which stabilised between FMQ and HM buffers and are characterised by dominant $3\text{Fe} \rightleftharpoons 2\text{Al}$, $3\text{Mg} \rightleftharpoons 2\text{Al}$ substitutions typical of peraluminous (S-type), reducing felsic melts. Muscovite in GGn ($\text{Mg}/\text{Mg}+\text{Fe}^t = 0.58$ – 0.66), EPG ($\text{Mg}/\text{Mg}+\text{Fe}^t = 0.31$ – 0.59), and TLg ($\text{Mg}/\text{Mg}+\text{Fe}^t = 0.29$ – 0.42) represent *celadonite* and *paragonite* solid solutions, and the tourmaline from EPG and TLg belongs to the *schorl-elbaite* series, which are characteristics of peraluminous, Li-poor, biotite-tourmaline granites. Geochemical features reveal that the GGn and EPG precursor melts were most likely derived from melting of biotite-rich metapelite and metagraywacke sources, whereas TLg melt appears to have formed from biotite-muscovite rich metapelite and metagraywacke sources. Major and trace elements modelling suggest that the GGn, EPG and TLg parental melts have experienced low degrees (~ 13 , ~ 17 and $\sim 13\%$, respectively) of kf-pl-bt fractionation, respectively, subsequent to partial melting. The GGn and EPG melts are the results of a pre-Himalayan, syn-collisional Pan-African felsic magmatic event, whereas the TLg is a magmatic product of Himalayan collision tectonics.

1. Introduction

The Himalayan Metamorphic Belt (HMB) in Himachal Himalaya is comprised of Higher Himalayan Crystalline (HHC) rocks in the north, and Lesser Himalayan rocks are exposed in numerous windows that form the lower margin of the HMB.

The HHC acts as the basement for the Phanerozoic Tethyan sedimentary pile (Bhargava *et al.* 1991) and is mainly composed of Palaeoproterozoic to Early Palaeozoic metasediments (pelitic and psammitic) and felsic magmatic rocks (400–500, 1200–1400 and 1800–2000 Ma), which are the reworked protoliths to the Neogene leucogranites

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(14–28 Ma, Rb–Sr whole rock isochron; Srikantia and Bhargava 1998) formed during the Himalayan collision event (Gansser 1964; Le Fort 1975; Srikantia and Bhargava 1998). The HHC in the Kinnaur district of the Himachal Himalaya forms the Vaikrita Group, and is mainly represented by Neoproterozoic (601 ± 19 Ma; Rb–Sr whole rock isochron; Mehta 1977) granite gneiss (GGn), intercalated metasedimentary rocks and Early Palaeozoic (474 ± 26 Ma; Rb–Sr whole rock isochron; Kwatra *et al.* 1999; Singh and Kumar 2005) granitoids (EPG), which are later intruded by Tertiary tourmaline-bearing leucogranites (TLg). The Palaeoproterozoic to Mesoproterozoic granitoids are, however, not exposed in the study area.

The EPG in the Indian Himalaya region represent a Pan-African tectonothermal event that occurred around the Cambro-Ordovician boundary, and are extensively exposed in the Crystalline Thrust Sheets of the Lesser Himalaya in the HHC and in the metamorphosed basal portions of the Tethyan sedimentary rocks (Kumar *et al.* 1996; Islam and Gururajan 2003). The EPG have mineralogical and geochemical features that are identical to syn-collisional, peraluminous granitoids with an elevated initial Sr-isotopic ratio ($Sr_i = 0.706\text{--}0.770$; Le Fort *et al.* 1986a, b).

The geology and structure of the Kinnaur basin have been described by many workers (e.g., Sharma 1976; Bhargava 1982; Bassi and Chopra 1983; Kakar 1988; Mishra 1993; Srikantia and Bhargava 1998). Geochemistry and whole-rock Rb–Sr geochronology of the EPG from the Satluj–Baspas valleys of Himachal Himalaya have been previously discussed (Kwatra *et al.* 1999; Islam and Gururajan 2003). Based on Rb–Sr whole rock isotopic data, Kwatra *et al.* (1999) have suggested two discrete felsic magmatic pulses as coarse grained Akpa granitoids (477 ± 29 Ma; $Sr_i = 0.721$) and medium grained Rakcham granitoids (453 ± 9 Ma; $Sr_i = 0.737$), both belonging to the Early Palaeozoic granitoids. However, contact relationships between these granitoid bodies cannot be established, and it is likely that both the granitoids are products of a single magmatic event that occurred at 474 ± 26 Ma (age calculated combining Rb–Sr data of Akpa and Rakcham granitoids by Singh and Kumar 2005). Based on published (Kwatra *et al.* 1999) and new database, a petrogenetic reappraisal of EPG from the Kinnaur region has been proposed by Singh and Kumar (2005). In this paper, we provide comprehensive field relations, measurements of magnetic susceptibility, petrography, mineral and whole-rock geochemistry of GGn, EPG and TLg from Kinnaur region, and using this we propose a viable petrogenetic model for the evolution of felsic magmatism in the collisional tectonic environment of the area.

2. Geology and field relation

The study area forms a part of the HHC, erstwhile Central Crystalline Zone (Srikantia and Bhargava 1998), of the Vaikrita Group located in the southern part of Higher Himachal Himalaya (figure 1a). The studied lithological units are best exposed along the Satluj and Baspa (Sangla) river valleys and their tributaries in, and around the Reckong Peo, Ribba, Akpa, Karcham, Rakcham and Chitkul areas and beyond (figure 1b). Some parts of these regions consist of metasedimentary rocks, migmatites and a variety of Neoproterozoic gneisses (psammitic gneiss, banded gneiss, granite gneiss, coarse psammitic gneiss; Kakar 1988; Bartarya *et al.* 1996; Gupta *et al.* 2001) collectively referred herein as granitic gneiss (GGn). They are spatially associated with Early Palaeozoic granitoids (EPG) and tourmaline-bearing leucogranites (TLg) of the Haimanta Group. The GGn and EPG are thrust over the Mesoproterozoic to Neoproterozoic Karcham Group of rocks ($\equiv$ Chail Group), which are largely composed of mica schist, gneiss and quartzite. These units are further thrust over the Jutogh Group which comprises the Wangtu Gneissic Complex.

The GGn show well-developed, leucocratic to mesocratic bands of variable thickness. K-feldspar dominates in the leucocratic bands, where it is elongated and exhibits a preferred orientation. Melanocratic bands are dominated by biotite. In places, augen (quartz and feldspar) follow the gneissosity but are randomly oriented. The GGn exhibit *in situ* leucocratic layers that have melanocratic borders suggesting the formation of localised migmatites close to a shear zone (trending $N35^\circ W$ – $S35^\circ E$ and dipping 60° – 70° towards NE) near Purbani village, which contains skarns (scheelite), pyrite, chalcopyrite, pyrrhotite and bornite mineralisation. The magnetic susceptibility (MS) values of GGn range from 0.052 to 0.220×10^{-3} SI units with an average MS value of 0.156×10^{-3} SI units (figure 2).

The EPG are fine- to coarse-grained, mostly porphyritic, two-mica (muscovite and biotite) granite (*sensu stricto*) that range from foliated to non-foliated varieties and show well-developed joints and fractures. Near the contact with the country rocks, the EPG are moderately foliated and exhibit a mylonitic structure, and in and around Ribba village, these exhibit leucocratic to melanocratic bands. Euhedral to anhedral felsic megacrysts composed of quartz and feldspar are common in the porphyritic varieties. In and around Rakcham village, the EPG exhibit schlieren-like, magmatic flow structures that are defined by mafic minerals. The EPG have sharp contacts with the Tethyan sequence near Akpa village. Enclaves in

Figure 1. (a) Tectonic framework of Himalayan collision zone of NW Himalaya (after Kwatra *et al.* 1999) and (b) geological map of study area (after Kwatra *et al.* 1999) showing the occurrence of Early Palaeozoic granitoids (EPG) and associated units. Tourmaline bearing leucogranite (TLg) is not mappable at present scale shown as intruding the EPG body.

the EPG are relatively rare and represent either surmicaceous material (biotite schists), xenoliths of country rocks (phyllite, biotite schist, gneiss, psammite), or are of felsic magmatic origin. The surmicaceous enclave (SE) is rounded to elliptical (20 × 5 cm) in shape and shows sharp contacts with its felsic host. Country rock xenoliths (CRX) are angular to rounded in shape, large in size (up to 1 m across) and closely resemble the older GGn unit, but show reacted margins. At places, quartz veins and TLg cross the xenoliths and the host

EPG. The felsic magmatic enclaves (FME) are fine-grained, rounded to lenticular in shape (up to 70 cm across) and exhibit sharp to partially diffuse contacts, as can be observed in and around the Akpa village. The EPG have MS values ranging from 0.016 to 0.187×10^{-3} SI (figure 2), the average ($N = 104$) for the MS being $\chi = 0.141 \times 10^{-3}$ SI (Singh and Kumar 2005).

Bands of tourmaline-bearing leucogranite (TLg) range in width from a few meters to about 250 m and commonly intrude the EPG and GGn, mostly

Figure 2. Bar diagram showing the variation range of magnetic susceptibility (MS) values ($\times 10^{-3}$ SI unit) for GGn, EPG and TLg measured in the field along various transects. (a) In and around Ribba village, (b) Powari-Akpa transect, (c) Shongtong-Purbani transect, (d) Rakcham-Chitkul transect, and (e) Karcham-Rakcham transect. Horizontal bars show range of MS values for GGn, EPG and TLg common to all transects.

along their foliation and fracture planes. The TLg commonly contain small tourmaline crystals upto 2.5 cm long, but large size (6–10 cm long) fibrolitic tourmaline crystals together with mica flakes can also be found in a local pegmatite facies. The MS values of TLg range from 0.011 to 0.088×10^{-3} SI with an average value of 0.049×10^{-3} SI unit (figure 2).

3. Analytical methods

The modal mineralogy of representative samples of GGn, EPG and TLg has been determined using a James Swift automatic point counter. The magnetic susceptibility of granitoids was measured on smooth and fresh rock surfaces in the field using hand held SM-20 MS meter, which operated at 10 kHz frequency with sensitivity 1×10^{-6} SI unit. The instrument can operate in the temperature range of 10 – 60°C . Measuring time of each reading is less than 3 seconds per sample in two steps. The MS value is corrected using recommended factors for degree of surface unevenness (1 mm = 1.07, 2 mm = 1.15, 3 mm = 1.23, 4 mm = 1.32, and 5 mm = 1.41). Electron microprobe analysis of minerals was carried out at the Indian Institute of Technology-Roorkee, India using a JEOL JXA-8600 M, which was operated at 15 kV accelerating voltage and 2×10^{-8} A current. An electron beam diameter of 2 μm was selected for most minerals, except feldspars for which a beam of 10 μm diameter was preferred. An oxide ZAF correction procedure was employed. Whole rock major and trace elements (Ba, Nb, Rb, Sr, Y and Zr) were determined by XRF at Yamagata University, Japan, using fused glass beads and an XRF (Rigaku RIX 2000) with a Rh anode tube,

operated at 50 kV accelerating voltage, 50 mA current. The preparation of glass beads, calibration, matrix effect corrections and the precision of results using this methodology are described (Yamada *et al.* 1985; Murata 1993; Ban *et al.* 2005). Trace and rare earth elements (REE) were also analysed at the National Geophysical Research Institute, Hyderabad, India using ICP-MS (ELAN DRC II, Perkin-Elmer) optimised for maximum intensity ($\sim 40,000$ counts/sec) across the mass range and a 1 ng/ml solution of Mg, Rh, In, Ba, Ce, Pb and U. Details of solution preparation, analytical methods, accuracy and precision of results are described (Balaram *et al.* 1996; Balaram and Gnaneshwar Rao 2003). Japanese rock reference materials (JG-2, JG-1a) were used to minimise the matrix effects.

4. Petrography, modal mineralogy and mineral chemistry

The granitic gneiss exhibits gneissose and hypidiomorphic to porphyritic textures and contains megacrysts (not porphyroblasts) of feldspars. A crude preferred orientation of flakes of biotite and muscovite gives rise to the gneissic appearance of the rocks. Some biotite and muscovite are bent suggesting deformation of ductile or non-ductile nature. Biotite is poikilitic with respect to plagioclase, K-feldspar and quartz. Plagioclase occurs as subhedral to euhedral laths, and is corroded at the margins due to replacement by perthitic K-feldspars (orthoclase and microcline). Quartz is recrystallised because of low grade metamorphism. Apatite encloses zircon, and iron oxides occur as disseminated grains. The colour index (M') of GGn ($M' = 6$ – 12) ranges from hololeucocratic to

leucocratic (LeMaitre 2002), and modal composition (table 1a) corresponds to Ms–Bt monzogranite and Ms–Bt granodiorite (figure 3). Representative analyses of plagioclase and K-feldspar from GGn are given in tables 2(a) and 3(a), respectively. Plagioclase from GGn (An₁₀ to An₃₁) represents oligoclase to andesine (figure 4); however, rim composition is slightly more anorthitic compared to the core and this suggests reverse zoning. K-feldspar in GGn (Or₈₈–Or₉₅) is mostly sanidine

to orthoclase. It is likely that 10 micron beam size might have re-integrated the compositions of exsolution into K-feldspar. Representative analyses of biotite from GGn are given in table 4(a). Ferrous (Fe²⁺) and ferric (Fe³⁺) iron was obtained from total iron by partitioning following the stoichiometric methods of Dymek (1983) and Yavuz and Öztas (1997) for biotites from GGn, EPG and TLg. The biotite from GGn (Mg/Mg+Fe^t= 0.34–0.45) are classified as ferrobites enriched

Table 1(a). Modal mineral analysis (vol%) and colour index (M') of representative granite gneiss (GGn).

Sample no.	C5	G1	G2	G4	S2	R1	R4
Quartz	30.00	26.00	31.00	38.00	31.50	42.50	30.00
K-feldspar	28.50	23.50	19.50	13.50	25.00	21.50	12.50
Plagioclase	32.50	39.50	40.00	29.00	35.35	19.00	48.50
Biotite	6.00	6.00	5.00	9.00	5.00	8.00	6.00
Muscovite	2.00	4.00	2.50	7.50	2.00	6.50	2.00
Tourmaline	–	–	–	–	–	–	–
Accessories	1.00	1.00	1.00	2.00	1.00	2.50	1.00
Colour index (M')	7.00	7.00	7.00	12.00	6.00	10.50	7.00

Accessories include zircon (Zrn), apatite (Ap), opaques, etc. Colour index (M') = M – light coloured minerals (Ms+Qtz+Kfs+Pl) after Streckeisen (1973), where M = 100. Following IUGS nomenclature (Streckeisen 1973; LeMaitre 2002) the GGn can be named as *Ms-Bt monzogranite* (sample nos. C5, G1, S2, R1) and *Ms-Bt granodiorite* (sample nos. G4, G2, R4). Mineral symbols are used after Kretz (1983).

Table 1(b). Modal mineral analysis (vol%) and colour index (M') of representative Early Palaeozoic granitoids (EPG).

Sample no.	C1	C7	C9	C10	C23	C19	C27	S1	R2	R3	R6	A1	A2	A3	A4	A6
Quartz	34.00	34.00	32.00	32.00	31.50	32.50	32.00	33.50	35.00	34.00	35.00	33.50	34.00	30.00	35.50	32.50
K-feldspar	24.00	28.00	23.50	26.50	23.00	29.00	26.50	28.00	24.00	25.50	25.50	24.00	31.50	29.50	30.00	28.50
Plagioclase	27.50	23.00	26.00	28.00	27.50	26.50	27.00	26.50	26.50	23.00	27.00	28.50	26.00	28.00	24.00	23.00
Biotite	7.50	7.65	8.50	7.50	8.00	5.50	6.00	7.00	8.00	7.50	6.50	7.00	5.00	6.50	6.00	7.50
Muscovite	4.00	4.25	4.50	3.00	4.50	2.50	4.50	3.00	4.50	5.50	4.50	5.00	2.00	4.00	2.00	3.50
Tourmaline	1.00	–	–	–	–	0.50	–	–	–	1.00	–	–	0.50	–	–	–
Accessories	1.50	1.50	1.50	1.50	2.50	1.00	2.00	2.00	1.00	2.50	1.00	1.00	1.00	1.50	1.50	2.00
Colour index (M')	10.50	11.75	15.50	10.50	13.50	10.00	10.00	6.50	10.00	15.00	8.00	6.00	6.00	8.50	8.50	12.50

Accessories include zircon (Zrn), apatite (Ap), opaques, etc. Colour index (M') = M – light coloured minerals (Ms+Qtz+Kfs+Pl) after Streckeisen (1973), where M = 100. Following IUGS nomenclature (Streckeisen 1973; LeMaitre 2002) all samples can be named as *Ms-Bt leucomonzogranite*. Mineral symbols are used after Kretz (1983).

Table 1(c). Modal mineral analysis (vol%) and colour index (M') of representative tourmaline bearing leucogranite (TLg).

Sample no.	C6	C17a	C17b	A5	TLg-2a	TLg-2b	TLg-2c	2-TLg
Quartz	30.00	34.00	49.00	10.50	36.50	33.00	39.50	34.00
K-feldspar	28.50	10.00	21.50	54.50	15.00	16.00	8.00	15.50
Plagioclase	25.00	45.00	5.00	27.00	40.00	39.50	46.50	35.50
Biotite	4.50	2.00	4.50	1.50	2.00	4.00	1.50	4.00
Muscovite	7.00	4.50	8.50	3.50	5.00	5.00	3.00	6.50
Tourmaline	3.00	2.50	4.00	3.00	2.00	1.50	1.00	2.50
Accessories	1.00	1.00	3.50	0.50	1.00	1.00	1.00	1.00
Colour index (M')	9.50	6.50	19.00	4.50	3.50	6.50	3.00	8.50

Accessories include zircon (Zrn), apatite (Ap), opaques, etc. Colour index (M') = M – light coloured minerals (Ms+Qtz+Kfs+Pl) after Streckeisen (1973), where M = 100. Following IUGS nomenclature (Streckeisen 1973; LeMaitre 2002) the TLg can be named as *Ms-Bt monzogranite* (sample no. C6), *Ms-Bt granodiorite* (sample nos. C17a, 2 TLg, TLg-2a, TLg-2b, TLg-2c), *Bt-Ms quartz rich granitoid* (sample no. C17b) and *Bt-Ms quartz syenite* (sample no. A5). Mineral symbols are used after Kretz (1983).

Figure 3. Modal compositions of EPG (○), GGn (+) and TLg (Δ) in a Q–A–P diagram (LeMaitre 2002). Q=Quartz, A=Alkali feldspar, P=Plagioclase. Fields 1: quartz-rich granitoids, 2: monzogranite, 3: granodiorite, 4: quartz syenite.

in siderophyllite component and crystallised from a magma that was buffered mostly between FMQ and NNO (figure 5). The biotites show compositional affinity with biotite syncrystallised with muscovite (De Albuquerque 1973). The peraluminous (S-type) and reduced nature of GGn melt is clearly indicated by the dominant $3\text{Fe} \rightleftharpoons 2\text{Al}$ and $3\text{Mg} \rightleftharpoons 2\text{Al}$ substitutions in the biotite (figure 6a, b) and by the large variations in the $\text{Fe}^{\text{t}}/\text{Fe}^{\text{t}}+\text{Mg}$ ratios (GGn = 0.55–0.66) during the evolution of the biotite from their respective felsic melts. Representative analyses of muscovite from GGn and their empirically estimated Li-contents (Tindle and Webb 1990; Tischendorf 1997; Tischendorf *et al.* 1999; Yavuz 2001) are given in table 5(a). Muscovite in GGn ($\text{Mg}/\text{Mg}+\text{Fe}^{\text{t}} = 0.58\text{--}0.66$) represent *celadonitic* and *paragonitic* solid-solutions (Miller *et al.* 1981) and belong to the Li–Al mica group; more precisely they represent *lithian muscovite*, *lepidolite* and *zinnwaldite* (figure 7), which were most likely crystallised in a peraluminous felsic melt that underwent differentiation. The substitution of ferro-celadonite in muscovite of GGn, EPG and TLg involves the octahedral sites where Al^{3+} is mainly substituted for by Fe, Mg^{2+} and minor amounts of Ti and Mn^{2+} because of the low Ti^{4+} content of the mica. The compositional gaps in the data set could indicate a geochemical *hiatus* caused either by inadequate sampling or may be geologic in nature.

The EPG exhibit fine- to coarse-grained, equigranular to inequigranular, hypidiomorphic textures and are composed of plagioclase, biotite,

muscovite, K-feldspar, quartz, tourmaline, apatite and zircon. Scattered iron oxides are present. Plagioclase (3–10 mm) occurs as subhedral to euhedral lath-shaped grains, which are intergrown with quartz to produce myrmekite. Primary biotites show sub-poikilitic to poikilitic relations with magnetite, apatite, zircon, monazite, and plagioclase. Randomly oriented crystals of muscovite exhibit an interlocking relationship with the primary biotite. Microcline contains inclusions of plagioclase indicating growth of perthite, whereas orthoclase displays simple twinning. Quartz that occurs as an interstitial phase contains inclusions of apatite, zircon, and tourmaline. Tourmaline also occurs in microveinlets. The colour index (M') of EPG ($M' = 6\text{--}12$) ranges from hololeucocratic to leucocratic (LeMaitre 2002), and modal composition (table 1b) corresponds to Ms–Bt monzogranite (figure 3). Representative analyses of plagioclase and K-feldspar from EPG are given in tables 2(b) and 3(b), respectively. Plagioclase from EPG ($\text{An}_{15}\text{--}\text{An}_{33}$) represents oligoclase to andesine composition (figure 4). Reverse zoning is common in plagioclase of EPG. K-feldspar in EPG ($\text{Or}_{86}\text{--}\text{Or}_{97}$) is mostly sanidine to orthoclase. Representative analyses of biotite from EPG are given in table 4(b). The biotite from EPG ($\text{Mg}/\text{Mg}+\text{Fe}^{\text{t}} = 0.27\text{--}0.47$) represents ferrobites enriched in siderophyllite component buffered mostly between FMQ and NNO (figure 5). EPG biotites show compositional affinity with biotite syncrystallised with muscovite (De Albuquerque 1973). Dominant $3\text{Fe} \rightleftharpoons 2\text{Al}$ and $3\text{Mg} \rightleftharpoons 2\text{Al}$ substitutions in EPG biotite (figure 6a, b) and large variations in the $\text{Fe}^{\text{t}}/\text{Fe}^{\text{t}}+\text{Mg}$ ratios (EPG = 0.53–0.73) suggests its peraluminous (S-type) and reduced nature. The observed large variation in the $\text{Fe}^{\text{t}}/\text{Fe}^{\text{t}}+\text{Mg}$ ratio of biotites from EPG and TLg should have been primarily controlled by changing the activity of silica (a_{SiO_2}) of the host magmas during fractional differentiation. Representative analyses of muscovites from EPG and empirically estimated Li-contents (Tindle and Webb 1990; Tischendorf 1997; Tischendorf *et al.* 1999; Yavuz 2001) are given in table 5(b). Muscovite in EPG ($\text{Mg}/\text{Mg}+\text{Fe}^{\text{t}} = 0.31\text{--}0.59$) represent celadonitic and paragonitic solid-solutions (Miller *et al.* 1981), belonging to the Li–Al mica (lithian muscovite, lepidolite and zinnwaldite, figure 7). Representative analyses of tourmaline from EPG is given in table 6(a). Fe^{3+} and Fe^{2+} were obtained from total iron by partition using the tourmal program (Yavuz 1997). It has been assumed that boron has a stoichiometric abundance of 3 apfu (e.g., Torres-Ruiz *et al.* 2003). Tourmaline from EPG belong principally to the vacancy and alkali groups (Hawthorne and Henry 1999) and contain minor amounts of Mn (tsiliasite component; Slivko 1959), but lack

Table 2. Representative electron microprobe analysis of plagioclase from (a) granite gneiss (GGn), (b) Early Palaeozoic granitoids (EPG), and (c) Tourmaline bearing leucogranite (TLg).

	Range	Mean	Std. dev.
(a) 18 samples Pl (GGn)			
SiO ₂	59.45–65.82	61.76	1.87
Al ₂ O ₃	21.11–25.47	24.29	1.16
CaO	2.04–6.35	5.48	1.33
Na ₂ O	7.68–9.87	8.64	0.64
K ₂ O	0.09–0.57	0.33	0.12
FeO	0.00–0.1	0.02	0.02
Structural formula based on 8 oxygen basis			
An (%)	10.20–30.80	25.42	5.95
Ab (%)	67.30–89.30	72.81	6.37
Or (%)	0.50–3.20	1.77	0.67
(b) 17 samples Pl (EPG)			
SiO ₂	59.58–65.82	63.27	2.21
Al ₂ O ₃	21.16–26.38	23.72	1.55
CaO	3.01–6.65	4.35	1.44
Na ₂ O	6.83–10.07	8.77	0.93
K ₂ O	0.11–0.96	0.45	0.31
FeO	0.00–0.05	0.01	0.02
Structural formula based on 8 oxygen basis			
An (%)	14.50–33.20	21.09	7.15
Ab (%)	65.80–84.30	76.46	6.26
Or (%)	0.60–5.10	2.46	1.70
(c) 26 samples Pl (TLg)			
SiO ₂	63.64–69.04	66.09	1.60
Al ₂ O ₃	25.69–29.31	22.29	1.15
CaO	0.62–3.11	2.23	0.78
Na ₂ O	7.33–12.48	10.26	1.10
K ₂ O	0.08–0.36	0.20	0.10
FeO	0.00–0.04	0.01	0.01
Structural formula based on 8 oxygen basis			
An (%)	2.80–15.10	10.74	3.79
Ab (%)	83.20–96.70	88.4	4.05
Or (%)	0.50–2.20	1.14	0.54

Note: The entire database can be obtained from the corresponding author.

absolutely any empirically estimated Fe³⁺ content, therefore, demonstrating an affinity with schorl-elbaite group (figure 8). In order to saturate vacant sites (<6 apfu), some Al substitute for Si at T-site (Foit and Rosenberg 1979) and Mg at Z-site (e.g., Torres-Ruiz *et al.* 2003) in the tourmalines from EPG and TLg. The Fe/(Fe+Mg) ratio increases with Al substitution [(Mg, Fe)₋₁Si₋₁Al₂] in the Y-site (London and Manning 1995) and, therefore, samples plot in the field below the line $\Sigma(\text{Fe}+\text{Mg}) < 3$. In terms of Al–Fe^t–Mg (Henry and Guidotti 1985) the tourmaline from EPG and TLg appear to have crystallised from a lithium-poor, tur-bt granitic melt or its derivative pegmatites and aplites (figure 9).

Table 3. Representative electron microprobe analysis of K-feldspar from (a) granite gneiss (GGn), (b) Early Palaeozoic granitoids (EPG), and (c) tourmaline bearing leucogranite (TLg).

	Range	Mean	Std. dev.
(a) 4 samples Kfs (GGn)			
SiO ₂	63.99–65.01	64.41	0.43
Al ₂ O ₃	17.93–18.75	18.49	0.38
CaO	0.02–0.08	0.04	0.03
Na ₂ O	0.55–1.40	1.13	0.39
K ₂ O	14.94–15.55	15.29	0.30
FeO	0.00–0.02	0.01	0.01
Structural formula based on 8 oxygen basis			
An (%)	0.10–0.40	0.23	0.13
Ab (%)	5.00–12.30	9.95	3.35
Or (%)	87.50–94.90	89.83	3.43
(b) 7 samples Kfs (EPG)			
SiO ₂	46.26–65.60	61.73	6.94
Al ₂ O ₃	18.25–33.12	20.99	5.37
CaO	0.00–0.04	0.02	0.01
Na ₂ O	0.11–1.68	0.80	0.61
K ₂ O	10.44–21.62	16.52	3.69
FeO	0.00–2.00	0.29	0.75
Structural formula based on 8 oxygen basis			
An (%)	0.00–0.20	0.09	0.07
Ab (%)	1.00–13.50	6.64	4.72
Or (%)	85.60–98.90	93.27	4.71
(c) 7 samples Kfs (TLg)			
SiO ₂	63.33–66.09	64.98	1.08
Al ₂ O ₃	18.28–19.33	18.66	0.38
CaO	0.01–0.04	0.02	0.01
Na ₂ O	0.66–1.44	1.08	0.33
K ₂ O	14.88–20.88	17.21	2.88
FeO	0.00–0.02	0.01	0.01
Structural formula based on 8 oxygen basis			
An (%)	0.00–0.10	0.08	0.04
Ab (%)	5.80–12.90	8.87	3.06
Or (%)	87.00–94.10	91.05	3.07

Note: The entire database can be obtained from the corresponding author.

The TLg is medium to coarse grained (1–10 mm) and exhibits perthite, myrmekite and graphic intergrowths. Plagioclase is partly altered to sericite, and poikilitically encloses mica. Primary biotite and muscovite occur as randomly oriented crystals. K-feldspar occurs as perthite microcline and orthoclase, which commonly enclose quartz, biotite and muscovite. Quartz is interstitial. Tourmaline occurs as zoned crystals. Apatite and zircon are included in the biotite, muscovite and feldspars, and iron oxides occur as disseminated grains. The colour index (M') of TLg (M' = 3–19) ranges from hololeucocratic to leucocratic (LeMaitre 2002), and modal composition (table 1c) corresponds to Bt–Ms monzogranite, Bt–Ms granodiorite, Bt–Ms

Figure 4. Albite-Orthoclase-Anorthite diagram showing plagioclase and K-feldspar compositions from GGn (+), EPG (○) and TLg (Δ) samples. Fields; 1: albite, 2: oligoclase, 3: andesine, 4: labradorite, 5: bytonite, 6: anorthite, 7: anorthoclase, and 8: sanidine.

Table 4. Representative electron microprobe analysis of biotite from (a) granite gneiss (GGn), (b) Early Palaeozoic granitoids (EPG), and (c) tourmaline bearing leucogranite (TLg).

	Range	Mean	Std. dev.
(a) 18 samples Bt (GGn)			
SiO ₂	32.71–37.38	34.85	1.00
Al ₂ O ₃	17.64–20.82	18.73	0.78
TiO ₂	4.05–5.34	4.59	0.38
FeO	17.26–23.82	20.09	1.30
MnO	0.00–0.11	0.05	0.03
MgO	5.04–8.95	8.01	0.85
CaO	0.00–0.07	0.01	0.02
Na ₂ O	0.00–0.32	0.16	0.10
K ₂ O	8.97–9.97	9.55	0.25
Structural formula based on 11 oxygen basis			
Si	2.53–2.81	2.65	0.05
Al ^{IV}	1.19–1.47	1.35	0.05
ΣZ = 4	4.00	4.00	0.00
Al ^{VI}	0.13–0.65	0.33	0.11
Ti	0.23–0.31	0.26	0.02
Fe ³⁺	0.02–0.68	0.22	0.18
Fe ²⁺	0.42–1.24	1.06	0.18
Mn	0.00–0.01	0.00	0.00
Mg	0.56–1.02	0.91	0.10
ΣY~3	2.53–2.91	2.78	0.08
Ca	0.00–0.01	0.00	0.00
Na	0.00–0.05	0.02	0.01
K	0.8–0.96	0.92	0.03
ΣX~1	0.80–1.00	0.95	0.04
Fe [#]	0.55–0.66	0.59	0.03
Mg [#]	0.34–0.45	0.41	0.03
(b) 47 samples Bt (EPG)			
SiO ₂	32.30–36.10	33.90	0.84
Al ₂ O ₃	13.78–19.25	16.75	1.11

Table 4. (Continued.)

	Range	Mean	Std. dev.
TiO ₂	2.10–3.95	3.36	0.35
FeO	19.52–24.44	22.61	1.01
MnO	0.01–0.62	0.35	0.11
MgO	5.01–7.26	6.44	0.59
CaO	0.00–0.14	0.03	0.04
Na ₂ O	0.00–0.56	0.07	0.10
K ₂ O	9.22–13.41	12.09	1.02
Structural formula based on 11 oxygen basis			
Si	2.60–2.78	2.68	0.04
Al ^{IV}	1.22–1.40	1.32	0.04
ΣZ = 4	4.00	4.00	0.00
Al ^{VI}	0.11–0.47	0.24	0.08
Ti	0.16–0.23	0.20	0.02
Fe ³⁺	0.11–0.50	0.24	0.09
Fe ²⁺	0.95–1.46	1.25	0.12
Mn	0.00–0.04	0.02	0.01
Mg	0.60–0.86	0.76	0.06
ΣY~3	2.62–2.82	2.72	0.04
Ca	0.00–0.01	0.00	0.00
Na	0.00–0.09	0.01	0.02
K	0.93–1.39	1.22	0.11
ΣX~1	0.95–1.39	1.23	0.11
Fe [#]	0.53–0.73	0.66	0.03
Mg [#]	0.27–0.47	0.34	0.03
(c) 09 samples Bt (TLg)			
SiO ₂	33.35–36.38	34.41	1.06
Al ₂ O ₃	18.53–20.61	19.55	0.74
TiO ₂	1.61–2.05	1.87	0.14
FeO	22.95–24.89	24.12	0.59
MnO	0.37–0.71	0.50	0.13
MgO	4.49–6.01	5.15	0.58
CaO	0.00–0.06	0.03	0.02
Na ₂ O	0.00–0.18	0.05	0.07
K ₂ O	9.35–9.85	9.64	0.17
Structural formula based on 11 oxygen basis			
Si	2.64–2.75	2.69	0.04
Al ^{IV}	1.25–1.36	1.31	0.04
ΣZ = 4	4.00	4.00	0.00
Al ^{VI}	0.40–0.58	0.49	0.07
Ti	0.09–0.12	0.11	0.01
Fe ³⁺	0.05–0.43	0.23	0.15
Fe ²⁺	1.09–1.58	1.34	0.19
Mn	0.02–0.05	0.04	0.01
Mg	0.52–0.70	0.60	0.07
ΣY~3	2.76–2.88	2.81	0.05
Ca	0.00	0.00	0.00
Na	0.00–0.03	0.01	0.01
K	0.93–0.98	0.96	0.02
ΣX~1	0.94–0.99	0.97	0.02
Fe [#]	0.70–0.75	0.73	0.02
Mg [#]	0.25–0.30	0.27	0.02

Fe[#] = Fe^t/Fe^t+Mg; Mg[#] = Mg/Mg+Fe^t.

Note: The entire database can be obtained from the corresponding author.

Figure 5. Annite–oxyannite–phlogopite plot for biotite showing (A) primary (Foster 1960) and (B) hydrothermal (Beane 1974) biotite fields. The HM, NNO and FMQ buffer curves are taken after Wones and Eugster (1965). Most EPG (○) biotites show slightly different trend as compared to GGn (+) and TLg (Δ) biotites.

Figure 6. (a) Al_2O_3 vs. FeO(t) plot for biotite from GGn (+), EPG (○) and TLg (Δ). The fields of biotite that crystallised in anorogenic alkaline, calc-alkaline orogenic suites and peraluminous (including S-types) magmas are shown, after Abdel-Rahman (1994). (b) Al_2O_3 vs. MgO plot for biotite from GGn (+), EPG (○) and TLg (Δ). The fields of biotite that crystallised in anorogenic alkaline, calc-alkaline orogenic suites and peraluminous (including S-types) magmas are shown after Abdel-Rahman (1994).

quartz rich granitoid and Bt–Ms quartz syenite (figure 3).

Representative analyses of plagioclase and K-feldspar from TLg are given in tables 2(c) and 3(c),

Table 5. Representative electron microprobe analysis of muscovite from (a) granite gneiss (GGn), (b) Early Palaeozoic granitoids (EPG), and (c) tourmaline bearing leucogranite (TLg).

	Range	Mean	Std. dev.
(a) 10 samples Ms (GGn)			
SiO_2	49.61–51.36	50.64	0.58
TiO_2	1.76–2.08	1.95	0.11
Al_2O_3	35.62–37.09	36.46	0.45
FeO	0.99–1.31	1.12	0.11
MnO	0.00–0.03	0.01	0.01
MgO	0.78–1.22	0.92	0.13
CaO	0.00–0.03	0.01	0.01
Na_2O	0.00–0.18	0.10	0.06
K_2O	4.22–5.10	4.72	0.26
Li_2O (c)	4.69–5.19	4.98	0.16
Structural formula based on 22 oxygen basis			
Si	3.00–3.04	3.03	0.01
Al^{IV}	0.96–1.00	0.97	0.01
$\Sigma Z = 4$	4	4.00	0.00
VI Al	1.56–1.62	1.60	0.02
VI Ti	0.08–0.10	0.09	0.01
VI Fe^{2+}	0.05–0.07	0.06	0.01
VI Mn	0.00–0.00	0.00	0.00
VI Mg	0.07–0.11	0.08	0.01
Li	1.15–2.16	1.30	0.30
$\Sigma Y \sim 3$	3	3.12	0.31
Ca	0.00–0.00	0.00	0.00
Na	0.00–0.02	0.01	0.01
K	0.32–0.39	0.36	0.02
$\Sigma X \sim 1$	0.34–0.40	0.38	0.02
$\text{Fe}^\#$	0.35–0.44	0.40	0.03
$\text{Mg}^\#$	0.58–0.66	0.62	0.03
(b) 17 samples Ms (EPG)			
SiO_2	49.16–52.90	50.38	0.96
TiO_2	0.02–1.05	0.57	0.29
Al_2O_3	32.20–37.25	35.15	1.76
FeO	1.31–2.13	1.68	0.24
MnO	0.00–0.06	0.02	0.02
MgO	0.46–1.65	0.99	0.29
CaO	0.00–0.04	0.02	0.01
Na_2O	0.00–0.42	0.22	0.13
K_2O	4.92–8.70	6.02	1.00
Li_2O (c)	4.56–5.63	4.91	0.28
Structural formula based on 22 oxygen basis			
Si	2.15–3.16	3.01	0.23
Al^{IV}	0.84–1.01	0.93	0.06
$\Sigma Z = 4$	4	4.00	0.00
VI Al	1.48–1.65	1.59	0.04
VI Ti	0.00–0.04	0.02	0.01
VI Fe^{2+}	0.06–0.10	0.08	0.01
VI Mn	0.00–0.00	0.00	0.00
VI Mg	0.05–0.15	0.09	0.03
Li	1.12–1.35	1.20	0.06
$\Sigma Y \sim 3$	2.90–3.10	2.99	0.05
Ca	0.00–0.00	0.00	0.00
Na	0.00–0.05	0.03	0.02
K	0.38–0.71	0.47	0.08
$\Sigma X \sim 1$	0.40–0.71	0.50	0.08
$\text{Fe}^\#$	0.41–0.69	0.50	0.08
$\text{Mg}^\#$	0.31–0.59	0.50	0.08

Table 5. (Continued.)

	Range	Mean	Std. dev.
(c) 13 samples Ms (TLg)			
SiO ₂	45.86–50.71	49.19	1.26
TiO ₂	0.11–0.35	0.19	0.06
Al ₂ O ₃	34.82–37.34	36.60	0.63
FeO	1.90–2.15	2.02	0.08
MnO	0.00–0.03	0.01	0.01
MgO	0.46–0.87	0.55	0.11
CaO	0.00–0.12	0.03	0.03
Na ₂ O	0.04–0.42	0.29	0.11
K ₂ O	3.12–6.97	5.75	0.87
Li ₂ O (c)	3.61–5.00	4.57	0.36
Structural formula based on 22 oxygen basis			
Si	3.00–3.05	3.02	0.02
Al ^{IV}	0.95–1.00	0.98	0.02
$\Sigma Z = 4$	4	4.00	0.00
^{VI} Al	1.65–1.70	1.67	0.02
^{VI} Ti	0.01–0.02	0.01	0.00
^{VI} Fe ²⁺	0.10–0.11	0.11	0.01
^{VI} Mn	0.00–0.00	0.00	0.00
^{VI} Mg	0.04–0.08	0.05	0.01
Li	0.95–1.21	1.13	0.07
$\Sigma Y \sim 3$	2.82–3.09	2.97	0.06
Ca	0.00–0.01	0.00	0.00
Na	0.00–0.05	0.04	0.01
K	0.24–0.55	0.45	0.07
$\Sigma X \sim 1$	0.24–0.60	0.49	0.09
Fe [#]	0.58–0.71	0.68	0.03
Mg [#]	0.29–0.42	0.32	0.03

Fe[#] = Fe^t/Fe^t+Mg; Mg[#] = Mg/Mg+Fe^t.

Note: The entire database can be obtained from the corresponding author.

respectively. Plagioclase from TLg (An₂–An₁₅) is mostly oligoclase, although a few are albite (figure 4); however, rim composition is slightly more anorthitic compared to the core suggesting reverse zoning. K-feldspar in TLg (Or₈₇ to Or₉₄) is mostly sanidine to orthoclase. Representative analyses of biotite from TLg are given in table 4(c). The biotite from TLg (Mg/Mg+Fe^t = 0.25–0.30) are classified as ferrobiotites enriched in siderophyllite component and buffered mostly between FMQ and NNO (figure 5). TLg biotites show compositional affinity with biotite syncrystallised with muscovite (De Albuquerque 1973). Dominant 3Fe^t⇌2Al and 3Mg⇌2Al substitutions (figure 6a, b) and large variations in the Fe^t/Fe^t+Mg ratios (TLg = 0.70–0.75) in the biotite from TLg suggests its peraluminous (S-type) and reduced nature. Representative analyses of muscovites from TLg and their empirically estimated Li-contents (Tindle and Webb 1990; Tischendorf 1997; Tischendorf *et al.* 1999; Yavuz 2001) are given in table 5(c). Muscovite in TLg (Mg/Mg+Fe^t = 0.29–0.53) represent *celadonitic* and *paragonitic* solid-solutions (Miller *et al.* 1981), belonging to the Li-Al mica group (*lithian muscovite*, *lepidolite* and *zinnwaldite*, figure 7). Representative analyses of tourmaline from TLg are given in table 6(b). Fe³⁺ and Fe²⁺ were obtained from total iron by partition using the *tourmal* program (Yavuz 1997). It has been assumed that boron has a stoichiometric abundance of 3 apfu (e.g., Torres-Ruiz *et al.* 2003). Tourmaline from TLg belong principally to the *vacancy* and *alkali* groups (Hawthorne and Henry 1999) containing minor amounts of Mn (tsiliasite component; Slivko 1959), but lack absolutely any empirically estimated Fe³⁺ content, suggesting

Figure 7. Classification of muscovite from GGn (+), EPG (O) and TLg (Δ) on a ternary R³⁺–Li–R²⁺ diagram (Foster 1960; Monier and Robert 1986; Stone *et al.* 1986). The solid line with arrow heads represents a transitional series between muscovite and zinnwaldite (Monier and Robert 1986).

Table 6. Representative electron microprobe analysis of tourmaline from (a) Early Palaeozoic granitoids (EPG) and, (b) tourmaline bearing leucogranite (TLg).

	Range	Mean	Std. dev.
(a) 6 samples Tur (EPG)			
SiO ₂	31.48–39.48	34.48	2.72
Al ₂ O ₃	19.33–29.30	24.97	4.04
TiO ₂	0.08–0.54	0.31	0.17
FeO	8.44–11.78	10.51	1.24
MnO	0.07–0.14	0.11	0.02
MgO	1.69–2.38	2.05	0.27
CaO	0.11–0.32	0.22	0.09
Na ₂ O	0.58–1.76	1.21	0.52
Structural formula based on 24.5 oxygen basis			
Si	6.00	6.00	0.00
Al ^{IV}	0.00	0.00	0.00
ΣT	6.00	6.00	0.00
B	3.00	3.00	0.00
Al(Z)	5.65–6.00	5.91	0.15
Mg	0.00–0.35	0.10	0.15
ΣZ	6.00	6.00	0.00
Al(Y)	0.00–0.26	0.07	0.10
Ti	0.01–0.09	0.05	0.03
Fe ²⁺	0.61–1.76	1.30	0.40
Mg	0.26–0.64	0.50	0.13
Mn	0.01–0.02	0.02	0.00
ΣY	1.22–2.60	1.92	0.49
Ca	0.02–0.07	0.05	0.02
Na	0.21–0.70	0.46	0.21
□	0.24–0.77	0.49	0.23
ΣX	1.00	1.00	0.00
Fe/Fe+Mg	0.71–0.77	0.74	0.02
Na/Na+Ca	0.87–0.93	0.91	0.02
(b) 7 samples Tur (TLg)			
SiO ₂	32.79–36.60	34.73	1.62
Al ₂ O ₃	24.32–34.83	29.37	4.11
TiO ₂	0.17–0.45	0.30	0.12
FeO	10.67–12.22	11.51	0.52
MnO	0.09–0.19	0.15	0.04
MgO	1.46–3.11	2.43	0.56
CaO	0.12–0.32	0.21	0.08
Na ₂ O	0.85–1.88	1.12	0.42
Structural formula based on 24.5 oxygen basis			
Si	5.91–6.00	5.99	0.03
Al ^{IV}	0.00–0.09	0.01	0.03
ΣT	6.00	6.00	0.00
B	3.00	3.00	0.00
Al(Z)	5.72–6.00	5.96	0.11
Mg	0.00–0.26	0.04	0.10
ΣZ	6.00	6.00	0.00
Al(Y)	0.00–0.72	0.29	0.30
Ti	0.02–0.06	0.04	0.02
Fe ²⁺	1.22–1.89	1.62	0.22
Mg	0.41–0.85	0.62	0.14
Mn	0.01–0.03	0.02	0.01
ΣY	2.00–2.96	2.59	0.36

Table 6. (Continued.)

	Range	Mean	Std. dev.
Ca	0.02–0.07	0.04	0.02
Na	0.29–0.60	0.38	0.12
□	0.38–0.67	0.58	0.11
ΣX	1.00	1.00	0.00
Fe/Fe+Mg	0.68–0.82	0.73	0.05
Na/Na+Ca	0.83–0.97	0.89	0.05

Note: The entire database can be obtained from the corresponding author.

its affinity with *schorl-elbaite* group (figure 8). In terms of Al–Fe^t–Mg (Henry and Guidotti 1985) the tourmaline from TLg appear to have crystallised from a lithium-poor, tur-bt granitic melt or its derivative pegmatites and aplites (figure 9).

5. Whole rock and trace element geochemistry

The mineral assemblage (ms–bt–pl–kf–qtz) and geochemical features of GGn (mol. A/CNK = 1.00–1.75), EPG (mol. A/CNK = 1.00–1.25) and TLg (mol. A/CNK = 1.08–2.80) suggest typical peraluminous (S-type) granites (figure 10) as defined by Chappell and White (1974) and Debon and Le Fort (1983). Major oxide content of seven GGn samples are given in table 7(a). The GGn is characterised by moderate to high K₂O (1.90–4.90 wt%), Al₂O₃ (14.11–15.79 wt%) and MgO (0.52–1.28 wt%) contents over a narrow range of SiO₂ (68.15–73.00 wt%). CaO, TiO₂ and Fe₂O₃^t show a broadly negative correlation with SiO₂ for most GGn samples, but Al₂O₃, Na₂O and K₂O show slight scatter (figure 11a–f). The major oxide contents of fifteen EPG samples are given in table 7(b). The EPG shows high Al₂O₃ (13.09–14.82 wt%) and low to high MgO (0.24–1.33 wt%) over a narrow SiO₂ range (69.48–74.99 wt%). TiO₂, Al₂O₃, Fe₂O₃^t, CaO, and, to a certain extent, K₂O show a broadly decreasing linear concentration with increasing SiO₂ content (figure 11a–d, f), this may be accounted for by the early crystallisation of feldspars, mica (muscovite and biotite), apatite and iron oxides. Na₂O does not exhibit any definite correlation with SiO₂ (figure 11e). Scattering of some data points probably reflects heterogeneous modal mineral abundance. Major oxides of eight TLg samples are given in table 7(a), which show a relatively wider range of SiO₂ (71.43–77.37 wt%) as compared to GGn and EPG. CaO, K₂O, Fe₂O₃^t, and TiO₂ show negative curvilinear trends against SiO₂ whereas Na₂O exhibits strong positive correlation with SiO₂ (figure 11a–f). Al₂O₃ shows scatter of data points. Trace elements of seven GGn samples are given in table 8(a). Th

Figure 8. EPG (○) and TLg (△) tourmalines in terms of $\text{Ca}/(\text{Ca}+\text{Na})$ vs. $\text{Fe}/(\text{Fe}+\text{Mg})$ showing affinity with schorl group (London and Manning 1995).

Figure 9. $\text{Fe}^{\text{t}}\text{-Al-Mg}$ ternary diagram showing affinity of tourmaline from the EPG (○) and TLg (△) with lithium-poor granitoids and associated felsic derivatives (field 2). Other fields are 1: Li-poor granitoid pegmatites and aplites, 2: Lithium-poor granitoids and associated felsic derivatives, 3: Fe^{3+} rich quartz-tourmaline rocks (hydrothermally altered granites), 4: Metapelites and metapsammities coexisting with an Al-saturating phase, 5: Metapelites and metapsammities not coexisting with an Al-saturating phase, 6: Fe^{3+} rich quartz-tourmaline rocks, calc-silicate rocks and metapelites, 7: Low-Ca metaultramafics and Cr, V-rich metasediments, and 8: Metacarbonates and metapyroxenites (after Henry and Guidotti 1985).

shows negative correlation with SiO_2 (figure 11j), whereas curvilinear antipathic correlation can be observed for Rb/Sr vs. Sr (figure 11o). Sr shows slight positive correlation with SiO_2 (figure 11i). Wide data scatter can be observed for Ba, Nb, Y, Zr versus SiO_2 (figure 11h, k, l, m) whereas Rb clusters in an area (figure 11g). Primitive mantle normalised multi elemental variation diagram for GGn (figure 12b) show lesser degree of variations for most elements compared to that of EPG and TLg, except Ta which varies widely in GGn and TLg (figure 12b, c). REE patterns for GGn (figure 13b) show uniform LREE and MREE

Figure 10. (a–b) Multicationic diagram (Debon and Le Fort 1983) plotted for EPG, GGn and TLg. The sectors I, II and III represent peraluminous, where I=muscovite > biotite (by volume), II=biotite > muscovite, III=biotite (usually alone, in some cases with minor amphibole). Fields IV, V and VI are for metaluminous rocks, where IV=biotite+amphibol ± pyroxene, V=clinopyroxene ± amphibole ± biotite, VI=unusual rocks (e.g., carbonatites). LG denotes the leucogranite field. Arrow with solid line shows the trend of Lesser Himalayan granitoids from Nepal–India–Pakistan (Le Fort *et al.* 1986a in Barbarin 1996). Arrow with dotted line shows EPG evolutionary trend.

(La to Ho) followed by flat HREE (Ho to Lu) patterns ($\text{La}_\text{N}/\text{Lu}_\text{N} = 13.9$ to 59.6) with moderate negative Eu anomalies ($\text{Eu}_\text{N}/\text{Eu}^* = 0.52$ to 0.61). Trace and REE contents (ppm) of 15 EPG samples are given in table 8(b). Large-ion lithophile elements (LILE) such as Ba, Rb, Sr and high-field strength elements (HFSE) such as Zr, Y, Th, Nb, U, and Ta show wide variations in their contents. Sr, Nb, Zr and Ga have broadly negative correlation with increasing SiO_2 (figure 11i, k, m, n). Data are scattered for Rb, Ba, Th, and Y against SiO_2 and show no correlation (figure 11g, h, j, l). In particular, Rb and Ba show a large range of variation for a given silica content, probably because of modal variations in biotite and K-feldspar, respectively, from sample to sample. Curvilinear antipathic correlation between Rb/Sr and Sr (figure 11o) is observed. Mantle-normalised spidergrams show elevated content (10–100 times) for most elements relative to the mantle (figure 12a). Both P and Ti exhibit strong negative anomalies, whereas Ba, U and Th show wide range of variations. Chondrite-normalised LREE and MREE seem coherent (Pr–Ho) then HREE (Ho–La) flatten out, but most notably the LREE (La and Ce) seem to be depleted (figure 13a). Moderate degree of LREE to HREE fractionation ($\text{La}_\text{N}/\text{Lu}_\text{N} = 5.6$ – 35.3) and negative Eu anomalies ($\text{Eu}_\text{N}/\text{Eu}^* = 0.35$ – 0.64) can be noticed. Trace elements of eight TLg samples are given in table 8(a). Relatively wider variations of Rb/Sr and Sr/Ba ratios of TLg can be observed as compared to

Table 7(a). Major oxides (wt%) data of granite gneiss (GGn) and tourmaline bearing leucogranite (TLg).

Sample no.	C5	G1	G2	G4	S2	R1	R4	Av.	C17a	C17b	TLg2a	TLg2b	TLg2c	2-TLg	TLg(2)	C6	Av.
	GGn (N = 7)								TLg (N = 8)								
SiO ₂	68.15	70.18	72.14	73.00	69.43	72.11	70.62	70.80	77.17	74.23	74.64	76.39	77.37	71.43	74.25	71.48	74.62
TiO ₂	0.72	0.27	0.27	0.47	0.64	0.77	0.52	0.52	0.05	0.33	0.20	0.06	0.14	0.54	0.24	0.55	0.26
Al ₂ O ₃	14.58	15.79	15.10	14.11	14.50	14.28	15.06	14.77	13.93	14.28	14.07	14.41	13.19	14.39	14.23	13.82	14.04
Fe ₂ O ₃ ^t	4.89	2.68	2.71	3.94	4.43	5.09	3.75	3.93	0.32	1.18	2.19	0.65	1.54	3.62	3.05	3.90	2.06
MnO	0.06	0.03	0.05	0.08	0.06	0.05	0.03	0.05	0.01	0.02	0.04	0.01	0.03	0.05	0.05	0.06	0.03
MgO	1.28	0.52	0.58	1.00	1.15	1.06	1.20	0.97	0.73	5.22	0.49	0.15	0.34	1.01	0.54	1.04	1.19
CaO	2.27	1.58	1.61	1.39	2.55	0.56	2.19	1.74	0.41	0.24	1.32	1.18	1.53	2.48	1.54	2.11	1.35
Na ₂ O	2.74	4.11	4.25	2.53	3.09	1.74	4.77	3.32	6.28	0.31	4.23	4.47	4.67	3.04	4.80	2.75	3.82
K ₂ O	4.84	4.90	3.27	3.09	3.86	3.99	1.90	3.69	0.99	3.42	2.33	2.38	1.07	3.43	1.46	4.07	2.39
P ₂ O ₅	0.11	0.17	0.10	0.11	0.13	0.04	0.12	0.11	0.12	0.14	0.06	0.05	0.05	0.13	0.04	0.13	0.09
Total	99.64	100.23	100.08	99.72	99.84	99.69	100.16	99.91	100.01	99.37	99.57	99.75	99.93	100.12	100.20	99.91	99.85
Mol. A/CNK	1.08	1.00	1.15	1.56	1.00	1.75	1.00	1.22	1.17	2.80	1.27	1.17	1.08	1.08	1.08	1.17	1.35
K ₂ O/Na ₂ O	1.77	1.19	0.77	1.22	1.25	2.29	0.40	1.27	0.16	11.03	0.55	0.53	0.23	1.13	0.30	1.48	1.93

Fe₂O₃^t as total iron; Mol. A/CNK = Molar Al₂O₃/CaO+Na₂O+K₂O. Av. = average; N = number of samples.

Table 7(b). Major oxides (wt%) data of Early Palaeozoic granitoids (EPG).

Sample no.	A1	A2	A3	A4	A6	C1	C7	C9	C10	C19	C23	C27	S1	R2	R6	Av.
	(N=15)															
SiO ₂	74.14	73.08	74.30	69.48	74.43	72.49	73.99	74.29	71.17	73.21	74.99	70.40	71.41	72.33	70.83	72.70
TiO ₂	0.35	0.40	0.19	0.60	0.37	0.38	0.17	0.19	0.66	0.34	0.20	0.64	0.54	0.30	0.50	0.39
Al ₂ O ₃	13.31	13.66	13.57	14.76	13.09	13.69	13.92	13.65	13.95	13.78	13.80	13.93	13.69	14.82	14.48	13.87
Fe ₂ O ₃ ^t	2.66	2.76	2.20	4.78	2.74	2.85	1.98	2.02	4.57	2.78	2.22	4.58	3.97	3.12	3.65	3.13
MnO	0.04	0.04	0.04	0.09	0.03	0.05	0.05	0.05	0.08	0.06	0.05	0.08	0.06	0.07	0.05	0.06
MgO	0.64	0.74	0.24	1.33	0.63	0.71	0.40	0.41	1.32	0.61	0.41	1.30	1.08	0.64	0.90	0.76
CaO	1.63	1.78	1.48	3.17	1.74	1.54	1.32	1.14	2.00	1.26	1.14	2.05	1.82	1.53	2.33	1.73
Na ₂ O	2.56	2.46	3.19	3.38	3.43	2.20	3.07	2.93	2.67	2.81	2.95	2.66	2.41	3.92	2.70	2.89
K ₂ O	4.68	5.08	4.86	2.55	3.47	6.01	4.95	5.27	4.22	5.10	5.28	4.13	4.53	3.25	4.45	4.52
P ₂ O ₅	0.12	0.11	0.05	0.11	0.10	0.05	0.12	0.12	0.15	0.15	0.11	0.17	0.12	0.14	0.11	0.12
Total	100.13	100.11	100.12	100.25	100.03	99.97	99.97	100.07	100.79	100.10	101.15	99.94	99.63	100.12	100.00	100.17
Mol. A/CNK	1.08	1.08	1.00	1.00	1.00	1.00	1.17	1.00	1.17	1.17	1.08	1.17	1.08	1.25	1.08	1.09
K ₂ O/Na ₂ O	1.83	2.07	1.52	0.75	1.01	2.73	1.61	1.80	1.58	1.81	1.79	1.55	1.88	0.83	1.65	1.63

Fe₂O₃^t as total iron; Mol. A/CNK = Molar Al₂O₃/CaO+Na₂O+K₂O. Av. = average; N = number of samples.

EPG. However, variation diagrams for TLg show some similarities with EPG. Rb, Ba, Nb, Y and Zr show negative correlation with SiO₂ (figure 11g, h, k, l, m). A wide scatter can be observed for Sr and Th contents against SiO₂ (figure 11i, j). The mantle-normalised spidergrams of TLg show much more elemental variation when compared to EPG and GGn and, therefore could be considered characteristic of Himalayan leucogranites (figure 12c). The observed trace elements characteristic of TLg might be a reflection of progressively evolving nature of crustal protoliths in space and time and its recycling during geological episodes, referred elsewhere as tertiary peraluminous granitoids (Clarke 1992). One garnet-bearing TLg (A5) bears elevated U and depleted Ba and Nb contents as compared to other TLg. Slightly inclined to flat LREE patterns and moderate to gently sloping HREE patterns with moderate negative Eu anomalies ($\text{Eu}_\text{N}/\text{Eu}^* = 0.32\text{--}0.46$) can be observed (figure 13c). La and Ce seem depleted in TLg and the HREE decreases rather more abruptly than in EPG. LREE to HREE fractionations ($\text{La}_\text{N}/\text{Lu}_\text{N} = 3.2\text{--}32.1$) of TLg are larger as compared to EPG and GGn. Enrichment of HREE is obvious in one garnet-bearing TLg (C6).

5.1 Tectonic setting

Syn-collisional tectonic affinity for GGn, EPG and TLg can be very well constrained on composition-tectonic plot (figure 14). In terms of trace elements (Rb, Nb, Y), GGn and EPG cluster at the boundary between VAG and syn-COLG granites, whereas the TLg spread over VAG to the syn-COLG fields (figure 15). However, on the normalised patterns of ocean ridge granite (ORG) (not shown) GGn, EPG and TLg all show high contents of Rb, Th and low Ce and Hf, which are characteristics of *syn-collisional* granites (Pearce *et al.* 1984). Dominant but to various degrees of crustal components in the genesis of all three granitoids can be inferred by the low contents of Ta and Nb relative to Rb in each.

6. Petrogenetic discussion

6.1 Field petrography, nature of felsic melts, granite series and evolution of mineral phases

The development of some local migmatitic components close to leucocratic and melanocratic layers in GGn and EPG appears to be synchronous with the Himalayan orogeny-induced compressional forces, which have formed melanosome and leucosome (haplogranite) components (Mehnert 1968). The presence of melanosome adjacent to each leucocratic layer is a common feature,

and suggests *in situ* formation rather than the migration of melt (Collins and Sawyer 1996). The presence of leucocratic and melanocratic bands near to a shear zone may however suggest synplutonic segregation of melt from crystallising pluton rather than partial melting (E W Sawyer, pers. comm.). The quartzofeldspathic megacrysts in EPG represent phenocrysts and not porphyroblasts because the K-feldspar megacrysts exhibit growth, twinning, shape, inclusion and dissolution features that are characteristics of magmatic processes (e.g., Vernon 1986). The presence of two micas (Ms–Bt) in GGn, EPG and TLg suggest that the granitic melts from which they crystallised were water rich, or even water-saturated melt (*sensu stricto*) and generated within a narrow temperature interval, by the partial melting of fusible crustal components (Wyllie 1997). Therefore they cluster within the anatectic granite field (Laymure and Bowden 1982) close to the granite eutectic (Harris and Inger 1992).

The range of variation in the magnetic susceptibility (GGn: $0.052\text{--}0.220 \times 10^{-3}$ SI; EPG: $0.016\text{--}0.187 \times 10^{-3}$ SI; TLg: $0.011\text{--}0.088 \times 10^{-3}$ SI) is strongly suggestive of the ilmenite series for these felsic magmas with a range of crustal residence times. Bulk MS values of GGn ($\chi = 0.168\text{--}0.190 \times 10^{-3}$ SI) and EPG ($\chi = 0.096\text{--}0.130 \times 10^{-3}$ SI) indicate *moderately* reduced rocks, whereas TLg ($\chi = 0.054\text{--}0.056 \times 10^{-3}$ SI) appear to be *strongly* reduced, which are mostly intrinsic to the source lithology (e.g., Ishihara 1977). The felsic magmatism from each of the different episodes (Neoproterozoic, Early Palaeozoic to Himalayan), thus show a trend of increasing reduction and were probably generated in the middle of the continental crust from source rocks with low Fe₂O₃/FeO ratios (Ishihara 1984), and/or reduction was due to the carbon contained in the pelitic protoliths (Ishihara and Matsuhisa 1999).

Most plagioclases from GGn (An₁₀–An₃₁), EPG (An₁₅–An₃₃) and TLg (An₂–An₁₅) have crystallised from felsic melt. The reverse compositional zoning of the plagioclase is a result of the changing water pressure on the liquidus (e.g., Yoder *et al.* 1957 in Vance 1965; Wiebe 1968), or the reduced undercooling, or a build-up of volatiles in the felsic melt (Loomis 1982). Most crystals of K-feldspar in GGn, EPG and TLg represent sanidine to orthoclase and are related to crystallisation of the felsic magmas, but some of them lack any anorthite component, possibly because they re-equilibrated at near solidus or subsolidus condition.

The sum of X-site occupancy more than unity in some biotites from GGn, EPG and TLg may be due to the replacement of K by Ba, Rb and Cs (Deer *et al.* 1963). Substitutions such as $3\text{Mg} \rightleftharpoons 2\text{Al}$ and $3\text{Fe} \rightleftharpoons 2\text{Al}$ together with an average $\text{FeO}^\text{t}/\text{MgO}$

Figure 11. (a–q) Major oxide and trace element *vs.* SiO₂ variation diagrams for GGn (+), EPG (○) and TLg (Δ) granite suites.

= 2.42 for GGn, FeO^t/MgO = 3.54 for EPG, and FeO^t/MgO = 4.73 in the TLg indicate that the biotites are characteristic of crystallisation from a peraluminous (S-type) felsic magma suite (Abdel-Rahman 1994), and are similar to those observed from the Strathbogie (S-type granite) batholith of Australia (Burkhard 1991). The 3Fe $\rightleftharpoons$ 2Al substitution predominates over 3Mg $\rightleftharpoons$ 2Al in GGn, EPG

and TLg, suggesting low lithium contents (estimated) in the biotites, and can therefore be termed as ferrous lithium mica because of the minor Li $\rightleftharpoons$ Fe and Li $\rightleftharpoons$ Ti substitutions.

The trend to increased reduction in the felsic melts, inferred from 100*Fe/Fe+Mg ratios (Wones and Eugster 1965) of biotite (GGn = 55–66, EPG = 53–73, TLg = 70–75) can be primarily

Table 8(a). Trace element (ppm) and elemental ratios of granite gneiss (GGn, 7 samples) and tourmaline bearing leucogranite (TLg, 8 samples).

Sample no.	C5	G4	S2	R4	G1	G2	R1	C17a	C17b	TLg-2c	C6	TLg-2a	TLg-2b	TLg2	2-TLg
	GGn							TLg							
Ga	19.1	17.7	19.4	22.9	13.6	13.7	18.3	13.4	15.4	16.8	20.3	13.4	12.6	14.7	13
Rb	214.1	178.6	180.4	181	225.1	161.6	250.9	48.3	158.4	74.3	309.2	131.8	85.9	115.7	196.3
Sr	133.8	172.5	136.8	179.8	165.2	221.4	99.1	33.6	6	326.7	104.5	273.8	193.6	337	109.8
Y	29.9	30.4	26.8	6.9	14.8	22.8	42	14.5	31.1	18.9	36.5	18.8	15.9	18.4	30.1
Zr	292.5	247.1	290.3	90	148.1	168.2	302.6	23.9	148.3	73.1	216	65.8	24.4	92.9	224.4
Nb	15.5	14.4	12.4	30.5	14.4	11.1	18.6	3.3	9.5	10.1	14	14.6	4.6	17.4	14
Ba	1939.6	447.2	1816.6	124.1	721.1	486	511.7	26.3	125.8	98.3	537	172.7	185	137.9	417.1
Ta	1.2	1.1	1.2	3	1.4	1.8	0.8	0.7	0.4	1.8	1.2	3.4	0.5	1	0.4
Th	19.3	8.5	18.7	12	9.2	10.1	12.8	4.3	14.5	21	22.2	11.8	4.3	9.2	9.4
U	2.6	2.5	2.6	4.4	3	3.6	2.1	1.2	1.7	2.2	1.6	2	1.1	2	1.6
K/Rb	187	143	177	87	180	168	132	170	179	119	161	146	229	104	145
Rb/Sr	1.6	1.04	1.32	1.01	1.36	0.73	2.53	1.44	26.4	0.23	2.96	0.48	0.44	0.34	1.79
Rb/Ba	0.11	0.4	0.1	1.46	0.31	0.33	0.49	1.84	1.26	0.76	0.58	0.76	0.46	0.84	0.47
Sr/Ba	0.07	0.39	0.08	1.45	0.23	0.46	0.19	1.28	0.05	3.32	0.19	1.59	1.05	2.44	0.26
Ti/P	9.3	2.26	7	6.16	2.26	3.84	27.36	0.59	3.35	1.33	6.01	4.74	0.57	8.53	6.09
La	48.59	26.85	46.14	28.66	26.83	28.56	35.12	3.39	17.38	27.79	30.87	30.39	11.37	28.69	25.59
Ce	98.29	55.49	92.31	54.29	52.71	56.93	73.33	9.6	46.14	71.66	80.8	62.94	23.39	59.83	53.03
Pr	10.55	5.75	9.81	5.38	5.47	6	8	1.37	6.46	9.86	11.23	6.86	2.54	6.5	5.79
Nd	42.32	22.77	39.8	19.46	20.95	23.27	31.53	4.51	21.96	34	38.47	27.44	9.91	26.25	23.17
Sm	8.19	4.45	8.1	3.23	4.28	4.99	5.66	1.48	4.92	7.13	8.96	5.98	2.5	5.78	5.09
Eu	1.28	0.78	1.36	0.49	0.79	0.81	0.79	0.17	0.42	0.79	1.13	0.57	0.38	0.82	0.61
Gd	6.43	3.44	6.24	2.6	3.18	3.81	4.19	1.04	3.31	4.5	6.21	4.38	1.83	4.65	3.67
Tb	0.93	0.5	0.94	0.32	0.45	0.55	0.48	0.29	0.71	0.82	1.46	0.59	0.28	0.73	0.48
Dy	5.28	3	5.45	1.51	2.36	2.69	1.92	1.51	3.05	3.22	7.01	2.74	1.34	4.21	2.25
Ho	0.51	0.28	0.52	0.11	0.2	0.23	0.15	0.23	0.43	0.41	1.07	0.21	0.11	0.37	0.17
Er	1.55	0.89	1.51	0.36	0.56	0.58	0.39	0.64	0.97	0.9	2.63	0.49	0.3	1.04	0.39
Tm	0.17	0.12	0.17	0.03	0.06	0.06	0.04	0.11	0.13	0.11	0.34	0.04	0.03	0.11	0.03
Yb	1.61	1.21	1.47	0.32	0.57	0.58	0.44	0.77	0.81	0.63	2.06	0.33	0.28	0.94	0.25
Lu	0.24	0.2	0.21	0.05	0.08	0.09	0.06	0.11	0.11	0.09	0.27	0.04	0.04	0.13	0.04
ΣREE	225.94	125.73	214.03	116.81	118.49	129.15	162.1	25.22	106.8	161.91	192.51	143	54.3	140.3	120.56
Eu*	27.3	14.7	26.7	10.9	13.9	16.4	18.3	4.7	15.2	21.3	28.1	19.3	8	19.5	16.3
(La/Lu) _N	21	13.9	22.8	59.6	34.8	33	60.9	3.2	16.4	32.1	11.9	78.9	29.5	22.9	66.4
(Ce/Yb) _N	15.8	11.9	16.3	44	23.9	25.4	43.3	3.2	14.7	29.5	10.2	49.5	21.6	16.5	54.9
Eu _N /Eu*	0.54	0.61	0.59	0.52	0.65	0.57	0.5	0.42	0.32	0.43	0.46	0.34	0.55	0.48	0.43

Rb, Sr, Y, Zr, Nb and Ba are XRF analysed, and other elements are ICP-MS analysed; La to Lu are ICP-MS analysed; Chondrite normalised values are taken after Taylor and McLennan (1985); $Eu^* = \sqrt{(Sm_N) \times (Gd_N)}$; ΣREE = Sum of total REE.

attributed to the source regions, and is consistent with the range of MS values obtained from the GGn, EPG and TLg that happen to be identical to ilmenite series granites (Ishihara 1977; Ishihara *et al.* 2002). The muscovites from GGn, EPG and TLg are celadonite to ferro-celadonite and are also typical to peraluminous felsic melts (e.g., Benincasa *et al.* 2003). Thus the micas (biotite and muscovite) in these felsic rocks represent primary liquid phases and not the *restite* or *secondary* phases.

6.1.1 Assessing the protoliths of the felsic magmas

All three granite suites are peraluminous; the GGn (Av. Alumina Saturation Index, ASI = 1.13),

EPG (Av. ASI = 1.10) and TLg (Av. ASI = 1.31) are similar to the Early Palaeozoic granitoids of Lesser Himalayan belts of Nepal–India–Pakistan (Barbarin 1996), which evolved by fractional differentiation following partial melting, and resulted in a moderate peraluminosity (figure 14). The potential source rocks from which peraluminous felsic partial melts were generated can be very well constrained by comparison with the composition of experimental felsic melts formed by mica dehydration of metapelites, metagraywackes and muscovite-rich metapelites (Patiño Douce 1999; Lee *et al.* 2003). Although it is difficult to choose certain samples to represent the initial melt (or starting melt=anatectic melt), the average of GGn

Table 8(b). Trace element (ppm) and elemental ratios of Early Palaeozoic granitoids (EPG).

Sample no.	A1	A2	A3	A4	A6	C1	C7	C9	C10	C19	C23	C27	S1	R2	R6
Ga	16.1	16.5	17.5	20.3	17.6	15.5	15.7	13.1	15.3	17.5	20.5	16.5	18.0	19.8	18.1
Rb	225.4	231.3	232.8	173.2	136.5	217.8	295.9	311.8	293.0	330.4	312.0	290.0	236.7	197.2	189.2
Sr	94.5	103.5	96.9	122.1	125.7	119.9	61.5	54.7	92.0	63.2	54.0	93.1	95.4	127.9	149.6
Y	25.7	23.2	38.4	15.7	24.7	32.2	27.4	31.0	44.0	23.6	32.0	42.0	34.3	17.2	33.0
Zr	153.4	158.5	168.8	250.1	196.5	161.4	102.1	102.3	293.0	144.4	111.0	298.1	258.6	158.0	206.0
Nb	9.4	9.6	13.7	13.2	10.3	9.1	7.8	6.5	17.0	12.2	9.0	16.6	13.9	16.1	11.5
Ba	548.4	710.7	856.2	233.6	673.3	766.6	251.1	207.4	487.0	369.7	209.0	443.9	601.0	344.3	836.0
Ta	0.9	1.0	1.4	1.2	1.1	0.8	1.1	1.2	1.3	1.9	1.6	2.3	1.3	1.5	1.3
Th	15.5	13.2	21.0	17.9	20.7	24.6	12.3	5.8	11.2	17.1	26.9	10.8	22.0	17.5	22.3
U	5.9	1.0	1.9	2.7	2.0	1.5	2.1	1.8	4.7	4.1	4.3	2.3	1.7	3.8	2.6
K/Rb	172.0	182.0	173.0	122.0	210.0	228.0	139.0	140.0	119.0	128.0	140.0	118.0	158.0	197.0	195.0
Rb/Sr	2.4	2.2	2.4	1.4	1.4	1.8	4.8	5.7	3.2	5.2	5.8	3.1	2.5	1.5	1.3
Rb/Ba	0.4	0.3	0.3	0.7	0.2	0.3	1.2	1.5	0.6	0.9	1.5	0.7	0.4	0.6	0.2
Sr/Ba	0.2	0.2	0.1	0.5	0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.4	0.2
Ti/P	4.2	5.2	5.4	7.8	5.3	10.8	2.0	2.3	6.3	3.2	2.6	5.4	6.6	3.1	6.5
La	30.59	21.69	37.08	36.95	36.17	33.27	14.81	13.17	13.38	22.67	41.91	32.12	32.83	26.23	36.37
Ce	64	55.77	93.53	93.84	91.31	87.43	39.41	28.38	35.9	60.46	109.8	67.7	85.5	63.08	93.97
Pr	7.01	7.63	12.81	12.56	12.49	12.18	5.44	3.12	5.06	8.52	15.37	7.45	11.74	8.25	13.13
Nd	27.42	26.48	43.29	41.8	43.35	41.14	18.41	12.28	17.18	29.04	53.55	30.41	39.71	26.57	45.31
Sm	6.01	6.09	9.12	8.05	8.97	9.03	4.87	3.27	4.53	6.76	11.29	6.61	8.36	5.11	10.05
Eu	0.81	1.05	1.28	1.11	1.39	1.39	0.65	0.38	0.51	0.74	1.08	0.71	1.1	0.68	1.5
Gd	4.74	4.09	6.11	5.26	5.66	5.76	3.47	2.75	3.29	4.54	7.68	5.38	5.66	3.08	6.52
Tb	0.73	0.92	1.41	0.99	1.14	1.18	0.99	0.56	0.93	1.07	1.65	0.84	1.2	0.62	1.48
Dy	4.01	4.63	7.22	4.24	4.72	5.13	5.27	3.84	5.08	5.03	7.41	4.75	5.65	2.83	7.09
Ho	0.34	0.71	1.19	0.64	0.64	0.78	0.82	0.36	0.82	0.76	1.14	0.45	0.89	0.44	1.16
Er	0.89	1.81	3.16	1.58	1.47	2	2.07	1.01	2.07	1.91	3.01	1.31	2.28	1.3	3.34
Tm	0.09	0.27	0.46	0.22	0.17	0.28	0.3	0.12	0.3	0.3	0.43	0.15	0.33	0.21	0.5
Yb	0.69	1.68	2.93	1.22	0.95	1.76	1.9	1.03	1.84	1.94	2.66	1.32	2.1	1.38	3.23
Lu	0.09	0.23	0.43	0.18	0.11	0.26	0.25	0.15	0.25	0.27	0.37	0.2	0.3	0.19	0.46
ΣREE	147.42	133.05	220.02	208.64	208.81	201.59	98.66	70.24	91.14	144.01	257.35	159.4	197.65	139.97	224.11
Eu*	20.1	18.8	28.1	24.5	26.8	27.1	15.5	11.3	14.5	20.8	35	22.4	25.9	14.9	30.5
(La/Lu) _N	35.3	9.8	9	21.3	34.1	13.3	6.2	9.1	5.6	8.7	11.8	16.7	11.4	14.3	8.2
(Ce/Yb) _N	24.1	8.6	8.3	19.9	24.9	12.9	5.4	7.1	5.1	8.1	10.7	13.3	10.6	11.9	7.5
Eu _N /Eu*	0.46	0.64	0.52	0.52	0.6	0.59	0.48	0.39	0.4	0.41	0.35	0.36	0.49	0.52	0.57

Rb, Sr, Y, Zr, Nb and Ba are XRF analysed, and other elements are ICP-MS analysed; La to Lu are ICP-MS analysed; Chondrite normalised values are taken after Taylor and McLennan (1985); $Eu^* = \sqrt{(Sm_N) \times (Gd_N)}$; ΣREE = Sum of total REE.

samples, and EPG (R6) and TLg (TLg 2a) samples free from cumulate textures without the least silica contents in their groups, have been assumed to represent parental melt compositions and compared with experimental melt compositions. The GGn (av.) and EPG (R6) melts have compositions similar to those commonly produced from biotite-rich metapelite and metagraywacke sources (figure 16). Thus, in the generation of GGn and EPG melts, the contributions of Proterozoic metasedimentary sources can be very well recognised as also suggested for Early Palaeozoic granitoids of other Himalayan segments (e.g., Kumar *et al.* 1996; Valdiya 1995; Islam *et al.* 2005).

Himalayan TLg (TLg 2a) lie in the field of melt compositions formed from metagraywacke

source, and a few TLg evolved to reach the compositional field of melts formed by partial melting of muscovite-rich metapelite (figure 16). It has been suggested that some TLg from other regions of the Himalaya have formed by muscovite dehydration melting of metapelites at $P \sim 300$ MPa and $T \geq 600$ – 710°C (Visonā and Lombardo 2002). Searle (1999) opined that melting of pelitic protoliths could have occurred through muscovite breakdown, either during fluid-absent partial melting at $<750^\circ\text{C}$, or by fluid-present partial melting at $<650^\circ\text{C}$. Kawakami and Kobayashi (2006) inferred that the production of tourmaline leucogranite is limited to low degrees of partial melting (~ 10 wt%), regardless of the P–T conditions and the reaction by which it was produced.

Figure 12. Primitive mantle (Sun and Mc Donough 1989) normalised trace element variation diagrams for (a) EPG, (b) GGn and (c) TLg.

However, partial contribution from the proximal protoliths like GGn and EPG during Himalayan collision tectonics to produce TLg melt cannot be entirely ruled out.

Comparing the alumina saturation index (ASI) of EPG ($\bar{x} = 1.10$, $n = 16$) and GGn ($\bar{x} = 1.13$, $n = 6$) with that of mean ASI values of anatectic granites used in the melting experiments (compilation of Acosta-Vigil *et al.* 2003; table 9), it is suggested that the EPG and GGn melts were generated by fluid absent biotite melting. The ASI of EPG and GGn are however lower than the experimentally predicted ASI values (≥ 1.20), which indicates that the EPG and GGn melts were undersaturated in aluminous minerals or failed to achieve equilibrium (Acosta-Vigil *et al.* 2003). The ASI of TLg ($\bar{x} = 1.31$, $n = 9$) compares well with upper limit of experimentally predicted ASI values (1.15–1.30) but higher than the mean ASI value ($\bar{x} = 1.17$, $n = 45$) noted for other Himalayan leucogranites (Le Fort 1981; Searle and Fryer 1986; Stern *et al.* 1989; Scaillet *et al.* 1990; Guillot and Le Fort 1995;

Figure 13. Chondrite normalised (normalisation values from Taylor and McLennan 1985) REE patterns for (a) EPG, (b) GGn and (c) TLg.

Figure 14. R_1 – R_2 multicationic diagram (De la Roche *et al.* 1980) showing compositional fields for felsic rocks from different tectonic settings (Batchelor and Bowden 1985) and samples from GGn, EPG and TLg. The encircled field 6 represents the field of anatectic granites.

Figure 15. Tectonic discrimination for granites from Pearce *et al.* (1984) with samples from GGn, EPG and TLg.

Figure 16. Chemical compositions of GGn, EPG and TLg compared with partial melts obtained from experimental partial melting studies of mica dehydration melting in metapelite and metagraywacke protoliths. Fields of experimental melt compositions are shown from compilation of Patiño Douce (1999) and Lee *et al.* (2003).

Searle *et al.* 1997), which suggests likely generation of TLg melt by fluid-absent muscovite melting.

6.1.2 Elemental variations and process diagnosis

• Granite gneiss (GGn)

Average composition of GGn has been considered equivalent in parental magma composition, which subsequently evolved through fractional differentiation mechanism forming the GGn rock suite. CaO, K₂O, TiO₂ and Fe₂O₃ behave as compatible elements during the crystallisation of felsic magmas most probably as a result of fractional crystallisation of biotite ($\pm$ muscovite), feldspars, Fe–Ti oxides and apatite. Negative anomalies for P and Ti suggest that apatite and ilmenite played an important role during the evolution of GGn. Variation in Ba and K contents suggest a prime role for mica during crystallisation. Lesser variation in Nb suggests retention of Nb-hosting phases in the residue during crystal melting event.

• Early Palaeozoic granitoids (EPG)

The linear variation of TiO₂, Al₂O₃, Fe₂O₃ and CaO against SiO₂ suggests a low degree of fractional differentiation. The variation in Sr contents supports the early crystallisation of Ca-rich phases, but Sr cannot be fully accommodated in calcic-poor plagioclase (An_{15–33}) because of preferential partitioning of Sr and Eu in anorthite-rich plagioclase (bytownite) which occurs at low oxygen fugacity conditions (e.g., Drake 1975, Blundy and Shimizu 1991). Rb variation suggests preferential partitioning and substitution in K-bearing fractionating phases such as K-feldspar, biotite and muscovite. A negative Sr-anomaly (figure 11i) suggests the fractionation of plagioclase which is further corroborated by negative Eu anomaly. It is more likely that EPG parental melt might have been derived from plagioclase depleted source. Anomalously high content of Y

Table 9. Single-stage major elements based least-squares fractionation solution models of granite gneiss (GGn), Early Palaeozoic granitoids (EPG) and tourmaline bearing leucogranite (TLg).

Parent felsic magma	Fractionating minerals (%)			R^2	F	Residual felsic magma
	K-feldspar (Kf)	Plagioclase (Pl)	Biotite (Bt)			
Granite gneiss (Average GGn, SiO ₂ = 70.80 wt%)	3.8	6.9	1.9	0.84	87.4	G4 (SiO ₂ = 73.00 wt%)
Early Palaeozoic granitoids (R6, SiO ₂ = 70.83 wt%)	5.5	5.2	5.8	1.26	83.5	A6 (SiO ₂ = 74.35 wt%)
Tourmaline bearing leucogranite (TLg 2a, SiO ₂ = 74.64 wt%)	6.2	2.5	3.5	0.15	87.2	TLg 2c (SiO ₂ = 77.67 wt%)

R^2 = sum of residual squares and F = percentage of residual felsic magma.

in a few EPG may be due to partial dissolution of monazite and apatite present in the source prior to the crystallisation of EPG melt. The Nb, Zr and Y rich nature of EPG is most likely a result of HFSE-rich (residual) phases derived from melting of crustal source rocks. However, some primary zircons might have also crystallised in EPG magma.

- Tourmaline bearing leucogranite (TLg)

The variation of major elements in TLg appears to have been generated by partial melting of heterogeneous crustal sources followed by a low degree of fractional crystallisation. Partial melting of a crustal source would result in a minimum melt composition enriched in Al_2O_3 , K_2O and Na_2O , whereas Fe_2O_3^t and TiO_2 are at low concentrations, because of negligible contribution of these elements from metasedimentary (crustal) sources to the melt. The variation in Zr, Ti and Y suggests a relatively minor role for zircon, whereas Y and Ti variations may account for early crystallisation of apatite and minor Fe–Ti oxides.

6.1.3 Modelling of major and trace including REE elements fractionation

Petrological mixing calculations (Bryan *et al.* 1969) can be employed to model crystal fractionation of felsic plutons (e.g., Kumar and Kmet 1995; Lee *et al.* 2003). The basic principle is that fractionation of early-formed minerals from a parent magma will give rise to residual (daughter) magma. The average GGn composition, EPG (R6) and TLg (TLg 2a) samples that were free from cumulate-like texture and without least silica content were chosen as the parental felsic model melts. The average compositions of the fractionating phases and residual melts as granitoids with high SiO_2 contents were used in calculations of several models of fractional crystallisation. The acceptable fractionation models in the evolution of GGn, EPG and TLg melts are summarised (table 9). In the model for GGn, about 13% fractionation of minerals (kf:pl:bt = 3.8:6.9:1.9) from a GGn parent magma (average GGn) will produce about 87% of residual liquid (G4). In the EPG model, about 17% fractionation of mineral assemblage (kf:pl:bt = 5.5:5.2:5.8) from the EPG parental magma (R6) will produce 83% of residual melt (A6). In TLg model about 13% fractionation of mineral assemblage (kf:pl:bt = 6.2:2.5:3.5) from TLg parent magma (TLg 2a) may produce 87% of residual melt (TLg 2c). The sum of residual squares (R^2) obtained from these models is reasonably low and acceptable (GGn: $R^2 = 0.84$, EPG: $R^2 = 1.26$, TLg: $R^2 = 0.15$). Addition of magnetite-ilmenite to the fractionating assemblage

Figure 17. Normalised trace element spidergrams for felsic parents showing calculated and observed residual liquids derived from model Rayleigh fractionation of (a) GGn, (b) EPG and (c) TLg melts.

and a change of parental and residual compositions do not provide good statistical-fit results.

Trace element modelling of single-stage fractional crystallisation has been carried out for selected elements that are of petrogenetic significance using obtained proportions of fractionating minerals from their respective felsic parents, distribution coefficients (K_d) appropriate to felsic melts (Nash and Crecraft 1985) and the equation for Rayleigh fractionation (Gast 1968; Cox *et al.* 1979). Calculated and observed trace element patterns of residual liquids derived from the fractionation of respective GGn, EPG and TLg felsic parents are more-or-less similar (figure 17a–c). However, differences for certain elements such as Ce, Nd, Sm for GGn, Yb for EPG and Sr and Zr for TLg, may be accounted for by either the use of an unrealistic K_d for these elements, or could be the result of accumulation and/or heterogeneous distribution effect of the accessory phases

that host these elements during the fractional differentiation process. Since the feldspars (pl+kf) are the dominant phases to fractionate the REE patterns of EPG samples therefore exhibit negative Eu anomalies.

Low to moderately fractionated REE patterns with negative Eu anomalies for GGn and EPG suggest a significant role for the accessory phases and rock-forming minerals during melting and crystallisation events. Combined role of residual and fractionated plagioclase has also been considered a prime factor in the evolution of Proterozoic granitoids from the Lesser Himalaya (e.g., Miller *et al.* 2000). The sum of REE in TLg is much lower (up to 193 ppm) compared to that of leucogranite suite II of Bandal felsic magmatism (upto 270 ppm; Sharma and Rashid 2001), but is identical to other Himalayan leucogranites (Vidal *et al.* 1982; Scaillet *et al.* 1990). Thorpe *et al.* (1990) suggested that the low abundance of REE accompanied by a negative Eu anomaly may be the result of the fractionation of minor REE-bearing phases (e.g., apatite, xenotime, monazite and zircon) combined with that of plagioclase and K-feldspar. Depletion of LREE (La, Ce) in EPG, compared to GGn, may indicate either role of aqueous fluids or a feature inherited from source region.

6.1.4 Relation to Pan-African felsic magmatism

The GGn (601 ± 19 Ma) and EPG (474 ± 26 Ma) felsic magmatism relate to Neoproterozoic and Early Palaeozoic crustal events, respectively (e.g., Kröner 1984), which Kennedy (1964) described as the period of Pan-African crustal evolution, part of which is known as the East African Orogeny (EAO, $850\text{--}500 \pm 50$ Ma; Stern 1994). The Pan-African event marks the time span between the fragmentation of Rodinia and the formation of Greater Gondwana (Roy 1999), prior to Caledonide event (400 Ma, e.g., Chappell and Stephens 1988). The recognition of Pan-African events in the Indian shield, Sri Lanka and Africa, parts of which presently constitute the Kinnaur regions of Himalayan domain that are represented by felsic magmatisms (GGn and EPG), essentially mark the sites where the ocean closed and continental crust collided. Amalgamation of Gondwana (Pannotia) is one of the major pre-Pangean supercontinent events that occurred at ca 600 Ma, and break-up of Rodinia may have led to the assembly of Gondwana (Nance *et al.* 2013 and references therein).

7. Conclusions

Felsic magmatism in Kinnaur region of Himachal Higher Himalaya is represented by Neoproterozoic

(601 ± 19 Ma) granite gneiss (GGn), Early Palaeozoic (474 ± 26 Ma) granitoids (EPG), and tourmaline-bearing Himalayan (14–28 Ma) leucogranites (TLg). The bulk magnetic susceptibility range for GGn ($\chi = 0.168\text{--}0.190 \times 10^{-3}$ SI), EPG ($\chi = 0.096\text{--}0.130 \times 10^{-3}$ SI), and TLg ($\chi = 0.054\text{--}0.156 \times 10^{-3}$ SI) indicates that the conditions for crustal anatexis became increasingly reduced from pre-Himalayan to Himalayan felsic magmatic episodes. Modal compositions of GGn, EPG and TLg correspond to the granite (*sensu stricto*) melts generated by partial melting of fusible crustal components.

Plagioclase (GGn: An₁₀–An₃₁, EPG: An₁₅–An₃₃, TLg: An₂–An₁₅) and K-feldspar (GGn: Or₈₈–Or₉₅, EPG: Or₈₆–Or₉₇, TLg: Or₈₇–Or₉₄) compositions suggest primary crystallisation from their respective peraluminous (S-type) felsic melts. Biotites from GGn (100*Fe/Fe+Mg = 55–66), EPG (100*Fe/Fe+Mg = 53–73) and TLg (100*Fe/Fe+Mg = 70–75) are ferri-biotites enriched in siderophyllite exhibiting 3Fe $\rightleftharpoons$ 2Al and 3Mg $\rightleftharpoons$ 2Al substitutions typical of peraluminous (S-type), reduced felsic melts. Muscovites (ferro-celadonite) from GGn, EPG and TLg and tourmalines (schorl–elbaite) from EPG and TLg also suggest crystallisation from peraluminous, biotite-tourmaline and Li-poor felsic melts.

GGn and EPG parental melts appear to have derived from biotite-rich metapelite and metagraywacke sources; whereas TLg melt appear formed from relatively heterogeneous crustal sources during Himalayan orogenesis. Major elements modelling suggests low degree of fractional differentiation of felsic melts, i.e., ca 13% fractionation of major rock-forming minerals (kf–pl–bt) from GGn parent produces 87% residual felsic liquid; ca 17% from EPG parent produces 83% of residual felsic melt and; ca 13% TLg parent produces 87% of residual felsic melt. Calculated and observed trace elements of residual felsic magmas derived from GGn, EPG and TLg parents are more-or-less similar, but discrepancies for some elements were most likely the result of heterogeneous mineral distribution or sorting during fractional differentiation.

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Corresponding editor: R K SRIVASTAVA