# Mineralogy and Geochemistry of mafic to hybrid microgranular enclaves and felsic host of Ladakh batholith, Northwest Himalaya: Evidence of multistage complex magmatic processes

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Felsic magmatisms in the north of Indus-Tsangpo-Suture Zone, referred herein Ladakh granitoids (LG), have been characterized dominantly as calc-alkaline, magnetite to ilmenite series (gradually changing from NW to SE) granitoids derived from partial melting of heterogenous protoliths in subduction environment. Field relation, petrography, mineralogy and geochemistry of ME and felsic host LG have been carried out along various transects covering Northwest (Dras-Kargil-Silmo-Batalik-Achina Thang), Central (Leh-Ganglas-S. Pullu-KhardungLa-N. Pullu-Khardung), Southeast (Himiya-Litse-Upshi-Karu-Sakti-Zingral-ChangLa) parts of Ladakh batholith in order to understand the physical and chemical processes of mafic and felsic magma interaction in plutonic condition.

The LG can be broadly classified into coarse-grained LG with abundant mafics (hbl-bt), medium-grained LG with low content of mafics, and fine-grained leucocratic LG with very low amount of mafics. Mesocratic to melanocratic, fine to medium grained and porphyritic (xenocrystic) hybrid microgranular enclaves (ME) are found hosted mostly in medium to coarse- grained LG. Double enclaves (one mafic ME into other porphyritic ME) and syn-plutonic disrupted mafic dykes are also hosted in K-feldspar megacrysts bearing LG in the Northwest part of batholith, which record evidence of multiple mafic to hybrid magma injection and thermal rejuvenation of partly crystalline LG. ME are absent or rare in the leucocratic variety of LG. The ME are rounded to elongate commonly having sharp, crenulate, and occasionally diffuse contacts with felsic host, and size varies from a few cm to metres across but cm-sized ME (d<30 cm) are common, which strongly suggest that several pulses of crystal-charged mafic and felsic magmas, coexisted, hybridized, co-mingled into plutonic setting. Most hybridized parts (active mixing region) of LG do not contain ME whereas isolated mixing regions of LG contain variable sizes of mingled and streched (sine flowage) ME. The ME (diorite, quartzdiorite) and felsic host LG (granodiorite, monzogranite) bear common mineral asemblages (hbl-bt-pl-kfs-qtz-ap-zrn-mt ±ilm) but differ in their mineral proportions. The ME lack cumulate-like texture and are fine to medium grained, and therefore oppose their co-genetic link with LG. Presence of patchy zoned (spongy, cellular) plagioclase xenocrysts, quartz ocelli and apatite needles in porphyritic ME strongly indicate mingling and undercooling of hybridized ME globules into cooler felsic host LG. Grain size differences, crystal index, and size of ME among the ME population, except to those of porphyritic ones, correlate well with degree of undercooling of ME. Disaggregated large ME into several smaller ones lack fine-grained chilled margin. Biotite composition of ME and LG from Northwest and Central parts represents Mg-Fe biotites stabilized in FMQ and NNO buffers exhibiting Mg$\rightleftharpoons$Fe substitution typical to its crystallization in a calc-alkaline (I-type) felsic melt but biotite of LG from Northwest sector is depleted in phlogopite component as compared to LG biotite of Central part. Biotites of ME and LG from Southeastern part of batholith also represent Mg-Fe biotite but are slightly enriched in Al-Ti-Fe contents and bimodal in nature exhibiting $2Al \rightleftharpoons 3Fe^{2+}$ and Mg $\rightleftharpoons$Fe substitutions typical to their crystallization in peraluminous (S-type) and calc-alkaline (I-type) felsic melts respectively. This is because ilmenite series granites dominants over magnetite series granites in the Southeastern transects. The LG batholith predominantly crystallized at elevated $fO_2$ (magnetite series) and subordinately at low $fO_2$ (ilmenite series) more prevalent in the Southeastern part. Amphiboles in ME and LG belong to calcic amphibole (magnesiohornblende slightly approaching to ferrohornblende). Changing $fO_2$ conditions of melt have indeed affected temperature-sensitive exchange vector $Fe^{3+} \rightleftharpoons Al^{vi}$ of hornblende and thus also have affected the Al-in-hornblende barometers. Taking into account of such limiting factors the Al-in-hornblende barometer estimates emplacement of Northwest LG at P=2.5-3.5 (±0.6 kbar), Central LG at P=3-4 (±0.6 kbar) and Southeastern LG at P=3.5 (±0.6 kbar) suggesting differential unroofing of LG magmachamber(s).The ME globules are mingled and undercooled more-or-less at the same level of LG emplacement but hybrid (ME) magma zone must occur sufficiently below it as some small sized ME have undercooled enroute at ca P=5.0 (±0.6 kbar).Whole rock composition of LG is calc-alkaline, largely metaluminous I-type (mol A/CNK<1.0) to slightly peraluminous S-type (mol A/CNK>1.05) but ME are highly metaluminous (mol A/CNK>0.9) and markedly differ from diorite, gabbro and mafic dykes of the region. Near linear to curvilinear compositional trends observed for $TiO_2$, CaO, $Fe_2O_3t$, MgO, against $SiO_2$ can be attributed to mafic-felsic magma mixing whereas data scatter for $Al_2O_3$, alkalies, MnO, $P_2O_5$, Rb and Ba are caused by combined effect of chemical diffusion and modal mineral variations between ME and LG. However, LG and ME might have experienced internal fractional differentiation prior to and during the mixing event. Wide data scatter observed for Nb, Yb, Zr in ME and LG are result of modal abundance of accessory phases (e.g. zircon) hosting these elements. K-feldspar megacrysts bearing LG in Northwest part and its porphyritic ME are Zr-Nb-U-Th-Rb-Ba-Sr-LREE enriched as compared to other LG-ME samples most likely due to retention and recycling of residual mineral phases hosting these elements mainly during mafic-felsic magma mixing event. The ME and LG from Northwest part of batholith exhibit almost flat REE patterns with low-degree of negative Eu-anomalies as compared to slightly inclined LREE and flat HREE patterns of LG and ME from central and southeast parts of the batholith. Identical trace and REE patterns of ME and LG, and higher sum of REE in ME compared to felsic host LG may be attributed to diffusion mechanism during postentrapment cooling and mingling of ME magma globules into partly crystalline felsic host LG. Gabbro, diorite and a few LG are depleted in sum of REE and exhibit positive Eu-anomaly, which strongly oppose a cognate origin for ME. Several lines of evidences suggest that calc-alkaline Ladakh granitoids and their microgranular enclaves are product of complex magmatic processes such as multistage magma mixing of multiple pulses of mantle- and crustal-derived magmas concomitant fractional differentiation, contamination, mingling, and diffusion mechanisms.