Felsic granites vis-à-vis leucosomes from the Shyok–Darbuk section of the Shyok Suture Zone, eastern Ladakh, India: a geochemical study

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The Shyok–Darbuk section of eastern Ladakh forms a part of the Shyok Suture Zone, and is dominantly comprised of Early Eocene orthogneisses and mafic enclaves, and Miocene felsic granites and migmatites. The aim of the present study is to establish genetic linkage between leucosome of the migmatites from mixed zone and the felsic granite in the Darbuk region (DFG). It is observed that, partial melting, with or without segregation of initial melts, seems to be the main cause for the generation of felsic melts as represented by leucosomes and felsic granites. Leucosomes are considered as felsic partial melts that were retained in the partially molten zone (migmatite), and that the complex intrusive networks of melt channels in the migmatite region are considered to merge and coalesce during their ascent to upper crustal levels resulting in stocks and plutons of felsic granites that are observed in the Darbuk region.

Keywords: Darbuk Felsic granite, eastern Ladakh, leucosomes, migmatites, Shyok–Darbuk section.

Introduction

IT is believed that along convergent plate margins, the growth of continental crust involves a two-stage melting process[1]: one that produces large calc-alkaline Andean-type batholiths and other producing crustal melts by remelting of mantle-derived basalts[2]. The accretion of the Kohistan–Ladakh passive margin to the Karakoram and closure of the Shyok Suture Zone (SSZ)[3] led to the generation of subduction-related calc-alkaline magmas. In the Shyok–Darbuk section (Figure 1) of the SSZ, the crustal growth involved generation of syn- to post-accretion subduction-related orthogneiss and mafic enclaves, and the more evolved felsic rocks that were produced during a later stage through reworking processes[4,5]. The calc–alkaline hornblende-biotite (hbl-bt) orthogneisses of Shyok–Darbuk section have been reported to be of Early Eocene to Late Cretaceous age; for example, U–Pb zircon ages of 50–51 Ma for diorites from Tangtse and Darbuk were reported by Ravikant *et al.*[6], while Jain and Singh[7] have reported U–Pb ages of 75.7 ± 1 Ma for the igneous zircons of Tangtse mylonites and 68–51.5 Ma for two mica granites from the Pangong Metamorphic Complex near Muglib. The more evolved felsic granites of Darbuk, on the other hand, have crystallization ages ~20.8 ± 0.4 Ma (ref. 7). However, in the other parts of the Karakoram Fault Zone, these rocks range between 19.1 ± 1.1 and 13.7 ± 0.2 Ma (refs 6, 8, 9). These Miocene leucogranites occur in the form of injection complex, stocks and plutons[4,10–12]. The following section presents the geochemical study of migmatites (Figure 2 *a* and *b*) and leucogranites (Figure 2 *c* and *d*) in the Shyok–Darbuk section of the SSZ in eastern Ladakh, to support a genetic linkage between leucosomes (LS) exposed in the migmatite crustal rocks in the mixed zone near Shyok village and the felsic granites of Darbuk pluton (DFG).

Geology of the area

The terrain separating the Karakoram and Pangong mountain ranges and the Ladakh magmatic arc is referred to as SSZ, and is characterized by geological history that spans from Jurassic to Tertiary[13]. The Shyok–Darbuk section, the region under study, represents a part of the northeastern SSZ of the Ladakh region. The rocks of the Shyok–Darbuk section (Figure 1) in general are broadly grouped into three units: (i) Shyok hbl-bt orthogneiss with mafic enclaves, (ii) Shyok mixed zone and (iii) Darbuk plutons[4,5].

The Shyok orthogneiss is a porphyritic, medium- to coarse-grained calc-alkaline, sphene (titanite)-bearing hbl-bt granitoid. The orthogneisses contain mafic enclaves[5], similar to those present within the Ladakh Batholith. The Shyok mixed zone starts near Shyok village and runs for about 6–8 km towards Darbuk village in the west (Figure 1). It is also referred to as migmatite zone elsewhere in the farther east[9–11,14]. The zone comprises of

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a variety of migmatites, which consist of biotite granite leucosomes forming a network and hbl-bt melanosomes (Figure 2 *a* and *b*) and high-grade metamorphic rocks, including amphibolites, orthogneisses, calc-silicate rocks and metapelites. Further away from the mixed zone towards Darbuk, one can see ubiquitous presence of muscovite–biotite–leucogranites with or without garnet in the form of dykes, stocks and plutons of tens to hundreds of metres size, collectively referred to here as 'Darbuk pluton'. It extends up to Tangtse, and is intrusive into the Shyok Ophiolitic mélange all along its southern margin[15,16]. Henceforth, in this article the felsic granitoid rocks from the Darbuk pluton will be referred to as Darbuk felsic granites (DFG).

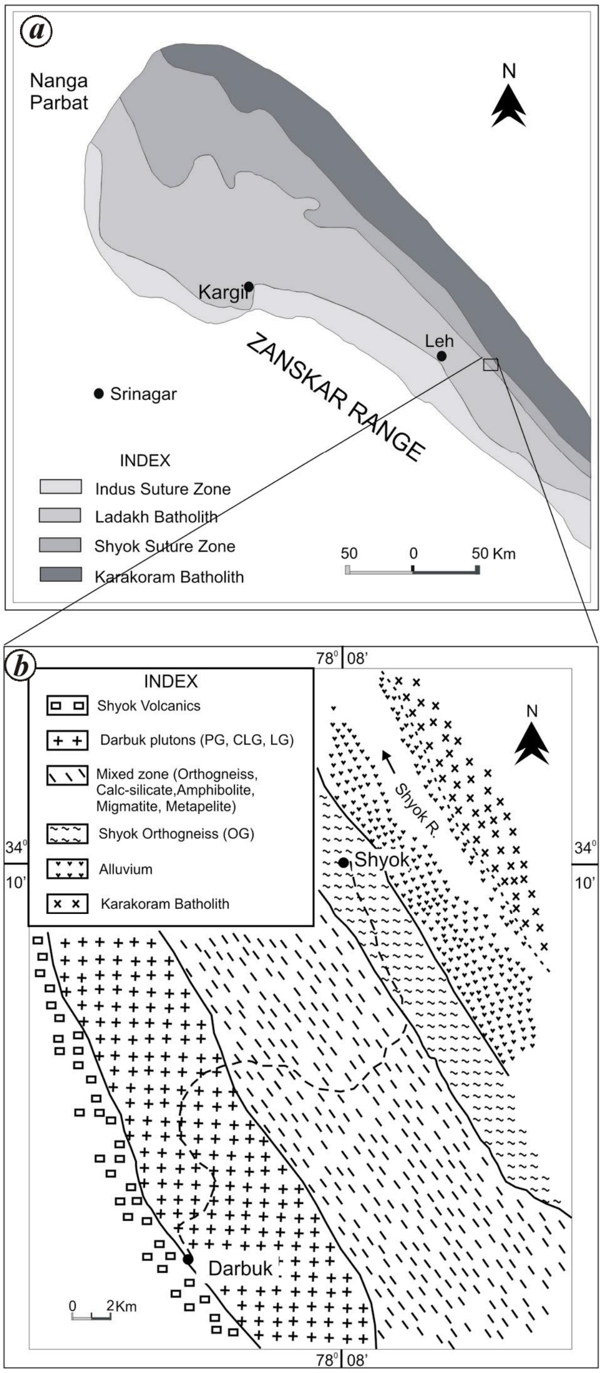

Figure 1. ***a***, A generalized geological map of Ladakh-Trans Himalaya[28]. ***b***, Map showing the general litho-units along the Shyok–Darbuk section of the Shyok Suture Zone, eastern Ladakh[4]. The dashed line represents the metal road connecting Darbuk and Shyok villages.

The DFG and LS from the Shyok–Darbuk section mineralogically do not show much difference. In general, they show hypidiomorphic granular to inequigranular texture; however, the felsic granites also show porphyritic texture. The rocks in general consist of K-feldspar (orthoclase/microcline), plagioclase, quartz, biotite and muscovite. Accessory minerals include apatite and zircon as inclusions in feldspar and quartz, along with minor amounts of opaques and epidote; garnet is present in some of the felsic granites.

Geochemistry of the rocks

In order to understand the genesis of the remnant magma network preserved as LS of mixed zone and its relation with felsic granites occurring as injection complex, stocks and plutons in the Darbuk region (DFG), their geochemistry was studied. The geochemical analyses of the major, trace and rare earth elements (REE) were carried at the analytical laboratories of Wadia Institute of Himalayan Geology, Dehradun using XRF (SIEMENS SRS 3000) and ICP–MS (Perkin-Elmer SCIEX). Range and mean values of the DFG and LS are shown in Table 1, and their major, trace and REE data are plotted in Figures 3–6. Detailed geochemical data of individual samples are given in Daga *et al.*[4]. The following section discusses the geochemical similarities of LS and DFG, and the genesis of parental felsic melt.

Leucosome of mixed zone versus DFG

Table 1 gives the major, trace and REE concentrations of LS and DFG. The mean geochemical values of DFG and LS are seen to more or less match with one another and show overlapping compositions. DFG and LS show compositional variation from granodiorite to granite and are characterized by metaluminous to peraluminous nature, with mol A/CNK ratio of LS in the range 0.83–1.04 and a mean value of ~0.95 and DFG in the range 0.93–1.06 with mean value of ~0.90 (Table 1). Also, both LS and DFG rocks are moderately evolved, and show mg# to be around 35 (Table 1). In order to see their mutual relation, the major oxide data of LS and DFG were plotted together in the Harker's variation diagram (Figure 3). On this diagram LS together with DFG shows general coherence of enrichment and depletion of elements. The REE concentrations of LS (ΣREE: 25–255; average 103) are more or less similar to the REE abundance of DFG (ΣREE: 28–332; average 93). Their chondrite-normalized

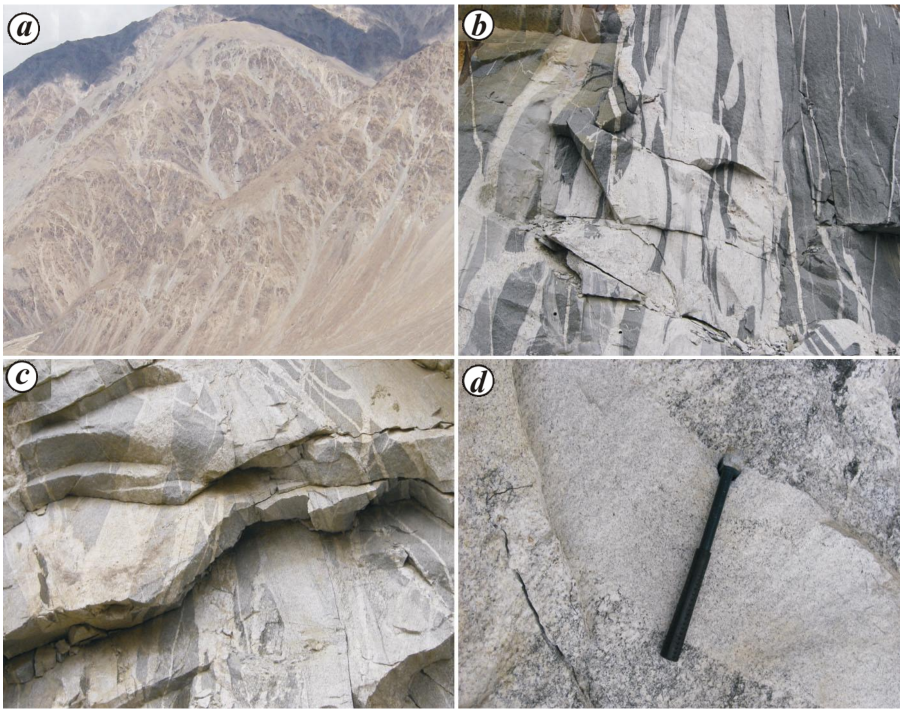

Figure 2. Field photographs: ***a***, mixed zone showing cross-cutting leucosomes of migmatite (LS) forming a melt flow network; ***b***, Migmatite showing leucosome and melanosome; ***c***, ***d***, Darbuk pluton showing various phases of felsic granite ranging from porphyritic to coarse- to medium-grained.

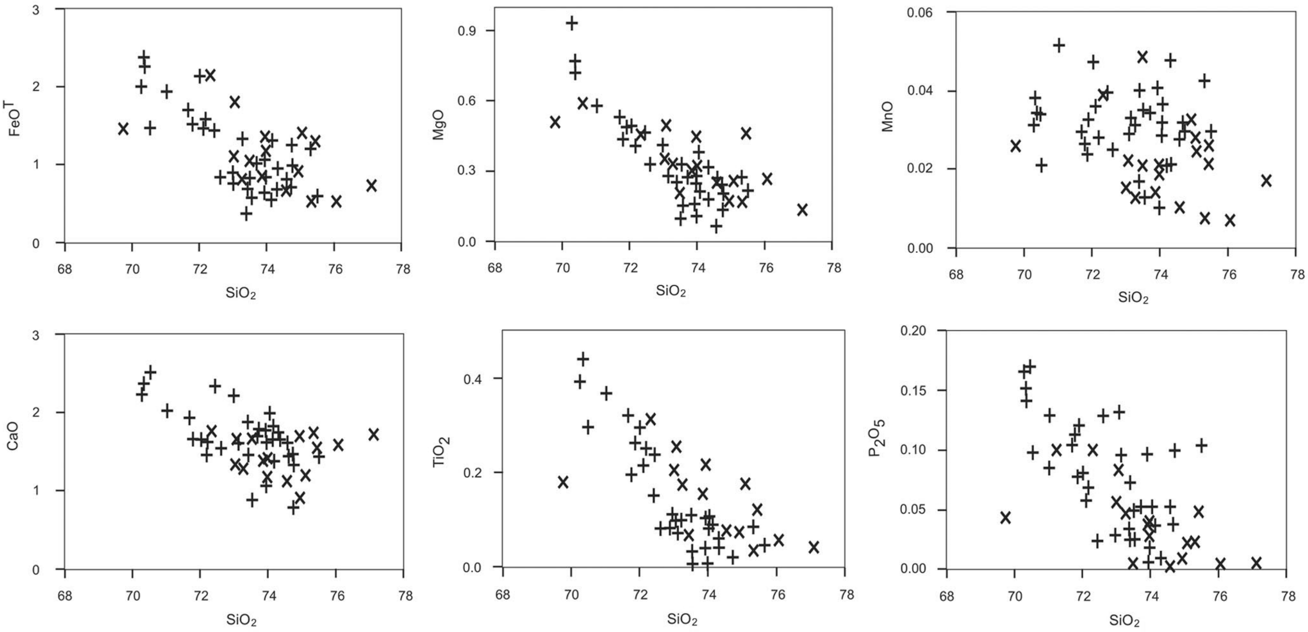

Figure 3. Harker's plot showing overlapping composition of some major oxides of leucosome of migmatites (LS) represented by cross symbol (x) and felsic granites from Darbuk represented by plus symbol (+). Data on individual samples are given in Daga *et al.*[4].

REE (normalized after Nakamura[17]) shows enriched LREE and depleted HREE patterns (Figure 4 *a*) with both the DFG (plus symbol) and LS (cross symbol) showing more or less similar variation along with the degree of depletion of Eu anomaly. The compatible and incompatible elements of LS and DFG also show similar pattern on the spider diagram (Figure 4 *b*) when normalized to lower crust values after Weaver and Tarney[18]. The foregoing discussion suggests that LS can be linked to felsic granites of Darbuk pluton that forms a complex melt flow intrusive sheet network, stocks and plutons.

Table 1. The range and mean values of leucosome of migmatite of mixed zone and felsic granite of the Darbuk pluton from the Shyok–Darbuk section, eastern Ladakh

	Leucosome of migmatite from the mixed zone		Felsic granite from the Darbuk pluton	
	Range	Mean value	Range	Mean value
Major oxides (wt%)		(*n* = 17)		(*n* = 46)
SiO_2	67.24–77.01	73.58	70.24–75.45	73.16
Al_2O_3	12.21–16.44	14.28	12.35–15.56	14.78
TiO_2	0.04–0.65	0.17	0.02–0.43	0.13
FeO^T	0.57–4.07	1.25	0.38–2.59	1.08
MgO	0.14–1.51	0.39	0.06–0.92	0.33
MnO	0.01–0.06	0.02	0.01–0.47	0.05
CaO	1.11–3.65	1.74	0.77–2.48	1.66
Na_2O	3.12–5.42	3.98	2.96–5.27	4.32
K_2O	2.31–6.46	4.77	3.07–5.46	4.13
P_2O_5	0.01–0.29	0.05	0.01–0.17	0.06
Trace elements (ppm)		(*n* = 17)		(*n* = 46)
Ba	260–1256	788	371–2188	721
Pb	14–57	33	24–58	46
Th	1–50	14	4–42	14
Rb	59–144	110	91–257	186
U	3–6	4	4–13	6
Sr	201–710	441	87–691	311
Y	3–31	11	5–66	12
Zr	19–347	121	30–168	76
Nb	1–26	8	2–20	9
REE (ppm)		(*n* = 7)		(*n* = 18)
La	5.55–63.53	24.57	5.27–75.73	20.55
Ce	10.83–114.34	45.22	11.25–144.95	40.50
Pr	1.13–11.42	4.67	1.30–15.57	4.28
Nd	4.46–40.64	16.72	5.39–60.37	16.35
Sm	0.97–6.14	2.91	1.63–8.89	3.04
Eu	0.23–1.35	0.68	0.23–1.61	0.61
Gd	0.91–5.55	2.64	1.45–7.90	2.51
Tb	0.09–0.79	0.36	0.17–0.99	0.35
Dy	0.38–4.45	2.04	0.69–4.99	1.97
Ho	0.06–0.92	0.38	0.09–1.16	0.35
Er	0.17–2.49	1.06	0.23–3.86	1.02
Tm	0.02–0.37	0.16	0.03–0.68	0.15
Yb	0.10–2.49	0.94	0.16–4.42	0.94
Lu	0.02–0.37	0.14	0.03–0.69	0.15
ΣREE	24.92–254.87	102.48	27.92–331.87	92.76
mol. A/CNK	0.83–1.04	0.95	0.93–1.06	0.90
mg#	25–48	35	12–51	36

n = Number of samples. The indvidual sample data are available in Daga *et al.*[4]; mol. A/CNK, Molecular $Al_2O_3/(CaO + Na_2O + K_2O)$; mg# = $MgO/(MgO+FeO^T)$.

Discussion

Large amounts of crustal shortening, thickening, metamorphism and magmatism followed the India–Asia collision in the Karakoram region[19], resulting in late phase younger Miocene collision-related granites and migmatites as found in Shyok–Darbuk section of eastern Ladakh. In the Shyok–Darbuk section, LS and DFG were generated by the intracrustal partial melting of hybrid magma source, involving predominantly orthogneiss, whose protoliths were derived from mantle source, and subordinate amounts of metapelitic crustal source[4]. Amphibole, a common and abundant mineral of subduction-related orthogneisses of the Shyok–Darbuk region seems to have played a role in the generation of anatectic melts. The breakdown of amphiboles in the deeper parts of arcs, released large amounts of H_2O that initiated anatexis at higher crustal levels and led to the formation of migmatites[20]. Both metatexites and diatexites occur in the migmatite zone. Diatexitic migmatites resulting from advance stage of melting, as evident from high melt fraction, flow foliation, enclaves and vein-like leucosomes, are more prominently observed[21]. Leucosomes, parallel to foliation, cutting across the foliation and a late phase coarse-grained leucosome are present. Their flow is controlled by low-pressure sites such as foliation, mineral lineation, fractures, and other structural control regions like fold hinge, axial surfaces and boudin necks. The presence of leucosomes in different orientations is interpreted to represent a melt flow network during anatexis. The leucosomes, having diffusive boundaries with melanosomes, form an irregular network of leucogranite pockets and veins, feeding into a larger leucosome with width varying even up to 1 m or more.

The effective separation of protoliths and melt-rich rocks can be judged from the compatible versus incompatible elements plot[22]. On the CaO + Na$_2$O versus K$_2$O diagram, the felsic granites (plus symbol), leucosomes (cross symbol) and protolith (orthogneiss, open circle symbol along with mafic enclaves, star symbol) define a linear negative trend (Figure 5). The melt-rich DFG and LS plot at the higher end of K$_2$O and represent the diatexites, while those near the protolith end represent the metatexites.

An attempt has also been made here to study the patterns of chondrite-normalized REE and primordial mantle-normalized trace elements of melanosome (MS) and LS pairs collected from two different locations from the migmatite in the mixed zone and felsic granite and orthogneiss (host) from the Darbuk pluton (Figure 1 *b*). Comparison of the studied samples shows that there is similarity in the REE distribution; LS are depleted in REE when compared to MS (Figure 6 *a–d*). For example, the REE pattern of LS (MD-293) from the migmatite zone is systematically in line with related MS, MD-291 (Figure 6 *c*). However, the behaviour of Eu anomaly is not uniform in the studied migmatites. The biotite-rich LS (MD-279) from the migmatite zone does not show any Eu anomaly (Figure 6 *a*), on the other hand, sample MD-293 shows distinct Eu anomaly (Figure 6 *c*). Since Eu is mainly incorporated in plagioclase, in some cases the relative high plagioclase content of LS may partially explain the observed Eu distribution. However, a pronounced positive Eu anomaly can also be observed in LS with a negative anomaly in MS, when the latter is rich in REE-bearing dark minerals and poor in plagioclase (not shown in the figure). The observed REE patterns of MS and LS suggest mobility of elements in a closed system during migmatization. The enrichment of incompatible elements and depletion of compatible elements in the LS samples (MD-279 and MD-293) from the migmatite zone with respect to the corresponding MS samples (MD-280 and MD-291 respectively) is distinctly seen in the primordial mantle-normalized diagram (Figure 6 *b* and *d*).

On the contrary, REE and primordial mantle-normalized pattern of felsic granite from the Darbuk pluton (MD-308) and the host orthogneiss (MD-307) away from the migmatite zone do not show any similarity (Figure 6 *e* and *f*). DFG can be interpreted to be accumulation of anatectic melt that possibly migrated from

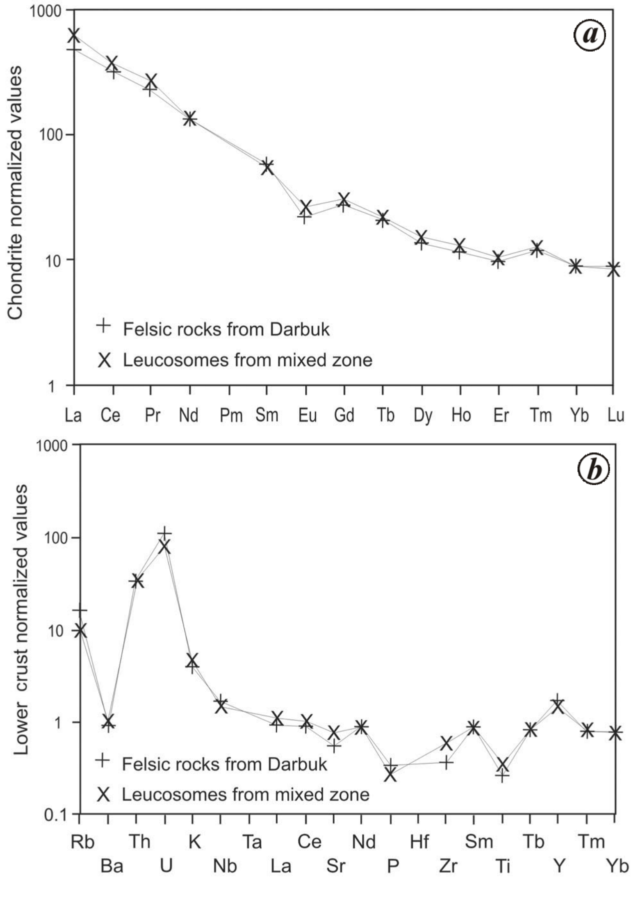

Figure 4. ***a***, Chondrite-normalized mean values of LS and DFG (normalized values after Nakamura[17]). ***b***, Spider diagram of mean values of elements of LS and DFG normalized to lower crust (normalized values after Weaver and Tarney[18]). Data from Table 1, and symbols as in Figure 3.

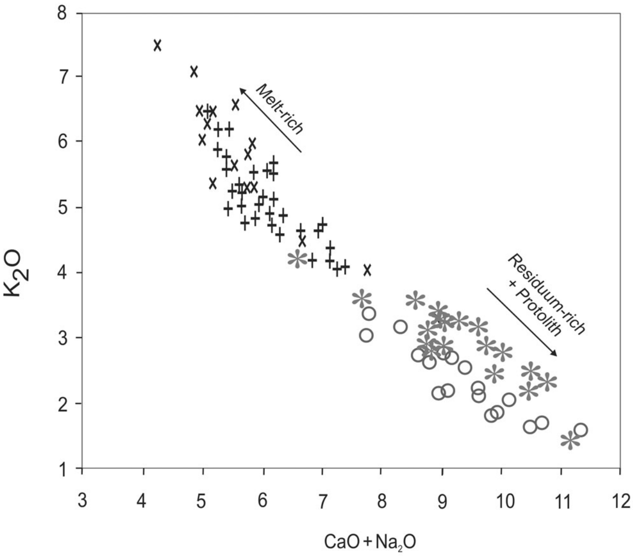

Figure 5. CaO + Na$_2$O versus K$_2$O variation diagram. The data on felsic granite (plus) and leucosomes (cross) are given in Daga *et al.*[4] and those on orthogneiss (open circle) and mafic enclaves (star) in Rameshwar Rao *et al.*[5].

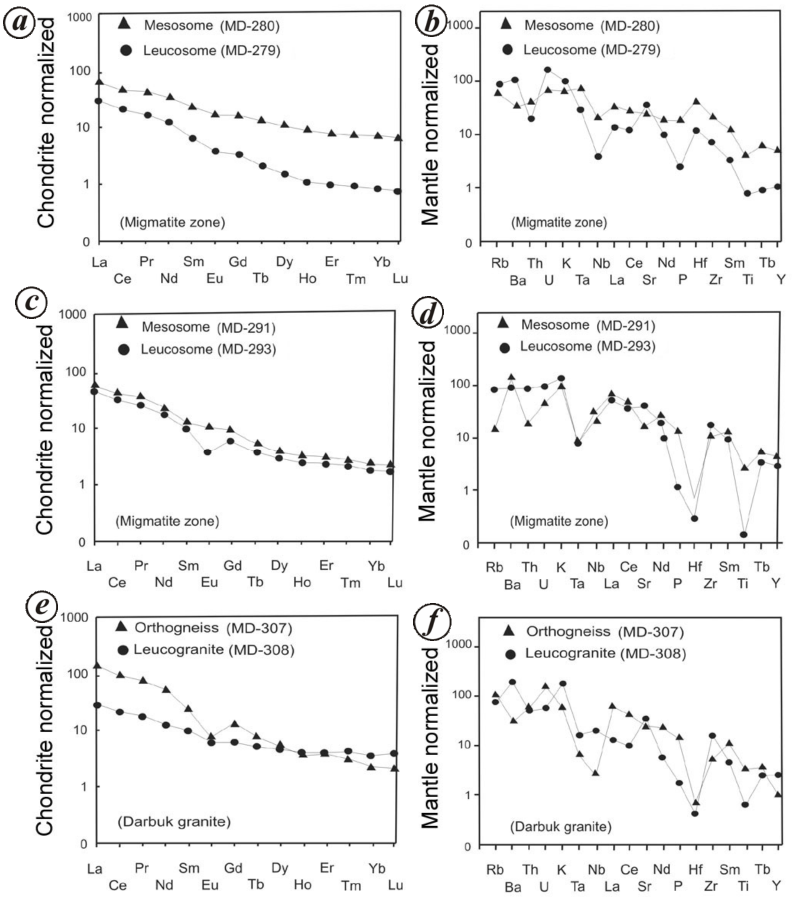

Figure 6. The chondrite-normalized REE and primordial mantle-normalized patterns of melanosome and leucosome pairs collected from two different locations from the migmatite rock of the mixed zone, as well as from the Darbuk felsic granite pluton (normalized values after Nakamura[17] and Wood *et al.*[29] respectively). Data references as given in Figure 5.

greater depths and emplaced into the host orthogneiss; Sawyer[23] called these as parautochthonous granites.

Migmatite genesis

The above illustrated REE patterns from the Shyok–Darbuk section can also be used to understand the migmatite genesis. The migmatite genesis, in general, involves (i) metasomatism at subsolidus or hypersolidus conditions, (ii) injection of foreign magmas along foliation planes, (iii) metamorphic differentiation at subsolidus temperatures, or (iv) partial melting (anatexis) with or without segregation of initial melts[24]. The REE patterns shown in Figure 6 indicate that no metasomatic reactions or injection could explain the Shyok migmatite formation, since the REE patterns of the metasomatized rock would be more or less similar to those of the protolith because REE distribution of metosomatizing fluid would be very low due to its low solubility in supercritical hydrous fluids[25]. In case of injection of magmas into a country rock, the REE patterns of the LS dykes should be unrelated to the adjacent MS layers[26]. A further argument against the injection model is the existence of melanosome, which would not be present in case of unequivocal intrusive LS. In the case of metamorphic segregation, LS are only composed of quartz and feldspar; thus the segregated LS should be poor in REE[27]. However, LS from migmatite zone have more enriched REE abundance (ΣREE: 25–255; average 103; Table 1). Partial melting (anatexis) with or without segregation of initial melts seems to be the viable mechanism which can explain the genesis of Shyok migmatites. In case of partial melting, the melanosomes and leucosomes show complementary REE patterns, the REE being preferentially concentrated in the melanosomes as observed in the sample from the migmatite zone discussed above (Figure 6). The metamorphism of metapelites and calc-silicate rocks in the region of Shyok–Darbuk section shows pressure–temperature estimates of ~7.4 kbar and 660°C respectively, which are ideal for generating anatectic melts in the region (M. M. Daga, unpublished). Also, an early Tertiary crustal thickening and regional metamorphism might have provided the heat for melting that produced the late phase Miocene leucogranites.

To sum up, it is conceivable from the foregoing discussion that LS of the migmatites (LS) and the felsic granites of the DFG are coeval, which record melt flow syntectonically through the deforming crust. The networks of LS magma channels in the mixed zone are considered to merge and coalesce during their ascent to upper crustal levels, resulting in feeding stocks and plutons. Moreover, partial melting with or without segregation of initial melts, seems to be the workable mechanism in the generation of migmatites observed in the mixed zone of Shyok–Darbuk section. Also, the felsic granite of Darbuk has been dated to be ~20 Ma, however, no radiometric dates are available for the leucosomes from the mixed zone of Shyok–Darbuk section for comparison. Hence, more radiometric dates are required to further substantiate our findings.

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