Review Paper:

Geochemical characters of Leptynite from Melur, Madurai District, Tamil Nadu, South India

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Abstract

Leptynite occur with minor bands of basic granulites, charnockites, calcsilicate rocks, quartzites and khondalites in the Melur area in the Southern granulite terrane (SGT), India. Interbedded grey and cream leptynite types are distinguished based on field relations and geochemistry. They are paragneisses (khondalites) comprising to quartz-felspar-sillimanite gneiss, quartz-felspar-garnet-sillimanite gneiss and their variants: charnockite series consisting of pyroxene granulites (basic) and charnockites (acidic), granites, pegmatites and aplites and dolerites. Charnockites, granites and dolerites are successfully emplaced into the basement rocks' interbanded paragneiss and pyroxene granulites. Leptynite is noticed at the contact of paragenesis and charnockite.

Based on whole-rock geochemistry, it is evident that both charnockite patches and host leptynites are isochemical. The adamellite composition, per-aluminous nature with positive Europium anomaly of host leptynite and charnockite patches, suggest their co-genetic relation. Higher values of $(La/Yb)_N$ and $(Gd/Lu)_N$ of leptynites indicate the highly fractionated HREE pattern of leptynites. The total REE, LREE/HREE and Eu-Eu∗ data indicate their derivation from the post-Archaean granodioritic upper crust comprising of large proportions of impure greywackes with K-rich granitic components.

Keywords: Petrology, Geochemistry, Leptynites, Melur, Madurai.

Introduction

The Madurai block is recognized as a composite geological entity, formed through the accretion of magmatic arcs, intermingled oceanic and supracrustal lithologies and subsequent regional metamorphism during the late Neoproterozoic-Cambrian orogeny[23]. It forms part of the Southern Granulite Terrain (SGT) which is a collage of crustal blocks with Neoarchean, Paleoproterozoic and Neoproterozoic ages, interpreted to have originated in active convergent margin settings like suprasubduction zones and arc magmatic environments[6]. The Madurai block is delineated by the Palghat-Cauvery shear zone to the north, considered a late Neoproterozoic collision zone and a trace of the Gondwana suture formed during the closure of the Mozambique Ocean[7,8,23].

Studies by Ghosh et al[14] and Plavsa et al[21] indicate that the Madurai block comprises of Archean to Neoproterozoic granite, charnockite, gneiss, calc granulite and quartzite. India, Madagascar, Sri Lanka, Antarctica and western Australia were once part of East Gondwana land until their Mesozoic break-up[13], highlighting the importance of understanding Precambrian tectonomagmatic and metamorphic events for reconstructing the East Gondwana assembly. Within this context, the Melur area in the Madurai district, part of India's Peninsular Gneissic Complex (PGC), contains leptynite interlayered with minor bands of basic granulites, charnockite, calcsilicate rocks, quartzites and khondalite.

This study focuses on the petrography, mineral chemistry and phase equilibria of schists and gneisses from two distinct metamorphic zones in Melur. The garnet metamorphic zone includes mica schist, garnet-bearing mica schist, felsic leptynite and interlayered plagioclase amphibolite. Garnet crystals here display growth zoning, with increasing almandine and pyrope and decreasing spessartine from core to rim. The sillimanite metamorphic zone consists of garnet-bearing biotite mica schist, sillimanite-bearing biotite-plagioclase gneiss and felsic leptynite, with garnets exhibiting a nearly homogeneous composition.

Petrographic and geochemical evidence strongly suggests a metasedimentary origin for the leptynite/pink granite in the Melur area, supported by: (a) their intercalation with talc-granulites, anhydrous aluminous minerals (almandine + sillimanite + cordierite ± sapphirine ± spinel) and quartzites; (b) higher Na_2O content; (c) chondrite-normalized rare earth element (REE) patterns of leptynite (47.6-238.2) and pink granite (71.8-673.4) and (d) molecular $Al_2O_3/(CaO + Na_2O + K_2O)$ values greater than 1.1. The study's primary objective is to investigate the field, petrography and geochemistry of granite/leptynite rock from the Melur area.

Geology of the study area: The Madurai block is bisected by the NE-SW trending Karur–Kamban–Painavu–Trichur (KKPT) lineament[14] which functions as an isotopic boundary, separating Archaean crust to the northwest from Proterozoic crust to the south and east[1,14,28]. This lineament also manifests as a series of south-dipping reflectors in deep reflection seismic surveys[22]. Proterozoic metasedimentary rocks in the Madurai Block primarily yield zircons aged 2.6 to 1.8 Ga[8,24], with occasional older Mesoarchaean and Mesoproterozoic zircons also reported[8,24]. Collins et al[8] proposed a correlation with central Madagascar's Itremo group, suggesting the Madurai block could be a southern extension of the Azania continent within the intra-East African Orogen[9]. However, others interpret the Madurai block's metasedimentary rocks as a metamorphosed passive margin to the Dharwar craton of India[1,14].

The Melur area has experienced significant crustal anatexis, forming a 15 km long ENE-WSW/E-W trending linear belt of garnetiferous quartz-felspathic rock (leptynite), extending from Kilaiyur to Keelavalavu-Purakuttu Malai within the gneiss/meta-sedimentary sequence. This white rock favored for dimension stone due to its pure white color and pink garnet dots, containing K-feldspar, plagioclase, quartz and minor biotite, with discontinuous bands of quartzite. The presence of garnet-biotite gneiss enclaves/schlieren suggests that the quartzo-feldspathic rock is an anatectic product of metasedimentary protoliths from intense migmatization. The Melur area also exhibits granulitic facies rocks, including khondalite and charnockite of the Eastern Ghat Supergroup.

Calc granulite bands, varying in size from 25 m to 2 km with widths of a few centimeters to 20-30 m, are present east and west of Karungalakkudi, widening around Malampatti possibly due to repeated folding. Garnetiferous sillimanite gneiss (metapelites) occurs as lenses within garnetiferous granulite in the Kilaiyur/Keelavalavu area and sulfide mineralization is noted in these metapelites, which are a disadvantage for dimension stone quarrying. This supracrustal assemblage primarily consists of quartz and feldspar (± sillimanite ± graphite ± garnet ± magnetite), interbanded with calc-silicate rocks, dolomite and garnetiferous gneiss or schist, all within a large expanse of biotite gneiss (± garnet).

Rocks around Melur are broadly categorized into khondalite and charnockite groups. Subsequent migmatization and reconstitution of these groups led to grey-colored migmatite including hornblende-biotite gneiss, garnet-biotite gneiss and garnetiferous quartzo-feldspathic granulite. Younger pink granite and pink pegmatoidal granite intrusions further transformed parts of the grey migmatite into pink migmatitic gneiss and pink augen gneiss.

Specifically, the white garnetiferous quartzo-feldspathic granulite east of Melur is interpreted as reconstituted garnetiferous sillimanite gneiss while the pink augen gneiss near Tiruchunai is attributed to the blastic growth of pink potash feldspar augen within the grey biotite gneiss. The area's final intrusive activity is marked by numerous minor pegmatite and quartz veins.

Five fresh rock chips of medium and coarse-grained Leptynite/ pink granite samples are prepared for thin sections based on the textural arrangement of minerals. Chip samples are sent to Continental Instruments (Lab Crystals, Thin Section Preparations, Lucknow) to make thin sections. For each location, samples are collected in the Melur leptynite/ pink granite for analyzing the crystallization texture. Textural analysis and petrographic properties are studied under the Leica DM2700 P (Leica Application Suite) petrological microscope at the Department of Geology, Periyar University, India. Samples are pulverised to 63µ using steel and agate mortars. The pulverised 17 samples are sent to the Activation Laboratory Limited, Canada, for litho geochemistry and whole rock analysis.

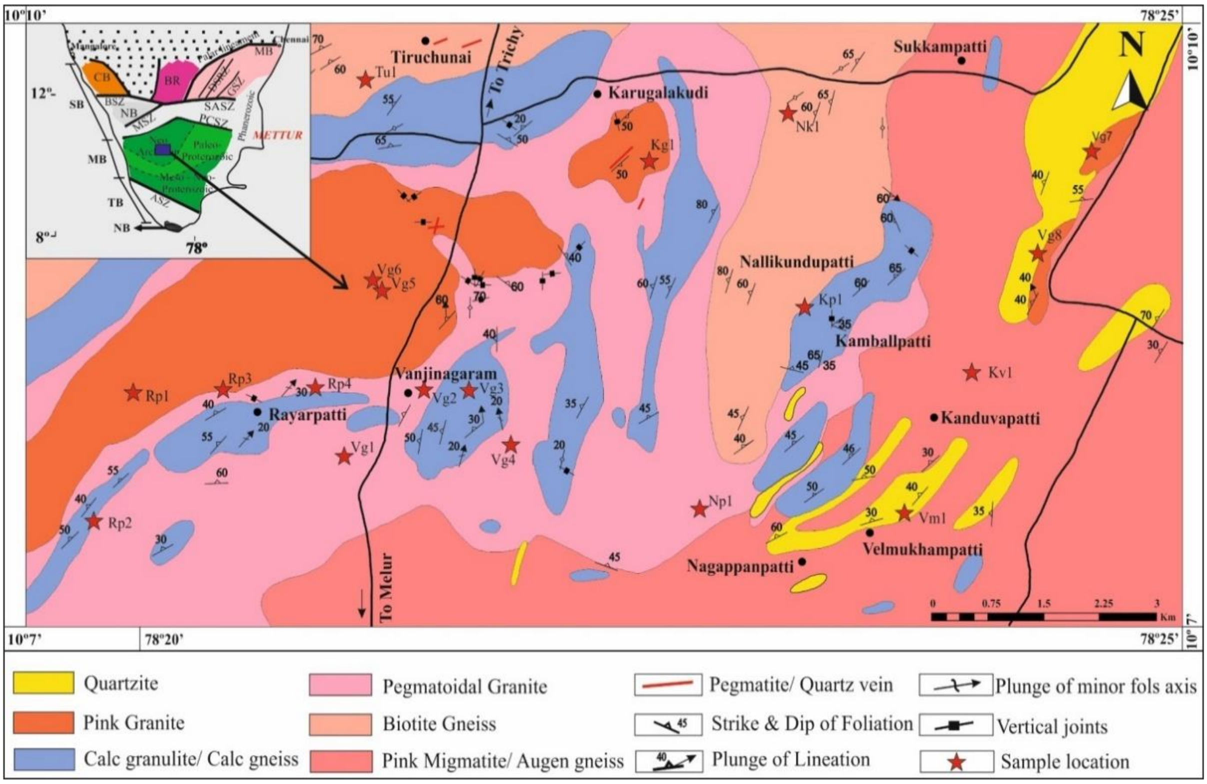

Figure 1: Geology and structural map of the study area

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The samples are analysed under the package code of 4 litho (WRA+ICP). The package needs 5g of the pulverised sample to pass 95% through 105 microns (μm). The most aggressive fusion technique employs a lithium metaborate/tetraborate fusion. Fusion is performed by a robot at Actlabs. The resulting molten bead is rapidly digested in a weak nitric acid solution. The fusion ensures that the entire sample is dissolved. With this attack, major oxides including SiO_2, refractory minerals (i.e. Zircon, sphene, monazite, chromite, gahnite etc.), REE and other high field strength elements are put into solution.

High sulphide-bearing rocks may require different treatment, but can still be adequately analyzed. The analysis is by ICP-OES and ICP-MS. Eu determinations are semi-quantitative in samples having extremely high Ba concentrations (> 5 %). The samples are run for major oxides and selected trace elements (4B) on an ICP. Calibration is performed using 14 prepared USGS and CANMET-certified reference materials.

Field Relationship - Leptynite: Leptynite rocks are typically light-colored (white, grey, or pinkish) due to abundant quartz and feldspar. They are fine- to medium-grained with a granoblastic texture indicating equigranular interlocking mineral grains formed under high-grade metamorphism (Fig. 2). Essential minerals include quartz, alkali feldspar (microcline/orthoclase) and plagioclase, while accessory minerals like garnet, biotite, sillimanite, or graphite may also be present, depending on protolith composition and metamorphic conditions. Their texture is generally granoblastic or lepidoblastic, sometimes exhibiting weak foliation or lineation from directed stress and faint compositional banding due to mineral segregation. Leptynite often forms smooth, rounded outcrops with slightly exfoliated or polished surfaces from quartz-rich layer weathering.

The Leptynite ("Kashmir White") is interpreted as a product of remelting pre-existing country rock garnetiferous sillimanite gneiss and pegmatite veins intruding granite at Royarpatti and Vanjinagaram (Fig. 2a). This image (Fig. 2a) illustrates the "Kashmir White" granite, showing its formation from partially melted garnetiferous sillimanite gneiss along with a cutting pegmatite vein indicating a later magmatic phase, providing insights into the area's complex geological history. At Sukampatti area, images (Fig. 2b-d) show pegmatite enclaves (inclusions) within a larger granite body, highlighting the contrast between the exceptionally large crystals of pegmatites and the surrounding granite. These variations may depict different sizes, shapes, or mineral compositions of the enclaves.

Near Karugalakudi, an image (Fig. 2g) displays pink pegmatoidal granite containing garnet-like crystals likely allanite. This pegmatoidal granite, characterized by its very coarse grains and pink color due to potassium feldspar, highlights the mineralogical diversity found within pegmatites and granites. Finally, images (Fig. 2e-f, h) show granite outcrops and quartzo-feldspathic granite (leptynite) exposures in the Vanjinagaram area, Melur Taluk, potentially illustrating variations in texture, color and weathering of these rocks.

Petrography - Leptynite: The leptynites in the study area exhibit several distinct textural features, including interlocking quartz and feldspar, graphic intergrowths of plagioclase and quartz, perthitic intergrowths between albite and K-feldspar and intergrowths of garnet and biotite. Minor constituents like ilmenite and spinel are also present, with ilmenite often found as inclusions within garnet. Some leptynite samples contain garnet porphyroblasts enclosing orthopyroxene and sillimanite (Fig. 4). The granite in the area is primarily composed of K-feldspar (~35%), plagioclase (~30%), quartz (~30%) and biotite (~5%), with minor accessory phases (Table 1) including apatite, zircon, allanite, opaques, muscovite, sericite, epidote, chlorite, calcite, titanite, garnet and tourmaline.

Microscopically, leptynite displays an inequigranular, medium- to coarse-grained texture dominated by quartz, white oligoclase plagioclase feldspars are string-like and stringlet-like perthite, microcline and minor rounded to subrounded garnet and biotite mica. Zircon and muscovite mica are common accessory minerals. Myrmekitic intergrowths of quartz and plagioclase feldspars and alteration of plagioclase feldspars to zoisite/kaolin are also observed. A higher proportion of microcline feldspar relative to plagioclase is often associated with a more common pink coloration in the leptynite deposit. Melur's leptynite shows evidence of garnet rusting, bent twin lamellae in plagioclase (indicating later deformation) and alteration of garnet to biotite which likely contributes to iron staining upon weathering.

The host leptynites are characterized by abundant plagioclase and alkali feldspar in roughly equal proportions, with common myrmekitic intergrowths of quartz and feldspars. Biotite, garnet and ilmenite are also present, with biotite arbitrarily distributed and small ilmenite inclusions being common. A pervasive granoblastic texture is characteristic. In some locations, small patches of pelitic assemblages (sillimanite – biotite – garnet – feldspar – quartz + ilmenite) occur as xenoliths within the leptynite (Fig. 3).

Microscopic description of leptynite (Kashmir white) - Garnet: Garnets occurred as coarse xenoblasts of anhedral structure. They are usually fractured due to high stress within the rocks, which are later filled with iron leaching. They are poikiloblastic including spinel, biotite, plagioclase, quartz and magnetite. In some sections of leptynite, garnet porphyroblasts are deformed and filled with sillimanite, biotite and orthopyroxene (Fig. 4a-c). Spinel occurs as a rhombic structure and was found as an inclusion in garnet and ilmenite (Fig. 4d). Under plane polarised light, spinel is green in colour, non-pleochroic and has no cleavage, while under cross-nichol, the mineral is black, hence isotropic. Spinel inclusion indicated the prograde metamorphic process (Fig. 4e-f).

Biotite: Biotites are subhedral with corroded surfaces. They are pleochroic from yellowish brown to dark brown. They are found as inclusions within garnet and those developed in garnet show no particular cleavage planes. They have formed assemblages with garnet, Plagioclase, K-feldspar and quartz. This textural relation suggested that biotite and quartz react to form garnet and potash feldspar (Fig. 4a). Zircon in biotite is widespread. Petrography also indicated the effects of radioactivity on biotite, which are indicated by dark radioactive halos within the minerals. Biotite was also included within K-feldspar (Fig. 4c). In some sections, biotite and quartz are included in garnet porphyroblast, which is again surrounded by biotite, orthoclase and quartz (Fig. 4e). The textural relation might suggest the following reaction: (Biotite + quartz = Garnet + K-feldspar).

Figure 2: Field photographs of (a) Leptynite (Kashmir White) is a product of remelting of the pre-existing country rock garnetiferous sillimanite gneiss and pegmatite vein intruded in granite rock at Royarpatti and Vanjinagaram, (b-d) pegmatite enclave within granite at Sukampatti area, (g) Presence of garnet like allanite produced within pink pegmatoidal granite, Karugalakudi, (e-f,h) granite rock exposed at Vanjinagaram area, Quartzo - Feldspathic Granite (leptynite) near Vanjinagaram area, Melur Taluk

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Plagioclase: Plagioclases were medium to coarse, colourless, nonpleochroic minerals with anhedral to subhedral structure. They have shown lamellar twinning, sometimes in two sets perpendicular to one another and developed perthitic intergrowth (Fig. 4). The Ab-An content in Plagioclase of leptynite in the study area varied from Ab21-28 and An2-14. Plagioclases in some sections are altered into clay minerals undergoing sericitization. Sericite is grungy-looking, fine-grained stuff that commonly replaces Plagioclase. Their birefringence is irregular and generally low because they comprise of tiny crystals.

K-feldspar: The potash-feldspar in the present leptynite is found as microcline. They occurred as anhedral to subhedral minerals. They have formed assemblages with Plagioclase, biotite and quartz surrounding xenoblasts of garnet crystal. They have displayed polysynthetic twinning (Fig. 4d). The perthitic intergrowth of albite and microcline is very common. Sometimes, microcline includes biotite (Fig. 4a).

Quartz: Quartz occurred in an anhedral form and was colourless under plane polarised light. They commonly occur as inclusions within garnet, K-feldspar and biotite (Fig. 4). They have displayed wavy extinction, which might indicate origin by syntectonic crystallization.

Sillimanite: Sillimanites occurred as inclusions in garnet porphyroblasts. They are colourless and found in a needle-shaped form under plane polarised light. They are observed in between the cracks of deformed garnet porphyroblasts. They found small prismatic forms of orthopyroxene within garnet and small biotite flakes (Fig. 4 b and e). The mineral association might indicate the following mineral reaction: (Garnet + K-feldspar +H_2O = biotite + sillimanite + quartz).

Figure 3: Field photographs showing in (a) Leptynite (Kashmir White) is a product of remelting of the pre-existing country rock garnetiferous sillimanite gneiss, (b) quartzo feldspathic granite at Melur, (c) pegmatite enclave within granite at Vanjinagaram area, (d and h) The mottled appearance with irregular bands and patches of pink and gray suggests a history of high-temperature and high-pressure metamorphism, (e-g) Quartzo Feldspathic Granite (Leptynite) near Vanjinagaram area, Melur.

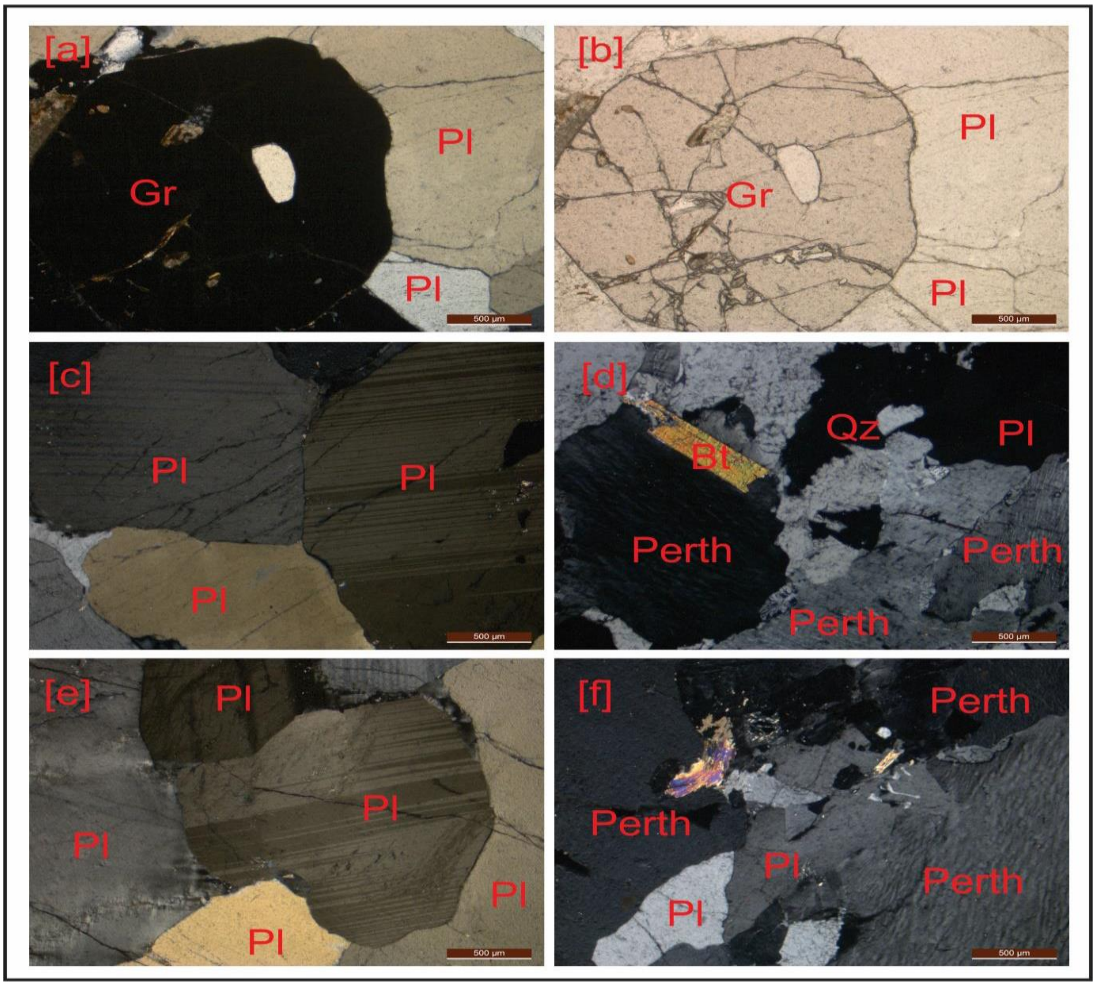

Figure 4: (a-f) Photomicrographs showing important textural features include interlocking texture between quartz and feldspar, graphic intergrowth of Plagioclase and quartz and intergrowth of garnet and biotite; Garnets occurred as coarse xenoblasts of anhedral structure; Biotite also occurred as an inclusion within K-feldspar; They have shown lamellar twinning which are sometimes in two sets perpendicular to one another and they developed perthitic intergrowth

Table 1
Textural and mineralogical characters of granite and leptynites of the Melur area

Type	Modal Mineralogy		Texture
		Average	
Granite	Quartz	32.1	Pink and white colour in fresh outcrop, fine to medium-grained, granoblastic rock. Stringlet perthites are remarkable. Bands and layers are conspicuous with well-defined streaky elongation of garnet and biotites. Reaction zones of silimanite and garnet are recorded between spinel and quartz.
	Plagioclase	27.3	
	K-Feldspar	29.2	
	Biotite	5.0	
	Spinel	2.5	
	Zircon	0.7	
	Apatite	0.6	
	Opaques	2.6	
Leptynite	Quartz	28.9	Mostly medium-grained, Leptynite (Kashmir white) exhibits a spotted appearance due to garnet porphyoblasts in coarse varieties. Patchy perthites and myrmekites are prominent.
	Plagioclase	16.9	
	K-Feldspar	38.4	
	Garnet	10.3	
	Biotite	2.8	
	Zircon	0.7	
	Apatite	0.4	
	Opaques	1.6	

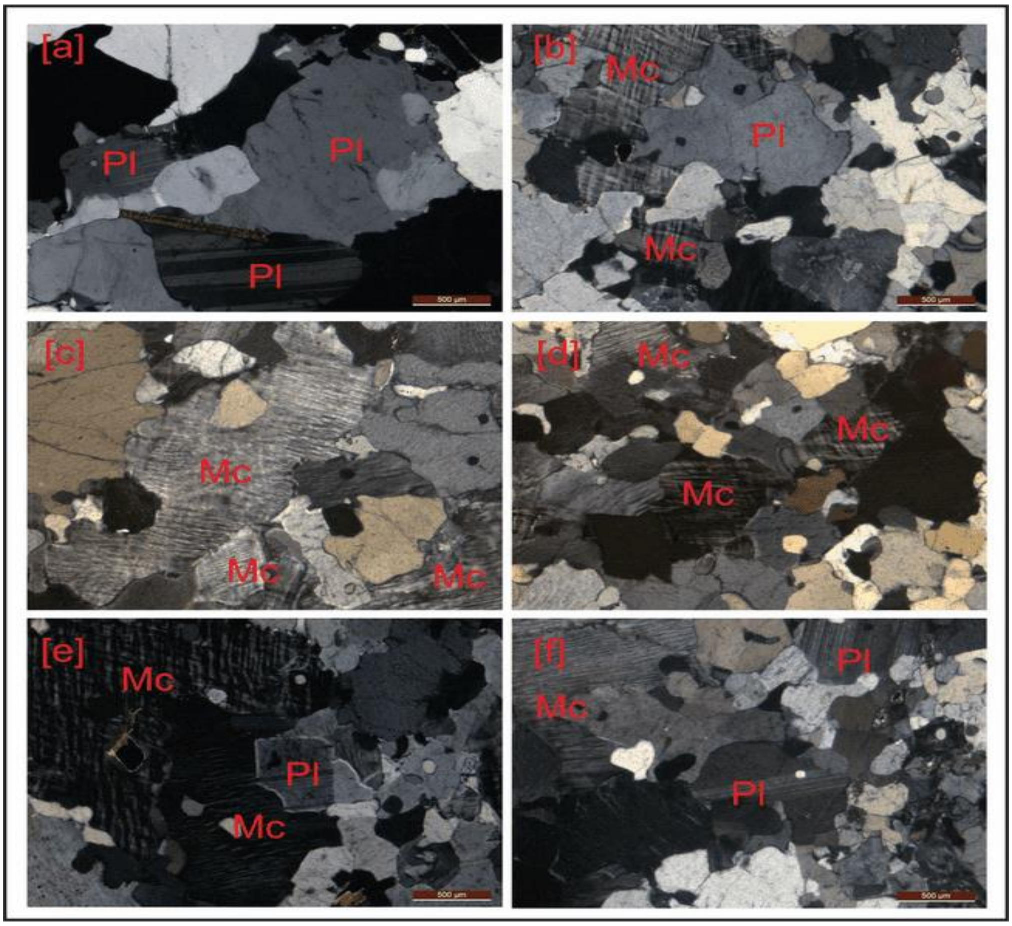

Figure 5: Photomicrographs showing (a-f) pink granite rock the microcline perthites show patch- and braided-perthites and are commonly surrounded and traversed by rims and veinlets of micro granulated and recrystallized quartz respectively; The plagioclases, particularly the larger crystals show varying degrees of sericitization and saussuritization; Large crystals of microcline exhibit characteristic grid (cross-hatched) twinning and sometimes take a significant percentage of the stage.

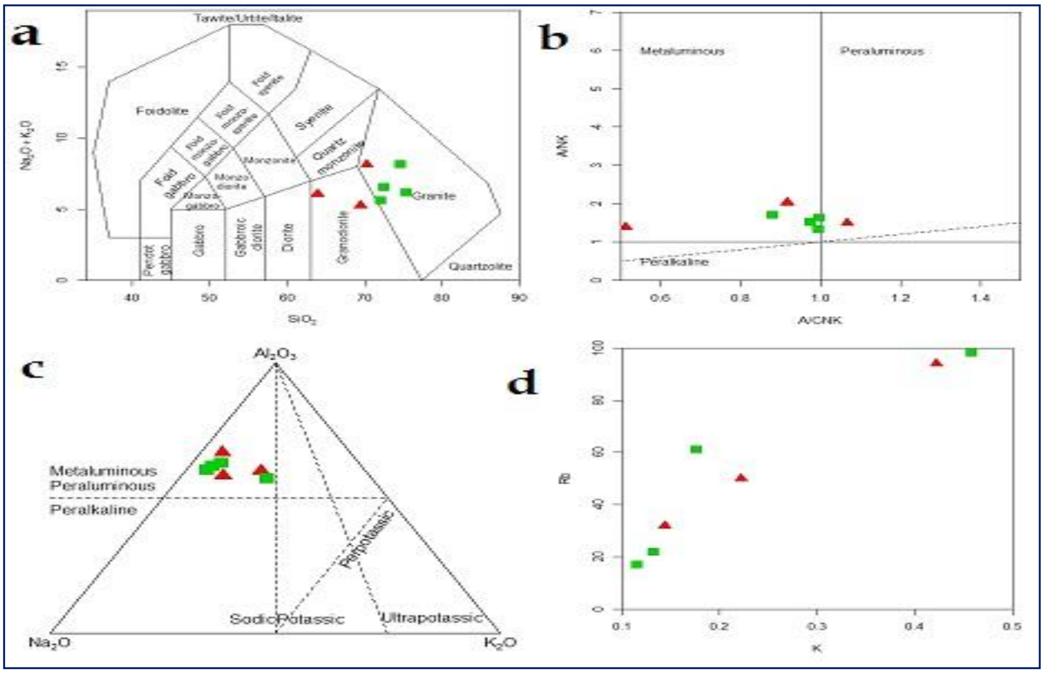

Figure 6: a) TAS; b) Discrimination diagram of Alumina saturation index Shand (1943) with the relative source of rocks; c) Maniar and Piccoli (1989) showing peraluminous nature for leptynite/ pink granite; d) K-Rb relationship diagram of leptynites.

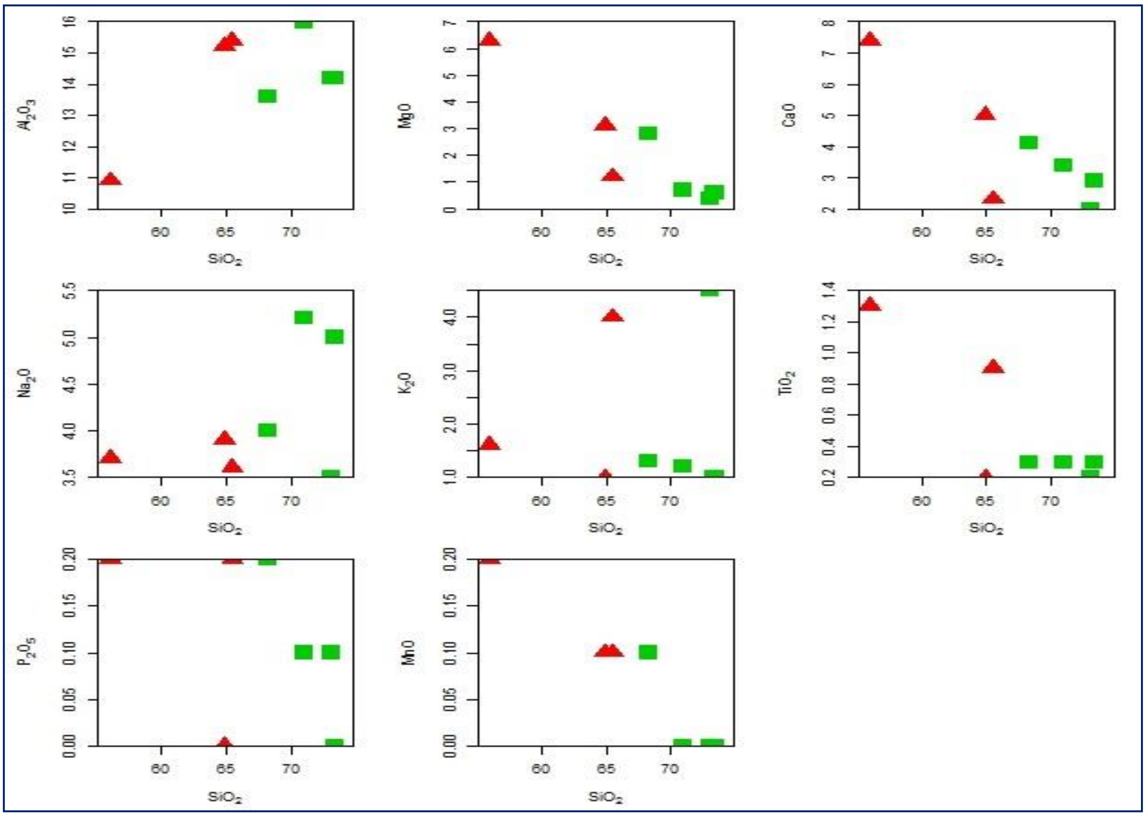

Figure 7: Major oxide elements vs. Si_2O (wt.%) variation diagrams of the Melur leptynite/ pink granite

Whole rock geochemistry

Major Oxide elements: The chemical data of leptynite/ pink granite and niggli and normative values (Q, Or, Ab) are listed in table 2. The chemical analyses of leptynite/ pink granite show variations in almost all major elements, reflecting the mineral phases of those particular samples. SiO_2 is >60% in all analyzed samples. The leptynite/ pink granite varies from 56 to 73.4%, averaging 67.4%. $A1_2O_3$ values commonly approach > 15% in the leptynite samples and rise to 16% in the leptynite/ pink granite due to higher sillimanite and spine1 concentrations (Fig. 6 and 7).

The averages of total Fe and MgO of leptynites (0.4% to 2.8%) are at higher levels than the pink granite (1.2% to 6.3%). The concentration levels of CaO, Na_2O, MnO and P_2O_5 do not show much variation among grey and cream leptynite samples. The K_2O content of leptynite samples (1.0-4.5 = 2%) exceeds pink granite (1.0-4.0 = 2.2%). A characteristic difference is the higher K_2O content than Na_2O in all analyzed samples, except that the local segregation of plagioclase feldspar is prominent in the sample.

K-feldspars mainly cause the higher K_2O content, in general, in the leptynite samples in the mineral assemblage. The abundance of K-feldspar may be related to intra-crustal melting of post-Archaean upper crust followed by production of K-rich granitic components.

Trace elements: The trace element data (Rb, Sr, Ba, Zr, Cr, Co, V, Ni, Cu, SC, Ta, Hf) and inter-elemental ratios of grey and cream leptynites are presented in table 2.

Large-ion lithophile elements (LILE): Table 2 shows that the leptynite samples are characterized by relatively high concentrations and substantial variations of large-ion lithophile elements (LILE). The Rb content of leptynites varies from 17 to 98 ppm and is comparable to that of pink granite (32- 94 ppm). The Sr content of analyzed samples does not show much variation. The Ba content of leptynite ranges from 219 to 1244 ppm, averaging at 569 ppm whereas the pink granite variety shows relatively high concentration, ranging from 166 to 1210 ppm at an average of 663 ppm. There is a significant positive correlation between K and Rb (Fig. 7d and 8). The ratio varies from a minimum of 17 to a maximum of 98, due to the erratic behaviour of Rb.

The overall K-Rb ratios indicate a severe depletion of both K and Rb on the one hand, while enrichment of both of these elements exhibited K-Rb ratios around 250. The K-Rb ratio in normal upper crustal rocks averages 250, but there was a slight tendency to increase with decreasing Rb content. A negative tendency was observed between K and Ba.

The variable K-Rb and K-Ba ratios may reflect the provenance differences, mineral fractionation during deposition or metamorphic effects. The Zr content does not show much variation between leptynite (143 ppm) and pink granite (177 ppm) samples and the concentration could be contributed by accessory zircon.

Ferromagnesium trace elements: Ferromagnesium trace elements show significant variations between grey and cream leptynites (Table 2).

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Table 2
Major, Trace and REE data of leptynite/ pink granite of Melur area

Name	**VG51**	**VG6**	**VG2**	**VG63**	**VG69**	**VG34**	**VG38**
	Pink Granite			**Letynite**			
SiO_2	65.5	64.9	56.0	71.0	73.4	73.1	68.3
Al_2O_3	15.4	15.2	10.9	16.0	14.2	14.2	13.6
Fe_2O_3(T)	6.1	6.1	13.1	2.1	2.3	2.0	3.9
MnO	0.1	0.1	0.2	0.0	0.0	0.0	0.1
MgO	1.2	3.1	6.3	0.7	0.6	0.4	2.8
CaO	2.3	5.0	7.4	3.4	2.9	2.0	4.1
Na_2O	3.6	3.9	3.7	5.2	5.0	3.5	4.0
K_2O	4.0	1.0	1.6	1.2	1.0	4.5	1.3
TiO_2	0.9	0.2	1.3	0.3	0.3	0.2	0.3
P_2O_5	0.2	0.0	0.2	0.1	0.0	0.1	0.2
LOI	0.6	1.1	-0.2	0.4	0.9	0.4	0.8
Total	99.8	100.6	100.3	100.3	100.6	100.3	99.3
Sc	5.0	9.0	19.0	2.0	3.0	2.0	19.0
Be	< 1	1.0	2.0	< 1	< 1	1.0	2.0
V	143.0	52.0	234.0	27.0	31.0	32.0	45.0
Ba	1210.0	166.0	614.0	484.0	332.0	1244.0	219.0
Sr	494.0	310.0	516.0	508.0	495.0	412.0	505.0
Y	11.0	7.0	15.0	5.0	5.0	6.0	42.0
Zr	377.0	31.0	124.0	114.0	145.0	192.0	121.0
Cr	20.0	140.0	360.0	50.0	50.0	40.0	110.0
Co	12.0	17.0	49.0	4.0	4.0	3.0	11.0
Ni	30.0	70.0	230.0	< 20	< 20	< 20	90.0
Cu	30.0	210.0	250.0	30.0	30.0	20.0	160.0
Zn	90.0	180.0	100.0	30.0	40.0	< 30	90.0
Ga	20.0	18.0	17.0	19.0	16.0	17.0	19.0
Ge	1.0	1.0	1.0	< 1	< 1	< 1	1.0
As	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Rb	94.0	32.0	50.0	22.0	17.0	98.0	61.0
Nb	6.0	3.0	8.0	2.0	2.0	2.0	9.0
Mo	< 2	< 2	3.0	2.0	< 2	2.0	< 2
Ag	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
In	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Sn	1.0	5.0	2.0	< 1	< 1	1.0	4.0
Sb	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Cs	0.5	0.5	1.7	0.5	0.5	0.7	1.1
La	178.0	17.2	21.4	12.8	12.2	31.5	48.0
Ce	334.0	31.4	45.2	22.8	21.1	52.4	96.4
Pr	31.8	3.4	5.5	2.5	2.1	4.9	11.4
Nd	104.0	11.8	21.6	9.1	7.3	16.2	45.2
Sm	12.3	2.1	4.8	1.6	1.3	2.3	9.2
Eu	0.8	0.8	1.4	0.6	0.5	1.0	1.0
Gd	6.8	1.4	4.0	1.4	1.0	1.7	8.0
Tb	0.7	0.2	0.6	0.2	0.2	0.3	1.3
Dy	2.8	1.3	3.5	0.9	0.8	1.3	7.9
Ho	0.4	0.3	0.7	0.2	0.1	0.2	1.5
Er	1.0	0.8	1.7	0.4	0.4	0.7	4.1
Tm	0.1	0.1	0.2	0.1	0.1	0.1	0.5
Yb	0.6	0.9	1.5	0.3	0.4	0.7	3.2
Lu	0.1	0.1	0.2	0.1	0.1	0.1	0.5
Hf	8.1	0.9	3.0	2.3	3.0	4.6	2.9
Ta	0.2	0.3	0.5	< 0.1	< 0.1	0.5	0.6
W	< 1	< 1	< 1	2.0	< 1	< 1	< 1

Tl	0.4	0.2	0.4	< 0.1	< 0.1	0.6	0.3
Pb	24.0	16.0	13.0	< 5	37.0	17.0	17.0
Bi	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4
Th	84.3	2.5	4.1	0.2	0.7	24.9	21.0
U	1.3	1.0	1.1	0.1	0.2	2.2	1.8
Eu/Eu*	0.27	1.42	0.98	1.22	1.34	1.54	0.36
La/Yb	201.9	13.01	9.71	29.04	20.76	30.62	10.21
La/Sm	9.07	5.13	2.79	5.01	5.88	8.58	3.27
Ce/Yb	146.56	9.19	7.93	20.01	13.89	19.71	7.93
Ce/Sm	6.58	3.62	2.28	3.45	3.93	5.52	2.54
Eu/Yb	3.82	2.55	2.67	5.73	3.58	4.09	0.89
Total REE	673.4	71.8	112.3	53	47.6	113.4	238.2
Niggli							
si	336.7	276.9	196.4	356.4	411.1	420.9	319.6
al	46.647	38.213	22.52	47.328	46.866	48.173	37.496
fm	9.632	20.08	33.527	5.239	5.01	3.433	19.928
c	12.67	22.85	27.79	18.3	17.4	12.33	20.55
alk	31.05	18.85	16.15	29.14	30.72	36.05	22.022
k	0.422	0.144	0.222	0.132	0.116	0.458	0.176
mg	0.955	0.982	0.982	1	1	1	0.176
c/fm	3.435	0.64	3.42	1.133	1.26	0.86	1.05
ti	0.435	0	0.297	0.212	0	0.244	0.396
p	1.31	1.138	0.829	3.473	3.473	3.59	1.031
qz	112.5	101.504	31.744	139.846	188.258	176.639	131.497

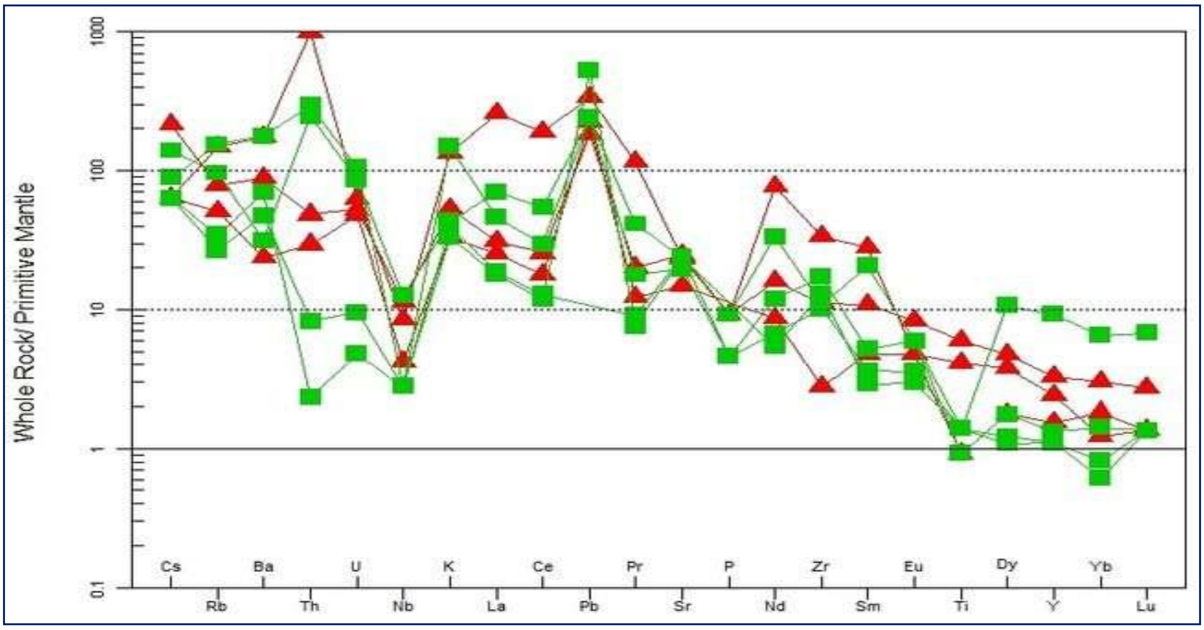

Figure 8: Trace element concentration of leptynite/ pink granite from the Melur area, Madurai.

The concentrations of these elements are found at higher levels in leptynites (Cr = 40-110 ppm, V = 27-45 ppm, Ni = 20-90 ppm, Co = 3-11 ppm, Sc = 2-19 ppm) and pink granite (Cr = 20-360 ppm, V = 166-1210 ppm, Ni = 30-230 ppm, Co = 12-49 ppm, Sc = 5-19 ppm). Ferromagnesium trace elements exhibit a positive trend with Fe_2O_3(t), particularly in the leptynite/ pink granite. The distribution of these elements shows a clear distinction between the leptynite/ pink granite varieties (Fig. 9). A close look at the analyzed data reveals that the leptynite/ pink granite samples show higher values of Si and LILE due to the abundance of quartz and K-feldspar. In contrast, the leptynite/ pink granite variety contains more Ti, Fe^{*+}, Fe^{3+}, Mg and ferromagnesium trace elements because of an appreciable presence of garnet, spinel, sillimanite and opaques.

Rare-Earth Elements (REE): The REE data of the analyzed samples are given in table 2 and these results normalized to chondrites[11], are plotted (Fig. 10). The REE data of leptynite/ pink granite displayed moderate to steep

LREE patterns. However, the behaviour of HREE patterns of leptynite/ pink granite looks different (Fig. 10). The sample shows a distinct rise from Tb to Lu. The higher abundance of garnet and zircon could explain the flat to enriched pattern of HREE. The depleted patterns of HREE of leptynite and pink granite are due to a lesser zircon concentration relative to garnet in those samples.

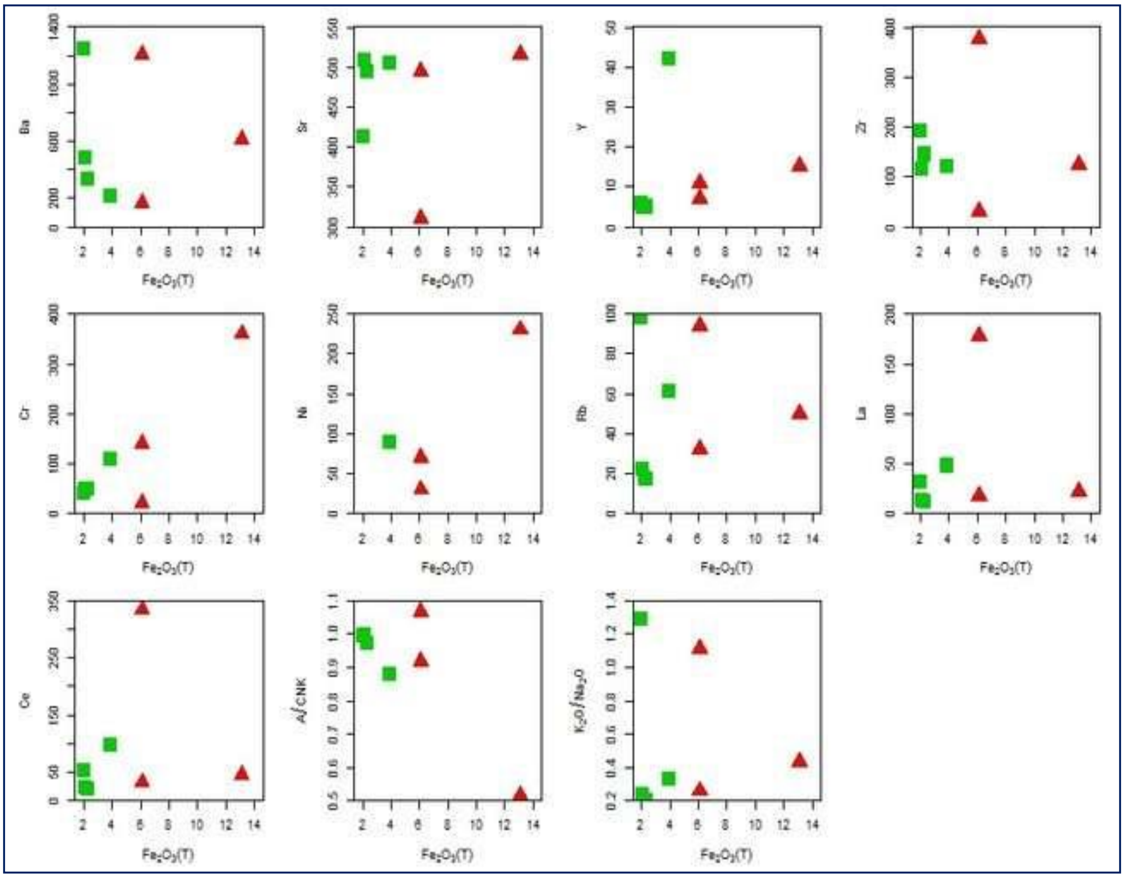

Figure 9: Plot of ferromagnesium trace elements (ppm) against total Fe_2O_3 (wt%) of leptynite/ pink granite.

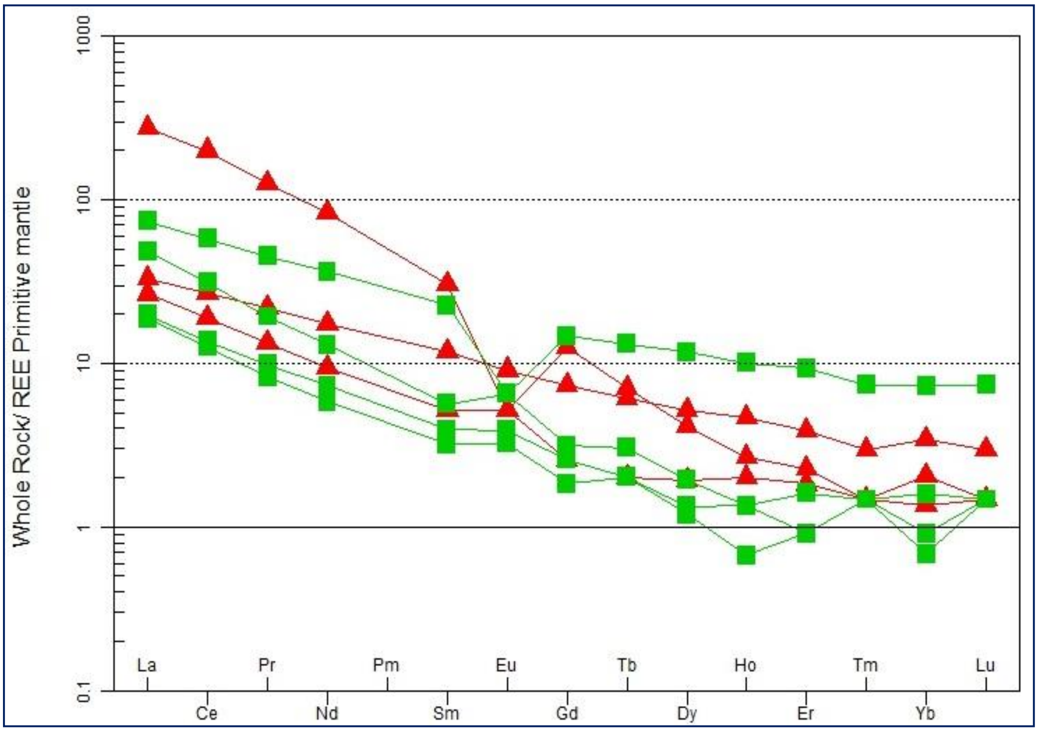

Figure 10: REE concentration of leptynite/ pink granite from the Melur area, Madurai.

The LREE enrichment and anomalous behaviour of Sm can be explained by the apatite and monazite distribution in the leptynite/ pink granite samples. The reason for Ce depletion is unknown, but it may be due to depositional and partly metamorphic conditions. The open ocean waters are known to be Ce depleted[12,15], hence, Ce depletion is more likely related to the depositional environment of the leptynite protolith. Leptynites are significantly negative and positive (Fig. 10). Conversely, leptynite/ pink granite has negative Eu anomalies, except two samples (VG51, VG38) showing positive anomalies.

The positive anomalies in the analyzed samples could imply the occasional abundance of plagioclase feldspar. The Eu depletion in the leptynites may result from K-rich granitic components in the source. The REE patterns show strong fractionation with La_N-Yb_N values ranging from 10.21 to 30.62 for leptynite and 9.71-201.90 for pink granite. The total REE of leptynite (47.6- 238.2 ppm) is slightly higher than that of the pink granite variety (71.8-673.4 ppm).

Discussion

The genesis of leptynite/ pink granite has an important bearing on understanding the deep crustal processes, particularly during Precambrian times. The leptynites were formed due to metamorphism of arenaceous with argillaceous mixtures[2] and rhyolite tuffs[18]. Viswanathan[29] opined that the leptynites are the sedimentary equivalents of greenstone belts. Partial melting of khondalite[25] and metapelite[16] are suggested for the genesis of leptynites. According to Chacko et al[3], the leptynites (K-rich granulites) of the Kerala Khondalite Belt (KKB) were formed from arkosic, argillaceous and possibly felsic volcanic protoliths.

The following field, petrographic and chemical evidences favour a metasedimentary origin for leptynite/ pink granite of the Melur area: (a) intercalations of talc-granulites and quartzites, (b) presence of anhydrous aluminous minerals (almandine garnet + sillimanite + cordierite and sapphirine f spinel), (c) higher K_2O-Na_2O and (d) molecular $A1_2O_3$ and $CaO + Na_2O + K_2O$) values (Table 2) greater than 1.1[4]. The Niggli values of leptynite / pink granite samples when represented in 100 mg-c-(al-alk) and (al-alk) vs c diagrams (Fig. 6) fall within the greywacke field. The leptynites generally have higher ferromagnesium trace element contents than pink granite (Table 2). Paragneisses' relatively low Cr and Ni contents differ from most Archaean greywackes and pelites, suggesting a felsic granitoid-volcanic predominant source[10].

The REE pattern has proven to be particularly useful in giving information on the source rocks of metasediments. REE are fractionated very little and are immobile during sedimentary processes[5,12,19]. The REE in metamorphic rocks is unaffected up to the upper amphibolite facies regional metamorphism[26] and sometimes little mobile during metamorphism[15,19,20]. The average REE distribution in elastic sediments has often been assumed to display the average content of the upper continental crust[19]. According to Taylor and McLennan[26], the sedimentary rocks of continental crust show a negative Eu anomaly for the upper crust, a positive anomaly for the lower crust and no Eu anomaly for the whole crust.

The leptynites derived from elastic sediments (impure greywackes) are potentially useful for estimating the REE composition of a portion of the upper continental crust. In the Proterozoic era, upper crustal rocks were highly differentiated and were granodioritic in composition; in Archaean times, they were more mafic and less differentiated with lower LREE/HREE ratios. The common sedimentary rocks of the post-Archaean, including sandstones, mudstones and carbonates, on average show a significant and constant depletion in Eu, whereas Archaean counterparts show an Eu-Eu* ratio without deviation from 1.0[19,26]. The REE pattern is also very important in providing information on the provenance of elastic sediments[19]. Primitive mantle -normalized REE data of leptynite/ pink granite are characterized by moderate to steep LREE with flat to enriched and depleted HREE patterns (Fig. 10).

The Eu anomaly is variable. However, on an average, there is no anomaly for leptynite and a negative anomaly for pink granite. Such REE patterns resemble felsic volcanics in Archaean terrains. The REE data and Eu-Eu* factor (leptynite 0.36-1.54; pink granite 0.27-1.42) of leptynite/ pink granite are broadly comparable with that of greywacke and post-Archaean upper crust[26]. High LREE/HREE (47.6-238.2) with Eu-Eu* depletion factor (0.27-1.54), low Na_2O, CaO contents and high K_2O and Na_2O ratios (Table 2) suggest K-rich granitic components in the source.

Conclusion

The leptynite in the Melur area originated from crustal anatexis and intense migmatization of metasedimentary rocks under granulitic facies conditions. Its mineral composition (quartz, feldspar, garnet) and granoblastic texture suggest slow cooling and partial melting at high temperatures. Textural features like perthitic textures, polysynthetic twinning in plagioclase and garnet equilibrium growth further support slow cooling and moderate to high-pressure dynamic metamorphism. The presence of equilibrium garnet, biotite and quartz, combined with observed textures, strongly indicates partial melting and high-grade metamorphism in the region.

Studying the Melur leptynite is crucial for understanding the area's metamorphic history and tectonic evolution, providing insights into the high-temperature and pressure conditions linked to regional tectonic processes and crustal thickening. The K-rich granitic components may have formed via intracrustal melting of a post-Archaean upper crust containing sediments. The consistent Eu-depleted pattern in KKB rocks suggests that the entire source region of KKB sediments underwent intracrustal melting, producing an Eu-depleted (granitic) upper crust[3].

Archaean sedimentary rocks from felsic volcanics also show significant negative Eu anomalies[19]. The REE patterns of the leptynites closely resemble those of greywacke and the post-Archaean upper crust (Fig. 7). Moreover, the trace element distribution (low Cr and Ni) and REE distribution (steeper LREE with flat HREE) suggest that the leptynites were derived from a heterogeneous post-Archaean granodioritic upper crust that included substantial impure greywackes with K-rich granitic components, a conclusion supported by the observed chemical variations in the leptynite/pink granite.

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