

Crustal reworking and magmatic evolution in the northeastern Dharwar craton: evidence from geochemistry and zircon U-Pb geochronology of Ghanapur granitoids

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ABSTRACT

The widespread occurrence of granitoids in Precambrian terranes provides crucial insights into crustal processes and geochemical evolution within cratonic blocks. The Eastern Dharwar Craton (EDC) of southern India, records extensive granitic magmatism during the late Archean, a transformative period in Earth's history marked by significant geological and geochemical shifts. This study presents a comprehensive, first-hand investigation of granitoids from the Ghanapur area in the underexplored north-eastern EDC, using integrated fieldwork, petrography, geochemistry, and zircon U-Pb geochronology, to provide new insights into the evolutionary history of granitic crust. The granitoids of Ghanapur are categorized into three suites: granitic gneisses, granodiorite gneisses and leucogranites. Zircon U-Pb dating reveals two distinct magmatic episodes: granitic gneisses at ca. 2697–2607 Ma, while granodiorite gneisses formed at ca. 2560–2545 Ma. Granitic gneisses are silica rich, weakly metaluminous to slightly peraluminous, and show high-K calc-alkaline to shoshonitic affinity, with magnesian character. They show variable Eu anomaly and REE fractionation. Their ages and geochemistry together suggest repeated crustal reworking and mixed origin. The granodioritic gneisses are weakly peraluminous and moderately silicic, with elevated Mg# and enriched in incompatible elements. They resemble Archean sanukitoids and suggest their origin from a metasomatized mantle wedge. These rocks record a two-stage evolutionary history: initial sanukitoid magmatism driven by partial melting of the enriched mantle wedge, followed by a younger migmatitic episode, resulting in their preservation as mesosome within the migmatitic complex. Leucogranites are garnet- or magnetite-bearing, silica-rich, peraluminous to strongly peraluminous, high-K calc-alkaline, ferroan rocks, likely reflecting the waning stages of late Archean crustal thickening. Taken together, the geochemistry and geochronology suggest progressive crustal reworking and differentiation over a period of at least 150 Ma during the late Archean in the Ghanapur region.

Keywords: Ghanapur granitoids, NE Dharwar craton, U-Pb Zircon dating, Sanukitoid, Crustal evolution, Leucogranites, Gneisses

INTRODUCTION

The late Archean (2.8–2.5 Ga) was a transformative period in Earth's history, marked by rapid continental growth and fundamental changes in tectonic style (Hawkesworth et al., 2020). While the precise volume of crust generated remains debated (e.g., Dhuime et al., 2012; Rosas and Korenaga, 2018), there is a broad consensus that this interval witnessed a compositional shift from sodic tonalite-trondhjemite-granodiorite (TTG) suites toward more potassic granitoids (Moyen, 2011; Laurent et al., 2014). The late Archean potassic granitoids are petrogenetically diverse, encompassing sanukitoids, two-mica granites, biotite granites, and hybrid varieties, each recording different source contributions and melt-generation processes (Laurent et al., 2014). Their appearance in the late Archean record is commonly linked to the progressive evolution of source compositions (Johnson et al. 2019) together with changing mantle thermal conditions and evolving subduction dynamics (Dash et al., 2025). Understanding their petrogenesis and relative timing provides important constraints on how Archean crust matured from juvenile additions to stabilized cratonic lithosphere.

The Eastern Dharwar Craton (EDC) of southern India, preserves an excellent record of the late Archean magmatism. The EDC is considered to have been accreted mostly during

the late Neoarchean (2.7–2.5 Ga) (Peucat et al., 1993; Jayananda et al., 2000, 2013), and is characterized by numerous NW-SE trending linear volcano-sedimentary sequences of Neoarchean with volumetrically dominant 2.57–2.50 Ga K-rich granitoids, and 2.67–2.58 Ga transitional TTGs (Jayananda et al., 2013, 2018; Dey et al., 2017). Various tectonic models, such as subduction-driven accretion, mantle plume-derived crustal growth, and accretion via combined plum-arc processes are used to explain crustal accretion in EDC (Chadwick et al., 2000; Manikyamba and Kerrich, 2012; Dey et al., 2017; Jayananda et al., 2018).

However, the current understanding of crust formation and tectonic evolution of EDC is mostly restricted to the southern and western parts of the craton whereas the northern part of the craton largely remains underexplored with limited comprehensive geochemical and geochronological studies. This study presents field, petrographic, geochemical, and zircon U-Pb geochronological data from granitoids of the Ghanapur area in the north-eastern EDC. We document three granitoid suites, granitic gneiss, granodiorite gneiss and leucogranite and constrain their petrogenesis, age relationships, and tectonic significance. The results provide new insights into late Archean sanukitoid magmatism, crustal anatexis, and the role of migmatization in crustal reworking within this underexplored segment of the craton.

GEOLOGICAL SETTING

The Dharwar craton is a classic Archean granite–greenstone terrane of southern India and is conventionally divided into the Western and Eastern Dharwar cratons on the basis of lithology, metamorphic grade, and crustal evolution (Chadwick et al., 2000; Jayananda et al., 2006; Chardon et al., 2008) (Figure 1a). The EDC is dominated by Neoproterozoic TTG gneisses, younger potassic granitoids, migmatites, and linear supracrustal belts (Peucat et al., 1993; Jayananda et al., 2000). It also preserves a wide range of late Neoproterozoic granitoids, including TTG, high-Mg diorite/sanukitoid suites, Closepet-type granites, and K-rich anatectic leucogranites, along with supracrustal assemblages recording two main age populations at ca. 2.75–2.67 Ga and 2.58–2.54 Ga (Balakrishnan et al., 1999; Moyen et al., 2003; Rogers et al., 2007; Manikyamba and Kerrich, 2012; Jayananda et al., 2013, 2018; Dey et al., 2017; Bhaskar Rao et al., 2020; Ashok et al., 2021). Craton-wide magmatism at ca. 2.56–2.52 Ga, marked by high-K calc-alkaline granitoids, represents the final stage of crustal stabilization in the EDC (Anand et al., 2014; Dey et al., 2017; Jayananda et al., 2018).

The northern and northeastern EDC show marked lithological and metamorphic variation, ranging from lower-grade TTG–migmatite–granite–supracrustal terrains in the

south to high-grade granulite crust around Karimnagar in the north (Figure 1a). Available geochronological data from the northern EDC are limited and are largely confined to granulite-facies rocks, which record emplacement ages of ca. 2.8–2.5 Ga and metamorphic overprints around 2.6 Ga (Rajesham et al., 1993; Yoshida et al., 1996; Santosh et al., 2004; Sarbajna et al., 2013; Prakash et al., 2017).

Geology of the Ghanapur area

The Ghanapur area lies within low-grade granite greenstone terrain of north eastern EDC and is characterized by variably foliated granitoids, migmatitic gneisses, and associated supracrustal rocks exposed as discontinuous outcrops (Figure 1b). The variably foliated granitoids and the migmatitic gneisses represent different structural states of the same granitoid assemblage. The granitoids preserve a gneissic foliation of variable intensity and, affected by younger anatectic event. This gives appearance of migmatitic outcrop with granitic leucosome and granodioritic mesosome, without being genetically related with each other. The granitoids commonly show intrusive relationships with the associated metasedimentary and mafic units, and many outcrops preserve enclaves, stretched xenoliths, and quartzofeldspathic segregation bands aligned parallel to the regional foliation.

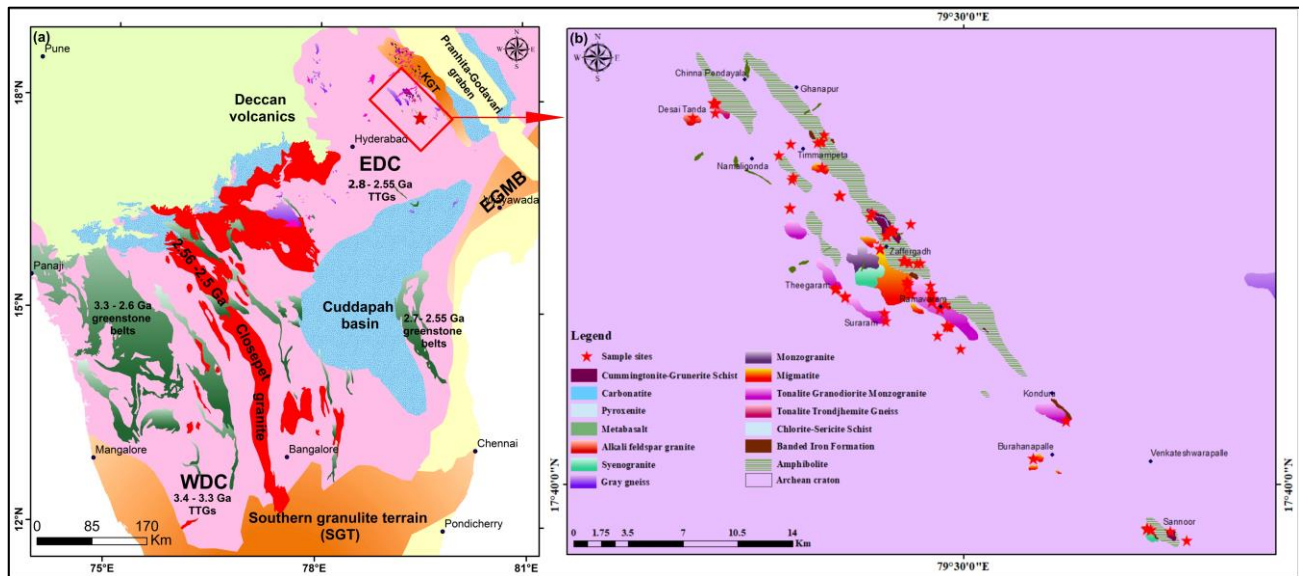


Figure 1. (a) A simplified geological map of southern India showing Archean Dharwar craton with dominant lithology. (b) Geological map of Ghanapur Belt (study area) with sampling locations, modified after the Geological Survey of India. WDC- Western Dharwar Craton, EDC- Eastern Dharwar Craton, EGMB- Eastern Ghat Mobile Belt, SGT- Southern Granulite Terrain, KGT- Karimnagar Granulite Terrain

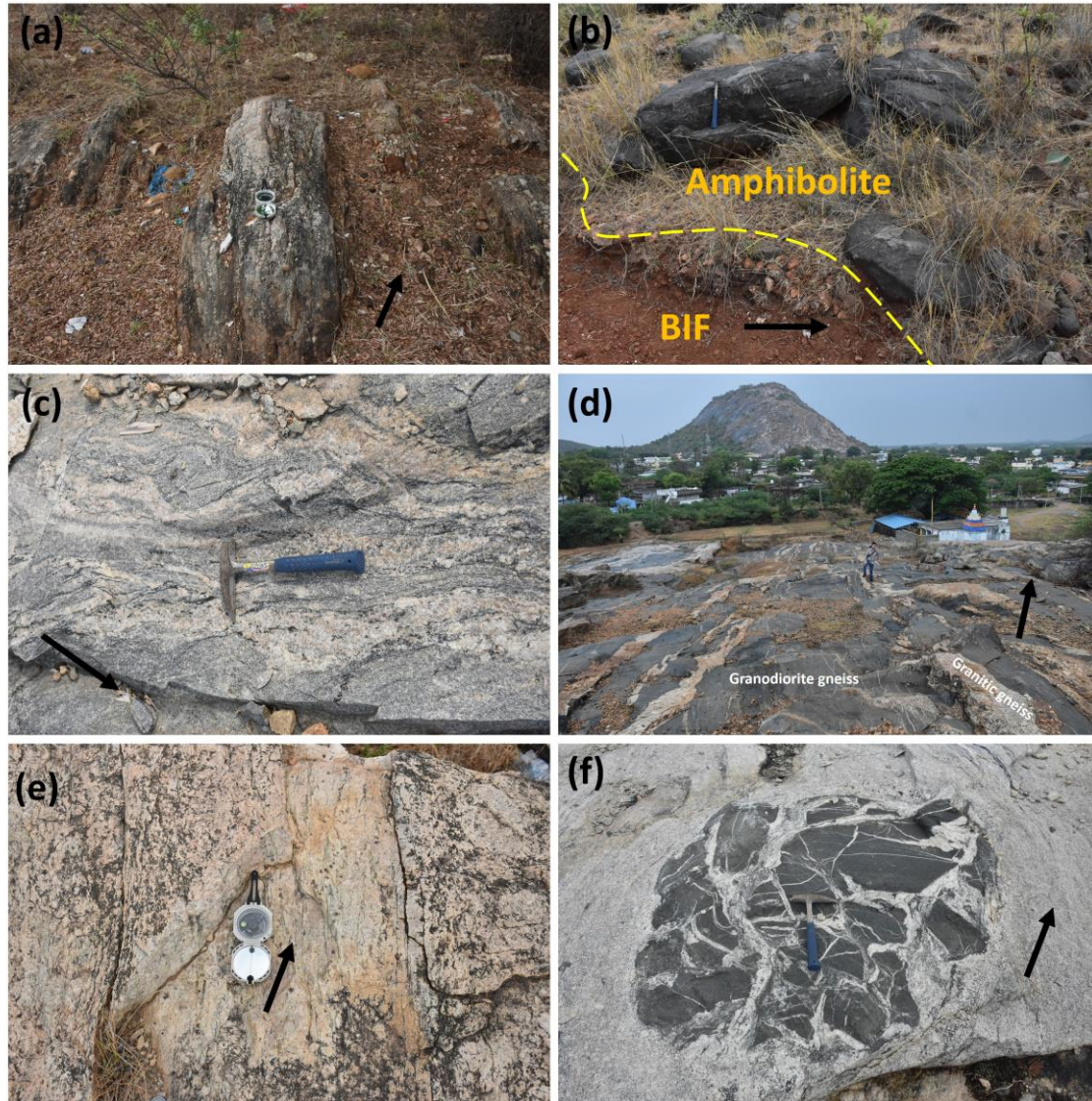


Figure 2. Field photographs with black arrow pointing north. **(a)** BIF exposure near Pamnoor village, showing alternate bands of magnetite and quartzite. **(b)** Contact of weathered BIF and amphibolite at foothill of Durgaya Tanda. **(c)** Coarse grained granitic gneiss from quarry of Theegaram-gutta. **(d)** Granodiorite gneiss of Zaffergadh hill showing variably deformed quartz veins with pygmatic folding intruded along the general gneissic foliation. **(e)** Outcrop of garnet bearing leucogranite near Durgaya Tanda. **(f)** Mafic enclave within granitic gneiss showing multiple injections of gneissic material.

In the Ghanapur area, the rock assemblage is dominated by granitoid gneisses with local amphibolites, schistose metasedimentary rocks, and banded iron formation (BIF). Field exposures of representative outcrops are given in Figure 2a-f. Earlier mapping by Guguloth and Manimaran (2019) recognized several granitoid varieties, including tonalite-trondhjemite gneiss, granodiorite to monzogranite, syenogranite, alkali feldspar granite, and garnet-bearing leucogranite. The granitoids are typically medium- to coarse-grained and locally porphyritic, with mafic enclaves and schlieren elongated parallel to the gneissic fabric. The associated metasedimentary and mafic units display compositional banding, tight folding, and localized shear

fabrics, while quartz veins intruded along the gneissic foliation are folded, boudinaged, and locally crosscut by younger quartz and epidote veins. Later brittle fractures and joints are also present in several litho-units. Together, these field relationships indicate a polyphase deformation history and provide the geological context for the present study.

METHODOLOGY

Sampling

This study focuses on three granitoid suites from representative outcrops in the Ghanapur, Zaffergadh, and Sannoor areas: granitic gneiss, granodiorite gneiss, and

leucogranite. Sample locations are shown in Figure 1b. Samples were selected based on field relationships, megascopic observations to represent the lithological diversity of the granitoid suite. Geochemical analyses were carried out on 39 samples, including 20 granitic gneisses, 12 granodioritic gneisses, and 7 leucogranites, while zircon U–Pb geochronology was undertaken on two granitic gneisses and two granodioritic gneisses.

Analytical techniques

Major and trace-element analyses of granitoid samples were carried out at National Centre for Earth Science Studies (NCESS), Trivandrum, and CSIR-National Geophysical Research Institute (NGRI), Hyderabad, respectively. Before analysis, the samples were cleaned, crushed, ultrasonically washed, and powdered to about 200 mesh. Loss on ignition (LOI) was determined by heating 1 g of powdered sample at 950 °C for 30 min.

Major elements were analyzed on fused glass beads prepared with 1 g of sample powder and 5 g of lithium borate flux using a Katanax X-300 X-Fluxer triple-station fusion apparatus, followed by measurement on a Bruker S8 Tiger sequential wavelength-dispersive X-ray spectrometer. Trace elements were determined by digesting 50 mg of powdered sample in HF–HNO₃–HClO₄ (3:1:0.5) in Savillex® Teflon beakers at 70 °C for 5–7 days, followed by evaporation and dissolution in 2% HNO₃. The solutions were analyzed using an Agilent 7800 quadrupole ICP-MS with Rh as the internal standard. Synthetic standards and international rock reference materials (G-2, JG-2, JR-2, JA-1, SY-3, AGV-2, BCR-2, and BHVO-2) were used for calibration. Analytical precision is better than 3% for major elements and better than 2% for trace and rare earth elements. Whole-rock geochemical data for the granitoids are summarized in Tables 1-3.

Zircon separation, mounting, and U–Pb dating were carried out at CSIR-NGRI, Hyderabad. Zircons were separated from 4 samples using standard mineral-separation procedures involving crushing, sieving, Wilfley table concentration, magnetic separation, and heavy-liquid separation. Handpicked zircons were mounted in epoxy, polished, and carbon-coated. Cathodoluminescence (CL) images were acquired using a TESCAN VEGA3 scanning electron microscope to guide spot selection. Zircon U–Pb analyses were performed using a 193 nm ArF excimer laser ablation system coupled with an Agilent 7800 Q-ICP-MS. Analysis is carried out with 30 µm spot size, with laser energy of 6.5 mJ while maintaining attenuation rate 25%, repetition rate of 10 Hz and ThO⁺/Th < 1.

Zircon U–Pb data reduction and age calculation

Raw LA-ICP-MS data were processed using Iolite software, and common Pb correction was applied during data reduction. Zircon U–Pb ages were calculated from the ²⁰⁷Pb/²⁰⁶Pb, ²⁰⁶Pb/²³⁸U, and ²⁰⁷Pb/²³⁵U ratios. Zircon standards including TEMORA, GJ-1, and MT were analyzed during the analytical session, with GJ-1 used for calibration. U–Pb data evaluation, error propagation and age calculations were performed using the open source software package IsoplotR (Vermeesch, 2018). Final ages are reported as upper-intercept ages obtained by linear regression of the discordant arrays on the concordia diagram; within each array, analyses that are 95–100% concordant are termed concordant and anchor the upper-intercept regression. All analytical uncertainties are reported at the 1σ level.

RESULTS

Petrography

The study area comprises supracrustal rocks and granitoids that occur as discontinuous exposures aligned broadly along the regional structural grain. Among the supracrustal units, BIF is exposed as small hematitic mounds with characteristic cherry-red weathered surfaces, whereas amphibolite occurs as dark, medium- to coarse-grained bodies that are locally foliated. In thin section, the BIF shows alternating quartz-rich and magnetite-rich bands, while the amphibolite is composed mainly of hornblende, plagioclase, and biotite (Figure 3a, b). Other supracrustal lithologies, such as schist, ultramafic rock, and carbonatite, are present in the area but are not illustrated here.

The granitoids are represented in this study by granitic gneiss, granodiorite gneiss, and leucogranite. Granitic gneiss occurs as mesocratic, light grey to pink, coarse-grained, foliated rocks, with quartz, alkali feldspar, plagioclase, and biotite as the main minerals and zircon and apatite as accessories. The foliation is a megascopic gneissic fabric developed at outcrop and hand-specimen scale; owing to the coarse grain size and alkali-feldspar-dominated mineralogy, it is not resolved at thin-section scale. In thin section, alkali feldspar is commonly perthitic and locally shows albite stringers, flame perthite, and myrmekitic intergrowths (Figure 3c). Granodiorite gneiss is a foliated, medium-grained granitoid of variable grey shades, richer in plagioclase than alkali feldspar and composed of quartz, biotite, and hornblende. In migmatitic outcrops, the granodiorite gneiss appears as the mesosome, occurring between leucocratic segregations. Microscopic observations of granodiorite gneiss commonly show plagioclase with polysynthetic twinning and local sericitization, whereas

microcline exhibits cross-hatched twinning and perthitic textures (Figure 3d).

Leucogranite occurs as milky white to pale pink, medium- to coarse-grained small lensoid bodies dominated by quartz and perthitic alkali feldspar with minor biotite. Garnet-bearing

and magnetite-bearing variants are recognized, with garnet occurring as dark pink grains in some samples and magnetite as conspicuous black crystals in hand specimen. In thin section, the rocks are quartz–feldspar rich and contain large, fractured garnet megacrysts (Figure 3e). They locally show minor recrystallization of quartz and alteration of feldspar.

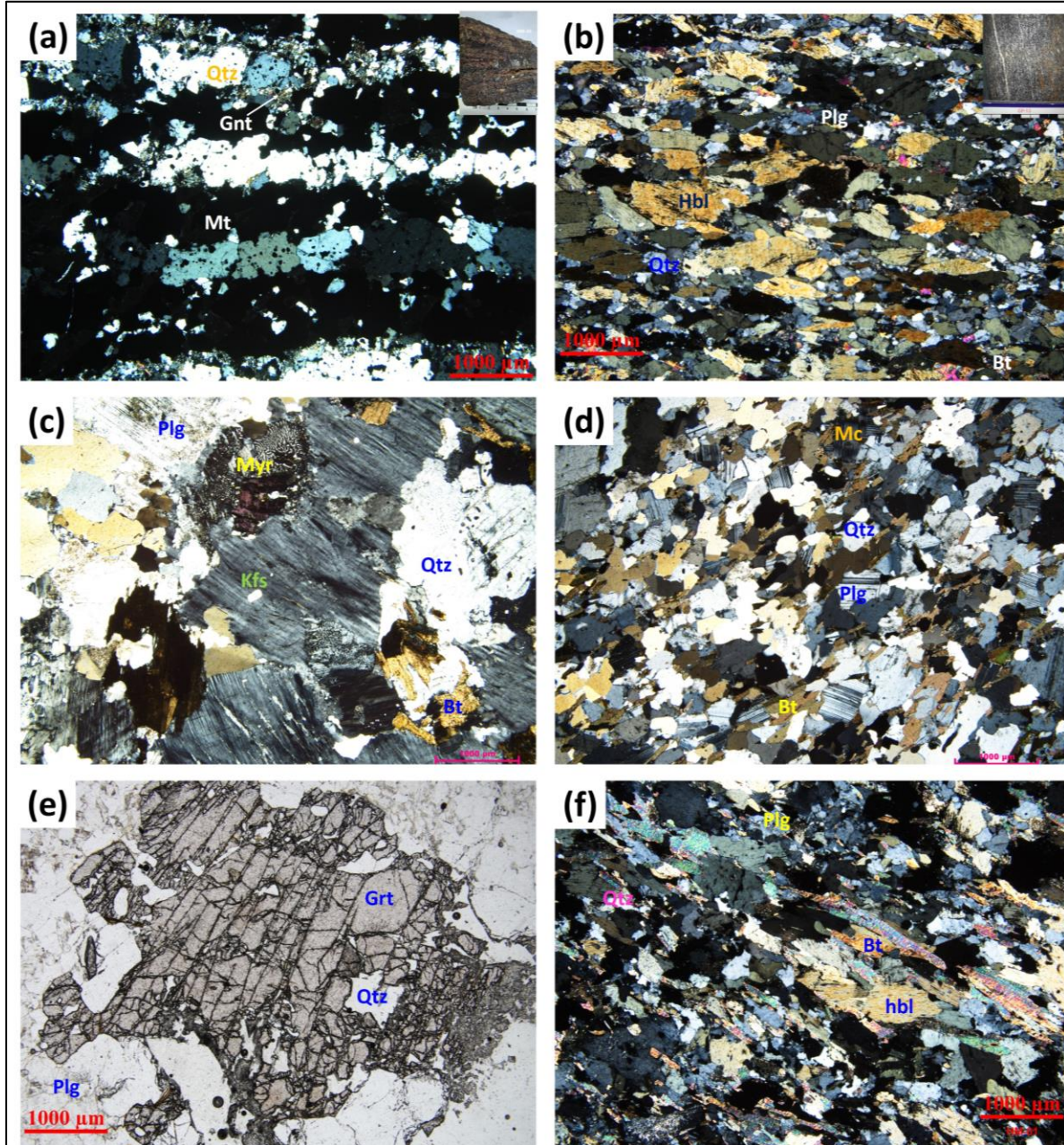


Figure 3. Microscopic images of Ghanapur belt rocks. (a) BIF in XPL showing alternate layers of quartz and magnetite; hand specimen in subset. (b) Foliated amphibolite in XPL with a subset showing hand specimen. (c) granitic gneiss in XPL showing perthitic K-feldspars and myrmekite texture. (d) Granodiorite grey gneiss in XPL showing lamellar twinning in plagioclase. (e) garnet-bearing leucogranite in PPL. (f) Mafic enclave in XPL with alignment of mica and amphiboles along the gneissic foliation trend. All images are under 2x magnification. Qtz- quartz, Plg- plagioclase, Mc- microcline, Kfs- Kfeldspar, Hbl- hornblende, Bt- biotite, Mt- magnetite, Grt- garnet, Gnt- grunerite and Myr- myrmekite

Mafic enclaves occur as mesocratic, medium-grained bodies enclosed within the granitoids and commonly show diffuse to gradational contacts with the host rock, locally with marginal reaction rims. Microscopically, the enclaves preserve a foliated texture defined by aligned platy mafic grains and elongated felsic minerals, superimposed on a hypidiomorphic-granular groundmass, and are composed of quartz, alkali feldspar, plagioclase, biotite, and hornblende (Figure 3f).

Geochemistry of granitoids

The granitoid suite is compositionally heterogeneous and includes granitic gneiss, granodiorite gneiss and leucogranite, spanning intermediate to highly evolved felsic compositions. The granitic gneisses are felsic, with SiO_2

contents of 67.0–78.0 wt%, and plot mainly in the granitic field, except for one sample that extends into the quartz monzonite field (Figure 4a). Major-element trends show decreasing $\text{Fe}_2\text{O}_3(\text{T})$, MgO , CaO , and TiO_2 with increasing SiO_2 , whereas K_2O increases with increasing SiO_2 . These rocks are metaluminous to slightly peraluminous, with A/CNK values of 0.88–1.09, and show high-K calc-alkaline to shoshonitic affinity, with magnesian character on the Fe -silica plot (Figure 4b–d). Chondrite-normalized (McDonough and Sun, 1995) REE patterns show variable fractionation with weakly negative to strongly positive Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.31\text{--}12.51$). Primitive mantle-normalized (McDonough and Sun, 1995) patterns show enrichment in large ion lithophile elements (LILEs) and depletion in Nb, Ta, and Ti (Figure 5a, b).

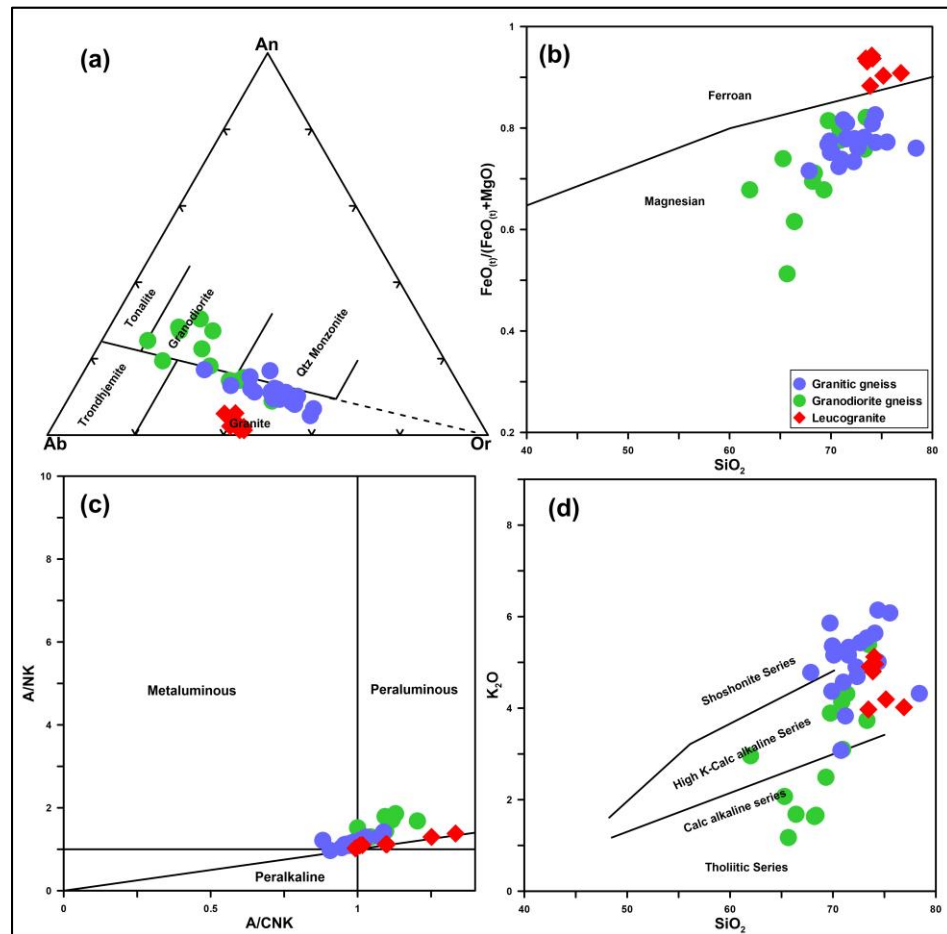


Figure 4. (a) Normative feldspar (Ab-An-Or) triangular diagram after O'Connor (1965) for classification of Ghanapur granitoids. (b) SiO_2 versus $\text{FeO}/(\text{FeO}+\text{MgO})$ granite tectonic discrimination diagram after Frost et al. (2001). (c) A/NK versus A/CNK diagram of Shand (1943) discriminating metaluminous, peraluminous and peralkaline compositions. (d) SiO_2 versus K_2O after Peccerillo and Taylor (1976). Symbols for the three granitoid suites are given in the legend and same code is maintained for all geochemical discrimination.

Table 1. Major oxide concentrations, trace element, REE concentrations and ratios of granitic gneisses from Ghanapur.

Granitic gneisses	GP-06	GP-11	GP-15	HM-02	KD-02	ND-02	PN-07	PN-08	SNR-01	SNR-02	SR-01	SR-03	TG-04	ZG-03	ZG-04	ZG-05	ZG-12	ZG-13	ZG-16
<i>Major oxides (wt%)</i>																			
SiO ₂	71.21	69.95	69.88	73.28	71.54	74.07	74.37	69.71	67.85	78.40	74.38	75.53	72.34	70.78	72.24	71.01	71.50	72.65	70.08
TiO ₂	0.22	0.31	0.25	0.17	0.19	0.06	0.04	0.18	0.33	0.03	0.15	0.11	0.41	0.31	0.18	0.30	0.23	0.14	0.41
Al ₂ O ₃	15.05	14.76	15.53	14.11	15.29	14.31	13.93	15.04	14.66	12.07	13.90	13.08	13.31	15.64	15.27	15.30	14.96	14.90	15.15
Fe ₂ O ₃ (T)	2.32	3.37	2.90	1.95	1.80	1.22	0.95	3.12	3.69	0.60	1.39	1.17	3.53	3.06	1.99	3.58	2.23	1.31	2.74
MnO	0.03	0.03	0.02	0.01	0.03	0.01	0.01	0.03	0.07	0.01	0.02	0.01	0.03	0.03	0.01	0.04	0.02	0.02	0.04
MgO	0.47	1.00	0.76	0.49	0.38	0.26	0.18	0.85	1.32	0.17	0.37	0.31	0.90	1.05	0.65	1.14	0.57	0.37	0.81
CaO	1.82	1.71	2.27	1.18	1.76	1.16	0.95	1.65	3.39	1.32	1.28	0.70	1.44	2.46	1.75	1.96	1.76	1.46	1.74
Na ₂ O	3.95	3.10	3.69	3.04	3.38	3.01	2.72	3.02	3.25	2.91	3.31	2.81	3.10	4.43	3.92	3.80	3.36	3.36	3.48
K ₂ O	3.83	5.36	4.37	5.53	5.33	5.64	6.14	5.86	4.78	4.32	5.01	6.08	4.69	3.08	4.90	4.57	5.16	5.43	5.16
P ₂ O ₅	0.10	0.18	0.15	0.05	0.08	0.09	0.05	0.21	0.27	0.01	0.04	0.04	0.07	0.11	0.12	0.24	0.08	0.15	0.18
Total	99.00	99.77	99.82	99.81	99.78	99.83	99.34	99.67	99.61	99.84	99.85	99.84	99.82	100.95	101.03	101.94	99.87	99.79	99.79
Fe#	71.33	62.94	65.79	66.73	70.48	70.28	72.68	64.91	58.49	64.01	65.44	65.54	66.41	59.49	60.68	61.28	66.35	64.09	63.03
Mg#	28.67	37.06	34.21	33.27	29.52	29.72	27.32	35.09	41.51	35.99	34.56	34.46	33.59	40.51	39.32	38.72	33.65	35.91	36.97
A/NK	1.30	1.16	1.29	1.09	1.17	1.10	1.04	1.12	1.22	1.11	1.11	0.97	1.14	1.42	1.16	1.22	1.17	1.13	1.17
A/KCN	1.07	0.98	1.03	0.97	0.99	0.98	0.95	0.96	0.88	0.96	0.98	0.91	0.98	1.09	0.98	1.01	0.99	0.98	0.99
K ₂ O/Na ₂ O	0.97	1.73	1.18	1.82	1.58	1.87	2.26	1.94	1.47	1.48	1.51	2.16	1.51	0.70	1.25	1.20	1.54	1.62	1.48
<i>TE (ppm)</i>																			
Cs	1.08	1.73	1.21	1.89	0.53	1.07	1.30	3.47	1.05	0.76	1.29	0.63	1.45	1.29	1.21	1.90	1.64	0.68	2.02
Rb	109.16	210.62	160.85	215.63	181.97	179.46	199.17	280.69	138.06	130.75	187.33	203.06	218.91	145.88	168.03	193.79	177.37	161.36	194.68
Ba	1869.65	748.99	773.05	585.13	1379.77	847.67	970.21	2492.59	2491.59	903.28	693.62	1014.59	707.53	631.22	747.96	865.55	1141.18	1135.04	759.87
Nb	5.77	8.80	12.65	13.54	7.88	5.93	4.90	8.17	8.45	5.12	15.87	14.53	37.17	11.25	11.77	17.29	7.06	4.41	7.18
Sr	418.72	260.03	270.68	143.67	344.41	231.47	286.24	402.98	530.99	249.38	86.95	70.67	96.48	345.89	287.63	286.85	246.46	298.71	224.60
Zr	138.34	273.54	147.16	253.60	124.83	117.01	174.34	49.55	157.35	85.78	120.90	147.75	240.36	145.63	115.06	160.84	90.74	132.02	342.30
Y	10.40	43.28	20.28	41.25	6.48	21.90	31.52	9.19	35.91	2.04	8.38	27.85	7.66	18.01	19.73	30.47	4.83	14.04	31.27
La	37.78	62.29	23.02	82.47	14.57	15.21	73.33	12.01	36.86	15.55	62.59	44.66	31.36	49.17	30.72	34.21	12.54	63.41	69.88
Ce	63.25	119.83	39.99	155.43	24.68	27.80	131.89	18.87	67.04	23.65	117.90	84.73	55.02	86.80	52.89	59.04	20.56	115.73	125.13
Pr	6.19	12.70	4.13	16.27	2.68	2.91	14.65	1.89	8.87	2.06	12.39	9.08	5.60	9.51	5.93	6.65	2.08	11.79	12.61

Continued

Nd	20.84	43.06	14.31	54.70	9.00	8.90	43.74	5.86	32.46	5.57	42.04	31.88	19.11	31.10	19.08	21.87	7.82	39.44	41.88
Sm	3.37	8.56	2.89	10.83	1.86	1.94	7.60	1.27	6.46	0.77	6.56	6.42	3.47	5.89	3.82	4.22	1.61	6.06	7.25
Eu	2.47	1.34	1.36	1.16	3.06	1.84	2.34	4.76	5.33	2.01	1.48	1.65	1.35	0.99	0.80	0.86	1.55	1.89	1.38
Gd	4.12	9.74	3.16	11.53	1.30	1.54	6.23	1.00	4.29	0.79	7.00	7.36	3.82	5.00	3.57	4.10	1.69	7.37	8.69
Tb	0.38	1.25	0.42	1.35	0.23	0.37	1.03	0.20	0.88	0.09	0.53	0.86	0.35	0.63	0.58	0.67	0.18	0.69	0.90
Dy	1.72	7.03	2.70	6.84	1.24	2.92	5.54	1.41	5.65	0.37	1.69	4.43	1.40	3.37	3.47	4.34	0.83	2.97	4.84
Ho	0.29	1.20	0.53	1.13	0.27	0.73	1.12	0.31	1.31	0.08	0.24	0.77	0.22	0.62	0.67	0.97	0.13	0.42	0.85
Er	0.81	3.21	1.63	3.07	0.56	1.75	2.27	0.67	2.85	0.19	0.67	1.98	0.60	1.56	1.73	2.86	0.36	1.06	2.35
Tm	0.13	0.49	0.27	0.46	0.08	0.30	0.30	0.11	0.46	0.04	0.10	0.26	0.09	0.20	0.21	0.25	0.05	0.18	0.34
Yb	0.76	2.85	1.65	2.69	0.43	1.68	1.62	0.60	2.50	0.22	0.55	1.47	0.65	1.23	1.23	0.91	0.28	1.41	1.73
Lu	0.12	0.43	0.24	0.43	0.06	0.24	0.25	0.09	0.36	0.04	0.10	0.24	0.12	0.16	0.16	0.11	0.05	0.22	0.26
Hf	3.59	7.82	4.26	7.66	3.34	3.73	5.96	1.34	4.32	2.78	3.75	4.74	6.72	3.76	3.26	4.15	2.13	3.76	9.04
Ta	0.31	2.71	1.06	1.40	0.53	1.05	1.11	1.06	0.49	0.18	0.44	0.49	0.83	1.24	1.38	1.55	0.27	0.66	0.77
Th	19.02	48.17	11.86	64.08	14.35	11.30	56.68	10.26	14.44	9.00	39.90	27.55	35.87	20.84	16.39	16.45	3.54	40.17	47.76
U	2.86	15.19	8.13	40.69	1.25	7.91	23.40	8.52	1.83	10.70	3.24	4.75	5.32	4.35	13.54	12.30	0.80	7.09	37.35
Pb	39.56	65.25	49.02	87.57	34.95	60.53	73.11	63.14	39.58	43.02	45.96	75.61	39.71	39.22	54.47	46.16	30.21	59.53	64.57
Sc	3.34	5.89	4.76	4.73	2.97	2.08	1.99	6.00	8.36	0.63	2.58	2.93	8.66	6.85	4.26	7.47	2.51	2.71	6.66
V	21.55	40.02	41.45	20.56	21.32	6.75	8.89	29.04	50.58	4.69	7.09	6.31	25.09	32.64	15.25	31.42	27.04	18.87	19.44
Co	4.53	7.52	5.20	4.11	4.19	2.60	1.89	7.15	9.42	1.38	1.72	1.70	5.86	8.39	3.74	8.67	5.17	3.14	5.66
Ni	12.34	17.24	10.66	10.44	9.81	5.86	6.05	21.56	35.45	5.53	2.17	1.99	4.57	244.46	84.84	180.04	11.24	7.06	14.65
Ga	16.07	18.00	17.74	16.66	16.26	13.35	14.61	18.48	18.73	12.74	14.92	12.83	15.69	20.78	15.65	19.55	15.41	15.46	17.94
Ba/Rb	17.13	3.56	4.81	2.71	7.58	4.72	4.87	8.88	18.05	6.91	3.70	5.00	3.23	4.33	4.45	4.47	6.43	7.03	3.90
Sr/Y	40.26	6.01	13.35	3.48	53.11	10.57	9.08	43.87	14.79	122.29	10.37	2.54	12.60	19.20	14.58	9.41	51.06	21.28	7.18
Nb/Ta	18.65	3.25	11.88	9.69	14.78	5.65	4.41	7.73	17.37	28.21	36.42	29.49	44.87	9.11	8.55	11.18	25.93	6.64	9.35
Lu/Hf	0.03	0.06	0.06	0.06	0.02	0.06	0.04	0.07	0.08	0.01	0.03	0.05	0.02	0.04	0.05	0.03	0.02	0.06	0.03
ΣREE	142.23	273.99	96.31	348.38	60.02	68.12	291.92	49.05	175.32	51.42	253.83	195.79	123.15	196.23	124.86	141.06	49.72	252.65	278.09
La _n /Yb _n	33.57	14.78	9.40	20.70	23.05	6.12	30.55	13.54	9.97	48.31	76.83	20.51	32.76	27.09	16.88	25.33	30.43	30.31	27.32
Eu/Eu*	2.02	0.45	1.37	0.32	5.72	3.15	1.01	12.51	2.92	7.84	0.66	0.73	1.13	0.54	0.65	0.62	2.85	0.86	0.53
Rb/Sr	0.26	0.81	0.59	1.50	0.53	0.78	0.70	0.70	0.26	0.52	2.15	2.87	2.27	0.42	0.58	0.68	0.72	0.54	0.87

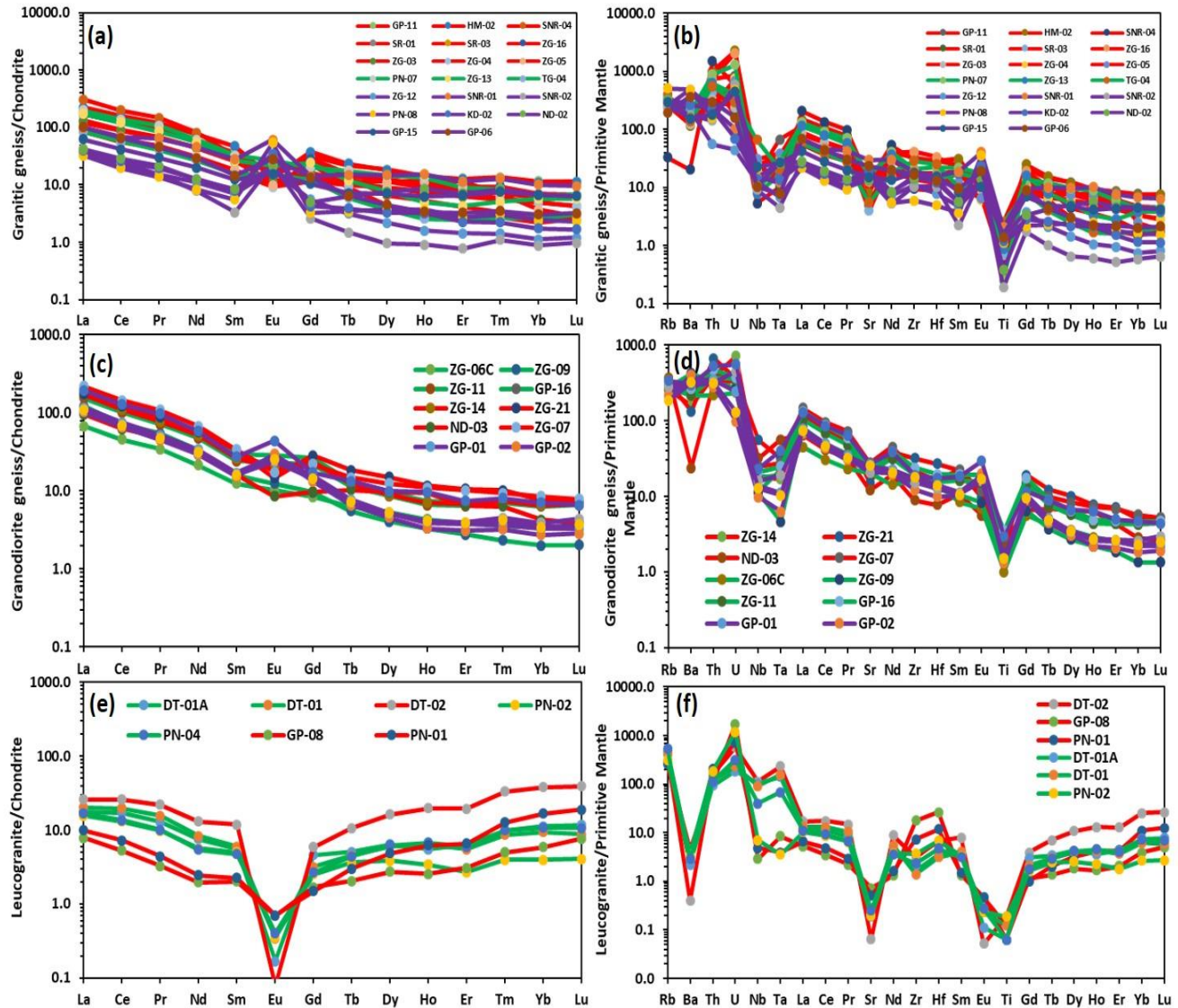


Figure 5. Normalized REE and trace element patterns for granitoids of Ghanapur. (a) Chondrite normalized REE patterns of granitic gneiss. (b) Primitive mantle normalized trace element spider plot for granitic gneiss. (c) Chondrite normalized REE patterns of granodiorite gneiss. (d) Primitive mantle normalized multi-element spider diagram granodiorite gneiss. (e) Chondrite normalized REE patterns of Leucogranite. (f) Primitive mantle normalized multi-element spider diagram Leucogranite. Normalization values are used after McDonough and Sun (1995)

The granodiorite gneisses are silica-rich to moderately silica-rich, with SiO_2 ranging from 61.98 to 73.31 wt%, and mostly plot in the granodioritic field, with a few samples extending into the granitic field (Figure 4a). These rocks show calc-alkaline to high-K calc-alkaline affinities and are generally weakly peraluminous, with A/CNK values of 0.96–1.20 (Figure 4c, d). Their trace-element patterns show moderate REE abundances and variable Eu behavior ($\text{Eu}/\text{Eu}^* = 0.47\text{--}2.07$), and show enrichment in LILE and depletion in high field strength elements (HFSE) elements. Relative to the granitic gneisses, the granodiorite gneisses record a stronger role for plagioclase in their petrogenesis, expressed as a wider spread in Eu anomalies, negative values reflecting

residual or fractionating plagioclase and positive values reflecting plagioclase accumulation (Figure 5c, d).

The leucogranites are the most evolved rocks in the assemblage. They are highly silica-rich, with SiO_2 values of 73.44–76.90 wt %, and all samples plot in the granitic field (Figure 4a). These rocks are peraluminous to strongly peraluminous, with A/CNK values of 0.99–1.33, and show high-K calc-alkaline to potassic affinities, consistent with highly evolved felsic melts (Figure 4c, d). Their trace-element patterns are marked by low REE contents and strong negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.01\text{--}0.38$), with enrichment in Rb, Th, U, Zr, and Hf, –

Table 2. Major oxide concentrations, trace element and REE concentrations and ratios of granodiorite gneisses from Ghanapur.

Granodiorite gneiss	ZG-06C	GP-01	GP-02	GP-04	GP-07	GP-16	KD-03	ND-03	ZG-07	ZG-09	ZG-11	ZG-14	ZG-21
<i>Major oxides (wt%)</i>													
SiO ₂	73.47	70.85	71.34	69.31	70.94	65.28	65.67	66.40	61.98	73.31	68.19	68.36	69.74
TiO ₂	0.16	0.24	0.21	0.25	0.24	0.57	0.47	0.40	0.53	0.22	0.46	0.45	0.33
Al ₂ O ₃	14.67	15.21	15.27	15.18	15.43	15.70	15.61	15.19	16.95	14.37	14.78	14.59	14.58
Fe ₂ O ₃ (T)	2.14	2.65	2.07	3.70	2.54	6.15	4.09	5.55	5.74	2.58	4.61	5.04	4.49
MnO	0.02	0.03	0.03	0.07	0.04	0.08	0.08	0.05	0.10	0.03	0.06	0.07	0.04
MgO	0.42	0.60	0.52	1.58	0.66	1.95	3.50	3.12	2.45	0.74	1.82	1.84	0.92
CaO	1.36	2.12	2.11	3.49	2.48	4.04	3.83	2.66	4.28	1.97	3.90	3.57	2.01
Na ₂ O	3.60	3.74	3.71	3.55	4.19	3.71	5.07	4.56	4.66	3.93	4.06	3.98	3.66
K ₂ O	5.39	4.14	4.31	2.49	3.10	2.07	1.17	1.68	2.96	3.73	1.63	1.66	3.89
P ₂ O ₅	0.10	0.09	0.07	0.08	0.07	0.15	0.22	0.23	0.19	0.08	0.22	0.21	0.14
Total	101.33	99.67	99.64	99.70	99.69	99.70	99.71	99.84	99.84	100.96	99.73	99.77	99.80
Fe#	71.97	69.00	66.74	54.13	65.98	61.38	37.07	47.27	54.14	63.73	56.07	57.99	71.10
Mg#	28.03	31.00	33.26	45.87	34.02	38.62	62.93	52.73	45.86	36.27	43.93	42.01	28.90
A/NK	1.09	1.30	1.28	1.71	1.44	1.86	1.75	1.68	1.52	1.26	1.79	1.78	1.30
A/KCN	0.96	1.04	1.03	1.12	1.10	1.13	1.11	1.20	1.00	1.02	1.09	1.12	1.05
K ₂ O/Na ₂ O	1.50	1.11	1.16	0.70	0.74	0.56	0.23	0.37	0.64	0.95	0.40	0.42	1.06
<i>TE (ppm)</i>													
Cs	0.88	1.96	1.32	3.50	1.55	2.56	6.07	5.31	2.90	1.28	2.53	2.07	1.76
Rb	190.01	115.41	118.65	154.20	102.38	171.56	185.09	202.02	158.23	152.31	146.70	139.34	175.68
Ba	1091.48	1751.87	2027.32	1473.04	1619.85	1369.49	1528.52	120.78	1117.83	2161.32	1109.87	807.90	683.87
Nb	6.51	7.63	5.51	8.89	7.15	11.59	12.94	17.81	13.89	6.21	9.90	10.42	31.20
Sr	361.82	442.24	432.08	367.41	451.66	402.26	481.82	216.05	496.35	473.24	382.34	327.71	270.27
Zr	135.83	144.13	101.71	127.41	147.50	198.20	159.44	73.46	176.04	134.32	159.47	157.56	263.82
Y	10.54	11.33	10.04	13.58	13.33	23.53	21.17	22.11	27.11	7.87	19.98	21.33	35.27
La	24.87	43.01	37.82	39.64	40.28	73.48	71.58	35.62	81.15	45.18	56.94	62.29	63.80
Ce	43.90	72.35	62.94	66.87	67.06	124.13	123.36	60.01	137.91	69.97	97.88	105.67	117.07
Pr	4.75	7.14	6.18	6.54	6.57	12.32	13.37	6.77	14.86	7.45	9.82	10.72	12.16
Nd	15.28	24.06	20.82	21.95	22.25	42.00	41.60	20.78	48.18	23.85	33.77	36.62	41.15
Sm	2.90	3.92	3.55	3.74	3.70	6.76	6.31	3.75	7.84	3.62	5.58	6.04	7.71
Eu	0.90	2.42	2.59	2.07	2.19	2.51	3.83	0.74	1.53	1.09	2.01	1.72	1.27
Gd	2.59	4.78	4.10	4.49	4.40	8.02	5.29	2.99	6.76	2.95	6.63	7.26	8.73
Tb	0.36	0.45	0.39	0.41	0.42	0.79	0.77	0.60	0.86	0.32	0.66	0.72	1.07
Dy	2.02	1.98	1.74	1.96	2.01	3.69	3.78	3.70	4.75	1.55	3.28	3.41	5.77
Ho	0.37	0.33	0.28	0.35	0.35	0.63	0.82	0.80	0.94	0.28	0.56	0.60	0.99
Er	0.96	0.94	0.77	0.99	0.97	1.78	1.86	1.62	2.55	0.69	1.61	1.70	2.64
Tm	0.13	0.13	0.12	0.16	0.15	0.27	0.29	0.23	0.34	0.08	0.25	0.27	0.37
Yb	0.85	0.81	0.68	0.97	0.86	1.71	1.76	1.07	2.13	0.50	1.58	1.61	1.89
Lu	0.12	0.13	0.11	0.17	0.14	0.27	0.25	0.15	0.30	0.08	0.25	0.26	0.28
Hf	3.94	3.82	2.70	3.45	3.78	5.26	4.69	2.10	4.43	3.43	4.19	4.11	7.32
Ta	0.91	0.45	0.25	0.76	0.41	0.99	1.62	2.26	1.11	0.18	0.76	0.68	1.28
Th	13.89	22.25	18.12	20.55	20.14	30.30	33.55	20.19	28.72	20.79	23.88	24.87	42.81
U	4.26	4.35	1.76	8.14	2.35	6.70	10.07	5.99	6.09	4.81	6.32	12.86	6.31
Pb	57.64	42.97	42.52	30.57	37.60	21.10	33.41	22.34	32.05	40.42	23.05	26.98	62.73
Sc	3.41	3.67	2.97	3.32	3.47	8.70	8.41	9.73	10.24	3.58	6.94	7.35	7.26
V	8.82	27.72	20.79	27.36	23.90	65.96	67.29	54.04	81.19	25.06	57.69	60.03	52.13
Co	4.33	5.20	3.78	6.10	4.81	12.87	12.31	10.01	16.87	5.30	10.39	11.16	7.25
Ni	109.22	15.22	10.01	12.19	12.40	44.25	32.08	20.24	466.16	178.35	29.71	29.78	17.33
Ga	17.26	17.33	16.36	22.01	16.78	19.34	19.61	24.12	24.44	17.99	16.70	17.42	21.33
Ba/Rb	5.74	15.18	17.09	9.55	15.82	7.98	8.26	0.60	7.06	14.19	7.57	5.80	3.89
Sr/Y	34.32	39.02	43.05	27.05	33.88	17.10	22.76	9.77	18.31	60.15	19.14	15.37	7.66
Nb/Ta	7.19	17.15	21.81	11.68	17.35	11.67	7.99	7.87	12.47	33.64	12.97	15.42	24.44
Lu/Hf	0.03	0.03	0.04	0.05	0.04	0.05	0.05	0.07	0.07	0.02	0.06	0.06	0.04
ΣREE	99.99	162.44	142.09	150.32	151.35	278.34	274.87	138.82	310.10	157.61	220.83	238.90	264.89
La _n /Yb _n	19.87	35.91	37.76	27.71	31.73	29.01	27.56	22.57	25.71	61.38	24.36	26.09	22.80
Eu/Eu*	0.99	1.70	2.07	1.55	1.66	1.04	1.97	0.65	0.63	0.99	1.01	0.79	0.47
Rb/Sr	0.53	0.26	0.27	0.42	0.23	0.43	0.38	0.94	0.32	0.32	0.38	0.43	0.65

Table 3. Major oxide concentrations, trace element and REE concentrations and ratios of leucogranites from Ghanapur.

	<i>Leucogranite (garnetiferous)</i>				<i>Leucogranite (magnetite bearing)</i>		
	DT-01	DT-01A	PN-04	DT-02	GP-08	PN-01	PN-02
<i>Major oxides (wt%)</i>							
SiO ₂	73.57	74.10	75.16	73.44	73.87	76.90	74.02
TiO ₂	0.02	0.01	0.01	0.03	0.01	0.02	0.03
Al ₂ O ₃	15.58	15.52	15.42	16.19	15.35	13.43	14.66
Fe ₂ O ₃ (T)	0.60	0.66	0.83	1.16	0.42	0.44	0.91
MnO	0.07	0.08	0.11	0.18	0.00	0.03	0.02
MgO	0.04	0.04	0.08	0.07	0.05	0.04	0.05
CaO	0.21	0.21	0.32	0.29	0.85	0.77	0.35
Na ₂ O	4.44	4.31	3.79	3.94	4.58	4.27	4.47
K ₂ O	4.91	4.96	4.19	3.97	4.80	4.02	5.12
P ₂ O ₅	0.02	0.03	0.03	0.01	0.02	0.04	0.04
Total	99.46	99.92	99.94	99.28	99.95	99.96	99.67
Fe#	88.32	89.27	83.95	89.31	80.89	84.72	90.17
Mg#	11.68	10.73	16.05	10.69	19.11	15.28	9.83
A/NK	1.12	1.12	1.30	1.38	1.10	1.09	1.03
A/KCN	1.10	1.10	1.25	1.33	1.02	1.01	0.99
K ₂ O/Na ₂ O	1.11	1.15	1.11	1.01	1.05	0.94	1.15
<i>TE (ppm)</i>							
Cs	0.88	0.57	1.81	0.46	0.96	0.98	3.20
Rb	249.04	238.16	292.75	222.35	158.10	140.52	170.80
Ba	15.70	11.36	14.75	2.04	23.26	12.06	18.60
Nb	51.85	58.00	22.56	63.10	1.60	2.72	3.92
Sr	4.19	3.42	4.52	1.14	12.94	9.15	3.47
Zr	11.68	14.09	19.51	25.62	149.04	61.51	30.57
Y	20.51	22.80	20.93	52.81	8.27	19.30	10.50
La	7.43	6.53	6.18	9.50	2.91	3.65	5.77
Ce	18.86	16.44	13.13	25.00	5.04	6.91	12.49
Pr	2.13	1.76	1.39	3.03	0.45	0.60	1.35
Nd	5.92	5.39	3.89	9.35	1.39	1.73	4.00
Sm	1.38	1.30	1.10	2.74	0.47	0.52	1.15
Eu	0.03	0.01	0.04	0.01	0.06	0.06	0.03
Gd	0.97	1.41	0.82	1.81	0.52	0.46	0.77
Tb	0.26	0.30	0.26	0.62	0.12	0.18	0.21
Dy	2.33	2.45	2.39	6.22	1.04	1.85	1.47
Ho	0.54	0.47	0.58	1.69	0.22	0.53	0.29
Er	1.38	1.59	1.50	4.82	0.77	1.64	0.67
Tm	0.31	0.35	0.36	1.20	0.18	0.46	0.14
Yb	2.34	2.79	2.69	9.52	1.47	4.16	0.99
Lu	0.34	0.45	0.40	1.50	0.29	0.72	0.16
Hf	0.84	0.95	1.27	1.84	7.15	3.17	1.85
Ta	6.27	5.67	2.73	9.24	0.34	0.16	0.14
Th	7.55	5.94	7.25	10.12	6.70	13.27	11.82
U	4.19	3.33	5.72	10.36	31.29	13.17	21.45
Pb	19.35	24.25	25.97	26.57	62.29	48.36	20.51
Sc	4.86	5.29	14.73	14.53	1.31	2.06	1.68
V	1.33	1.22	1.34	1.26	1.36	1.76	1.51
Co	0.61	0.62	0.80	0.59	0.61	0.79	0.62
Ni	2.72	2.01	3.20	2.64	1.89	3.42	2.88
Ga	26.28	24.78	25.76	31.11	14.82	16.57	24.32
Ba/Rb	0.06	0.05	0.05	0.01	0.15	0.09	0.11
Sr/Y	0.20	0.15	0.22	0.02	1.57	0.47	0.33
Nb/Ta	8.27	10.23	8.27	6.83	4.74	17.35	27.33
Lu/Hf	0.40	0.47	0.32	0.81	0.04	0.23	0.08
ΣREE	44.22	41.25	34.71	77.00	14.93	23.47	29.50
La _N /Yb _N	2.15	1.58	1.55	0.67	1.33	0.59	3.96
Eu/Eu*	0.08	0.03	0.11	0.01	0.37	0.38	0.09
Rb/Sr	59.42	69.58	64.72	194.44	12.21	15.35	49.16

coupled with depletion in Ba, Sr, Eu, and Ti. Their low Mg# values (9.83–19.11), and very low CaO contents are consistent with highly evolved felsic compositions. Garnet-bearing varieties show flatter HREE patterns and stronger Eu depletion, whereas non-garnetiferous samples retain relatively higher HREE concentrations (Figure 5e, f).

Zircon geochronology of granitoids

Granitic gneiss

Many zircons show variable metamictization; therefore, upper-intercept concordia ages are preferred for age interpretation. Sample TG-04 (17.77884, 79.42641) is collected from an inactive granite quarry at Theegaram village along the western margin of the Ghanapur belt. The sample is coarse-grained, and well-foliated. Separated zircons are mainly elongated to prismatic, 80–100 μm long, with few slightly rounded grains having 50–80 μm length. CL images show disrupted concentric oscillatory zoning and irregular homogeneous domains, indicating modification of the original magmatic zoning (Figure 6a). Seventeen analyses record U contents of 7–896 ppm, Th contents of 5–335 ppm, and Th/U ratios of 0.10–1.05. The analyses define a discordant array; regression of the array yields an upper-

intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2697 ± 24 Ma (MSWD = 6.0), anchored by four 95–100% concordant spots (spot locations shown in Fig. 6a) and taken as the best possible estimate of the crystallization age (Figure 7a). The elevated MSWD is attributed to minor scatter from variable, metamictization-related Pb-loss; ablation spots were sited on preserved oscillatory-zoned magmatic domains and away from recrystallized or resorbed zones.

Sample SR-01 (17.77354, 79.43184) is collected from a granitoid mound near Suraram village in the western part of the Ghanapur belt. The sample is coarse-grained, foliated, and banded. Separated zircons are mainly tabular, with a few elongated grains, and show rounded to prismatic terminations (Figure 6b). CL images show zoning-free grains with dark homogeneous interiors and minor bright patches, whereas a few grains preserve resorbed and distorted zoning (Figure 6b). Twenty-nine analyses yield U contents of 27–321 ppm, Th contents of 7–83 ppm, and Th/U ratios of 0.11–0.82. The analyses define a discordant array; regression of the array yields an upper-intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2607 ± 41 Ma (MSWD = 2.6), anchored by two 95–100% concordant spots, interpreted as the crystallization age (Figure 7b).

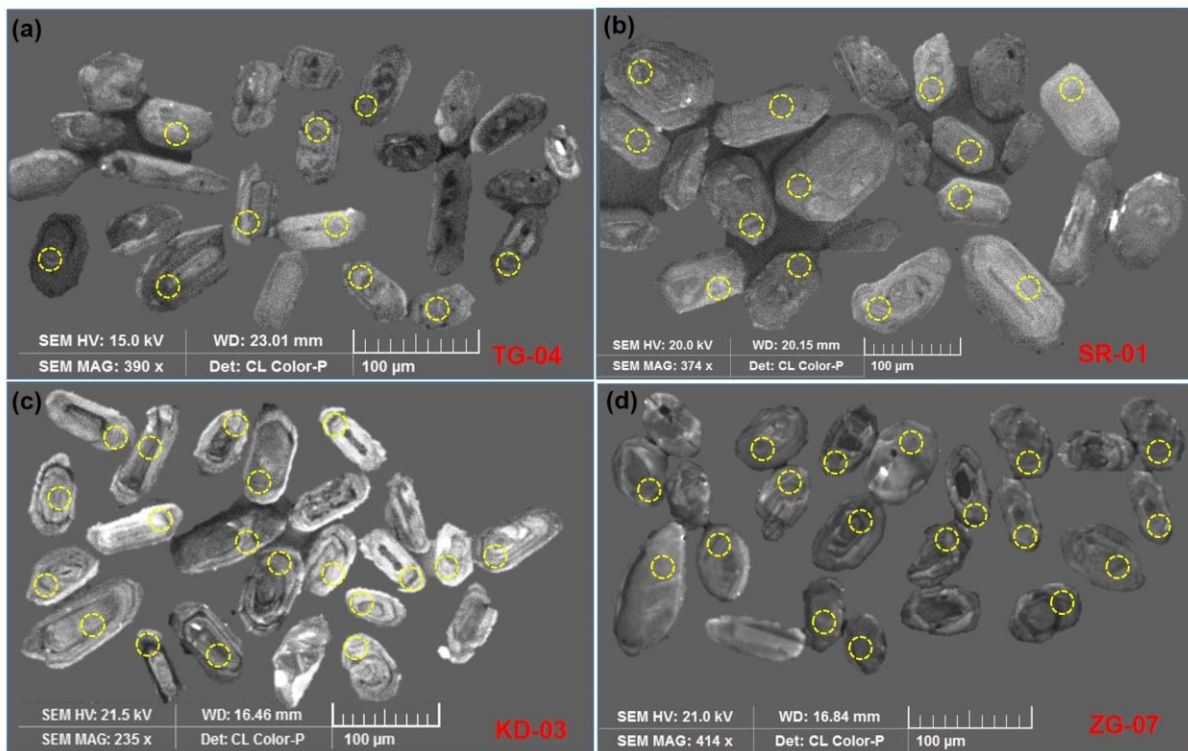


Figure 6. CL-SEM images of representative zircons from granitoids of Ghanapur (a–b) Zircons from granitic gneiss samples. (c–d) zircons from granodiorite gneiss samples. Yellow circles represent ablation spots.

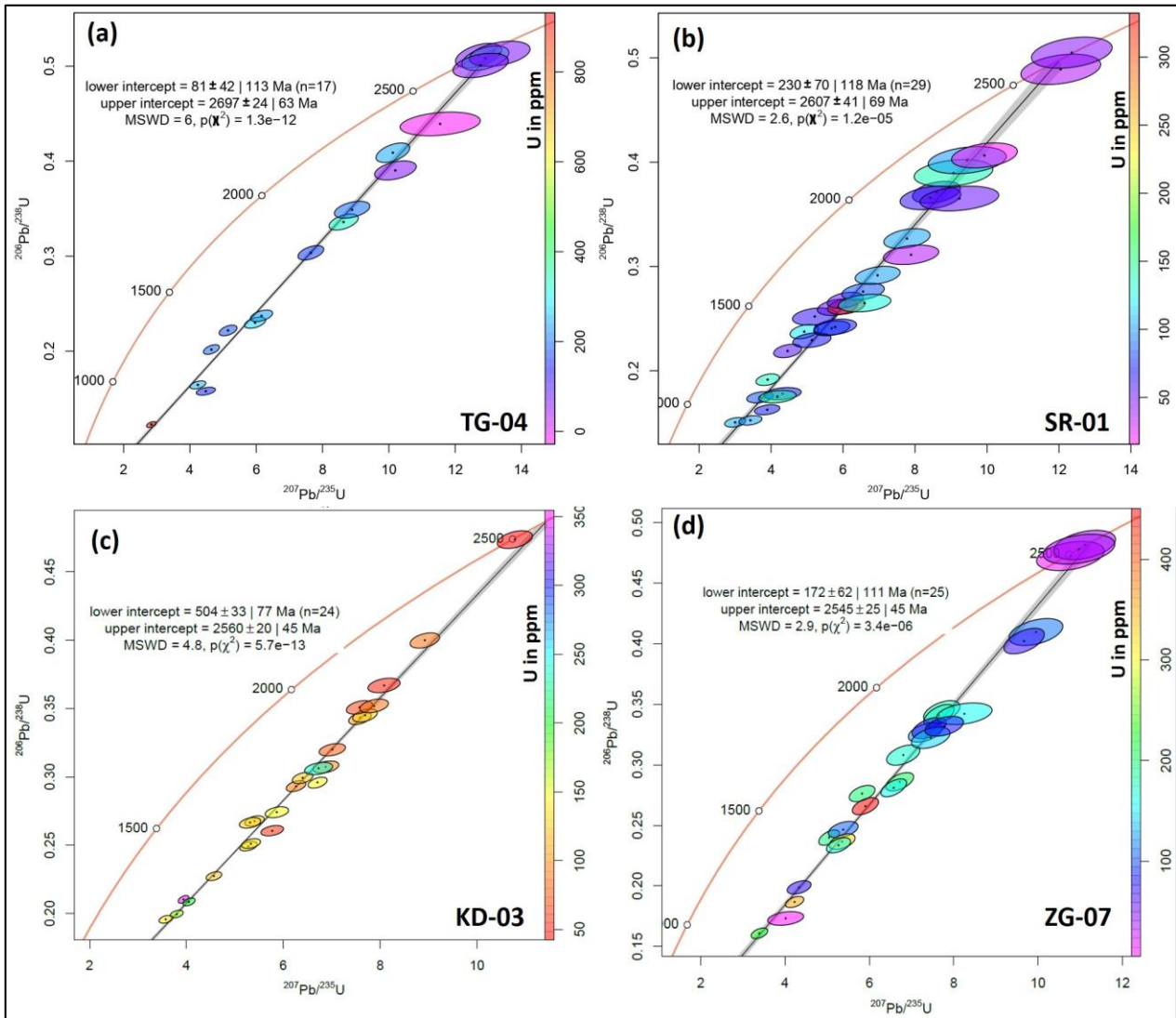


Figure 7. U-Pb concordia diagrams for zircons analysed. **(a-b)** Granitic gneiss samples. **(c-d)** Granodiorite gneiss samples.

Granodiorite gneiss

Two granodiorite gneiss samples appearing as mesosome in migmatitic outcrops were dated. Sample KD-03 (17.70269, 79.55881) is melanocratic gneiss collected from Kondur Gutta granite hill in the southern part of the Ghanapur belt. Separated zircons are mostly elongated to subrounded, 80–120 μm long, and commonly preserve rounded pyramidal terminations (Figure 6c). CL images show resorption of primary magmatic zoning, and some grains preserve dark xenocrystic cores mantled by thin dark rims, together with dark homogeneous domains, indicating post-magmatic recrystallization in the presence of aqueous fluids (Figure 6c). Twenty-four analyses record U contents of 54–343 ppm, Th contents of 33–190 ppm, and Th/U ratios of 0.21–1.11. The analyses define a discordant array; regression yields an upper-intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2560 ± 20 Ma (MSWD =

4.8), anchored by a single 99% concordant spot and interpreted as the crystallization age (Figure 7c).

Sample ZG-07 (17.771386, 79.481862) collected from the temple hill of Zaffergadh, is a mesocratic quartz-monzodiorite gneiss representing the mesosome portion of the migmatite outcrop. Separated zircons are mostly rounded to subrounded, 50–100 μm long, and pale yellow to light brown in color. CL images show resorption of primary zoning, with non-luminescent to weakly luminescent homogeneous xenocrystic cores and deformed rim zoning, indicating recrystallization of igneous zircon in the presence of magmatically derived aqueous fluids (Figure 6d). Twenty-five analyses yield U contents of 22–434 ppm, Th contents of 4–465 ppm, and Th/U ratios of 0.19–1.10. The analyses define a discordant array; regression of the array yields an upper-intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2545 ± 25 Ma (MSWD =

2.9), anchored by three 95–100% concordant spots, interpreted as the crystallization age (Figure 7d).

DISCUSSION

Petrogenesis and source characteristics of the granitoid suite

The granitoid suite of the Ghanapur area records progressive crustal reworking and magmatic differentiation rather than derivation from a single homogeneous source. Its petrographic variability, together with the compositional transition from granitic gneiss to granodiorite gneiss and leucogranite, indicates that the suite formed through multiple melt-generation and reworking events within a heterogeneous Archean crust. Major-element trends, including decreasing Fe_2O_3 (T), MgO , CaO , and TiO_2 with increasing SiO_2 , point to progressive fractionation during magma evolution, whereas enrichment in LILEs together with Nb–Ta–Ti depletion reflects strong influence of the source (Figure 5). These signatures are consistent with evolved Archean granitoid systems formed through prolonged crustal melting and reworking (Moyen, 2011; Laurent et al., 2014).

The granitic gneisses preserve the clearest evidence for mixed source contributions. In the Archean granitoid classification diagram, the granitic gneisses plot mainly in the biotite two-mica granite field, with two samples extending into the sanukitoid field, indicating a dominantly crustal granite lineage with local mafic imprint or hybridization (Figure 8a ; Moyen, 2011; Laurent et al., 2014). This is

further supported by their position in the Laurent et al. (2014) source-discrimination diagram, which suggests a contribution from metasedimentary protoliths alongside tonalitic and high-K mafic sources; in the absence of radiogenic-isotope data, this metasedimentary contribution is treated as suggestive (Figure 8b). The geochemical variability of the suite together with their weakly metaluminous to slightly peraluminous character and variable Eu anomaly, is consistent with melting of heterogeneous crustal protoliths at different crustal levels. Experimental studies have shown that peraluminous granites may form by dehydration melting of metasedimentary rocks, whereas more metaluminous, Ba–Sr–Ni–Cr-enriched compositions are commonly linked to partial melting of mafic lower crust or tonalitic material (Patiño Douce and Johnston, 1991; Chappell and White, 2001; Clemens, 2003).

In the Laurent et al. (2014) ternary classification diagram for Archean granitoids, the dated granodiorite gneissic samples plot in the sanukitoid field (Figure 8a), whereas the remaining samples fall in the overlapping zone between the sanukitoid, biotite two-mica granite, and TTG fields. The geochemical characteristics of the granodioritic gneisses, including their calc-alkaline to high-K calc-alkaline affinity, elevated Mg#, high Ba+Sr, and LILE and LREE enrichment, are consistent with a sanukitoid affinity and indicate derivation from an enriched mantle source wherein the mantle wedge was previously metasomatized by fluids and/or melts derived from a subducting slab, including oceanic crustal and sedimentary components (Laurent et al., 2014).

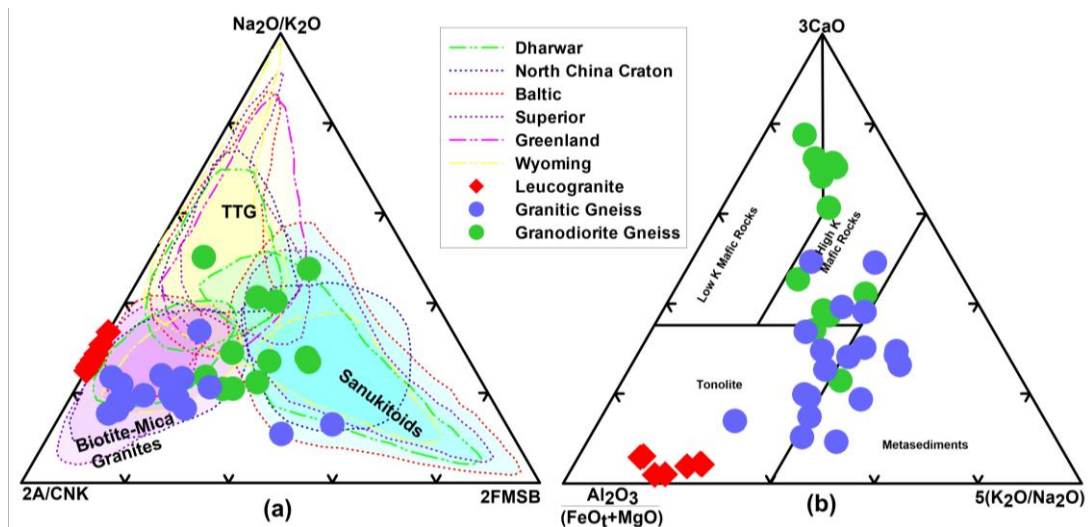


Figure 8. (a) Ternary synthetic classification diagram of Laurent et al. (2014), showing the petrogenetic processes involved in the genesis of the Late Archean granites. **(b)** Ternary source-discrimination diagram of the Ghanapur granitoids after Laurent et al. (2014). The fields represent the composition of melts derived from a range of potential sources (tonalites, metasediments, low- and high-K mafic rocks).

Although the granodiorite gneiss suite shows internal compositional heterogeneity, the two dated samples (KD-03, ZG-07) plotting unambiguously in the sanukitoid field and the remainder distributed across the overlap zone. The cumulative geochemical signature e.g., high Ba+Sr, LILE enrichment, elevated Mg#, low-to-moderate HREE fractionation, and dominantly $K_2O/Na_2O > 0.5$ supports a common sanukitoid parentage. The spread therefore reflects variable fractional crystallization and crustal assimilation rather than distinct source affiliations. Accordingly, the two dated samples are treated as geochemically unambiguous sanukitoids that constrain the timing of sanukitoid magmatism. Such rocks are widely interpreted as products of partial melting of mantle peridotite enriched by the addition of crustal-derived fluids or melts in a subduction zone setting. Subsequent evolution of these magmas was governed by fractional crystallization, with variable contributions from crustal assimilation during ascent. In the Laurent et al. (2014) source discrimination diagram, the samples plot predominantly in the low-K to high-K mafic rock field (Figure 8b), consistent with derivation from a mafic mantle source. Notably, the appearance of sanukitoid as mesosomes within migmatite outcrops likely reflects entrainment within a younger post-2545 Ma migmatitic episode, such that these rocks in the incorporated as mesosomes within a younger anatectic system. Ghanapur area preserve a dual identity: primary sanukitoid intrusive by origin, subsequently incorporated as mesosomes within a younger anatectic system.

The leucogranites represents the most evolved members of the suite, and although undated in this study, are interpreted as terminal products of crustal anatexis. Their high SiO_2 , stronger peraluminous character, low REE budget, low Mg# and pronounced negative Eu anomalies indicate derivation by partial melting of older tonalitic to granodioritic crustal material. The pronounced negative Eu anomalies, together with low Ba, Sr, and Ti, record a dominant control by residual and/or fractionating plagioclase (with K-feldspar and Fe-Ti oxides), whereas the marked enrichment in Rb, Th, and U reflects extreme late-stage fractionation. The elevated HREE profile in leucogranites is related to the presence of peritectic garnet, which is evident from petrological observation. Collectively, these features are consistent with high-temperature, fluid-absent (biotite-dehydration) anatexis of tonalitic to granodioritic crust during regional crustal thickening, thermal relaxation, and migmatization, which generated and mobilized these small-volume peraluminous melts (Harris et al., 1993; Clemens, 2003). In the Laurent et al. (2014) source-discrimination diagram, the samples plot in tonalite field (Figure 8b), consistent with derivation from

felsic to intermediate crustal protoliths. This is consistent with model in which small volume leucocratic melts segregate during thermal relaxation and migmatization of thickened crust, pointing to the waning stages of late Archean crustal thickening as most possible tectonic setting (Harris et al., 1993).

Geochronological constraints and tectonic implications

The zircon U–Pb ages define a prolonged late Archean magmatic and reworking history for the granitoid suite, spanning from 2697 ± 24 Ma to 2545 ± 25 Ma. The granitic gneisses yield crystallization ages of 2697 ± 24 Ma (TG-04) and 2607 ± 41 Ma (SR-01), whereas the granodiorite gneisses yield ages of 2560 ± 20 Ma (KD-03) and 2545 ± 25 Ma (ZG-07) (Figure 7). This age spread indicates that granitoid generation was not a single short-lived event but rather a protracted process involving repeated melt extraction, emplacement, and crustal reworking. Such stepwise granitoid development is typical of late Archean terranes, where crustal thickening, thermal reworking, and episodic magma addition operated together during craton assembly (Manikyamba and Kerrich, 2012; Jayananda et al., 2018).

Although widely used, the tectonic discrimination diagrams of Pearce et al. (1984) were developed primarily for post-Archean granitoids and should be applied to Archean granitoids with caution. The tectonic-affinity interpretations derived from these diagrams are therefore treated as suggestive rather than definitive, and the strongly peraluminous leucogranites in particular are interpreted with corresponding caution, as such compositions are not well suited to these discrimination schemes (Whalen and Hildebrand, 2019). Most importantly, differentiation can produce compositional trends that cross field boundaries, particularly from the volcanic arc granite (VAG) to within plate granite (WPG) field (Pearce et al., 1984). Nevertheless, the granitoids from Ghanapur area cluster mainly in the syn-collisional and volcanic-arc granitic fields, with few samples extending towards the within-plate granite field in the Pearce et al. (1984) discrimination diagram (Figure 9a-d). This distribution suggests a broadly convergent-margin affinity that evolved through time towards increasingly fractionated and internally reworked felsic magmatism. Such a pattern is consistent with Archean crustal growth involving subduction-related mantle metasomatism and subsequent melting, followed by magma hybridization, crystal fractionation, and variable contributions from remelting of older crustal material (Moyen, 2011; Laurent et al., 2014). The granitoid suite of the Ghanapur region therefore records a late Archean magmatic history spanning at least 150 Ma, reflecting a progression from early crustal melting

represented by the older granitic gneisses, through younger hybrid crust-mantle magmatism expressed by the granodiorite gneisses, to terminal high-temperature crustal anatexis preserved in the leucogranites.

The sanukitoid affinity of the granodiorite gneiss is however of particular importance because sanukitoids are widely interpreted as markers of crust-mantle interaction (e.g., Martin and Moyen, 2002; Laurent et al., 2014). It is worth noting that, sanukitoid magmatism in the EDC has been attributed to melting of an enriched mantle source following subduction along the EDC-WDC convergent margin, with slab breakoff commonly invoked as the trigger for asthenospheric upwelling and juvenile magma addition (Jayananda et al., 2020; Raju et al., 2024). The broadly synchronous occurrence of this magmatic episode across the craton at ca. 2570–2510 Ma (e.g., Jayananda et al., 2020; Dey et al., 2017) may, however, indicate melting of a previously enriched lithospheric mantle on a craton-wide scale rather

than a direct response to a single, spatially continuous convergent margin. The northeastern EDC presents a particularly important yet poorly constrained case in this context. The Ghanapur area is geographically distant from the proposed collision zone. Whether the sanukitoid magmatism documented here at ca. 2560–2545 Ma was generated through the same tectono-magmatic processes proposed for the other parts of the EDC remains unresolved. Alternatively, it may reflect a distinct history of mantle enrichment linked to the crustal architecture of the northeastern margin. Addressing this question will require further investigation of the Ghanapur granodioritic gneisses together with structural constraints on the deformation associated with the ca. 2560–2545 Ma magmatic event. Consequently, the northeastern EDC provides an important opportunity to evaluate the extent to which late Neoproterozoic mantle enrichment and sanukitoid-like magmatism varied across the Dharwar craton.

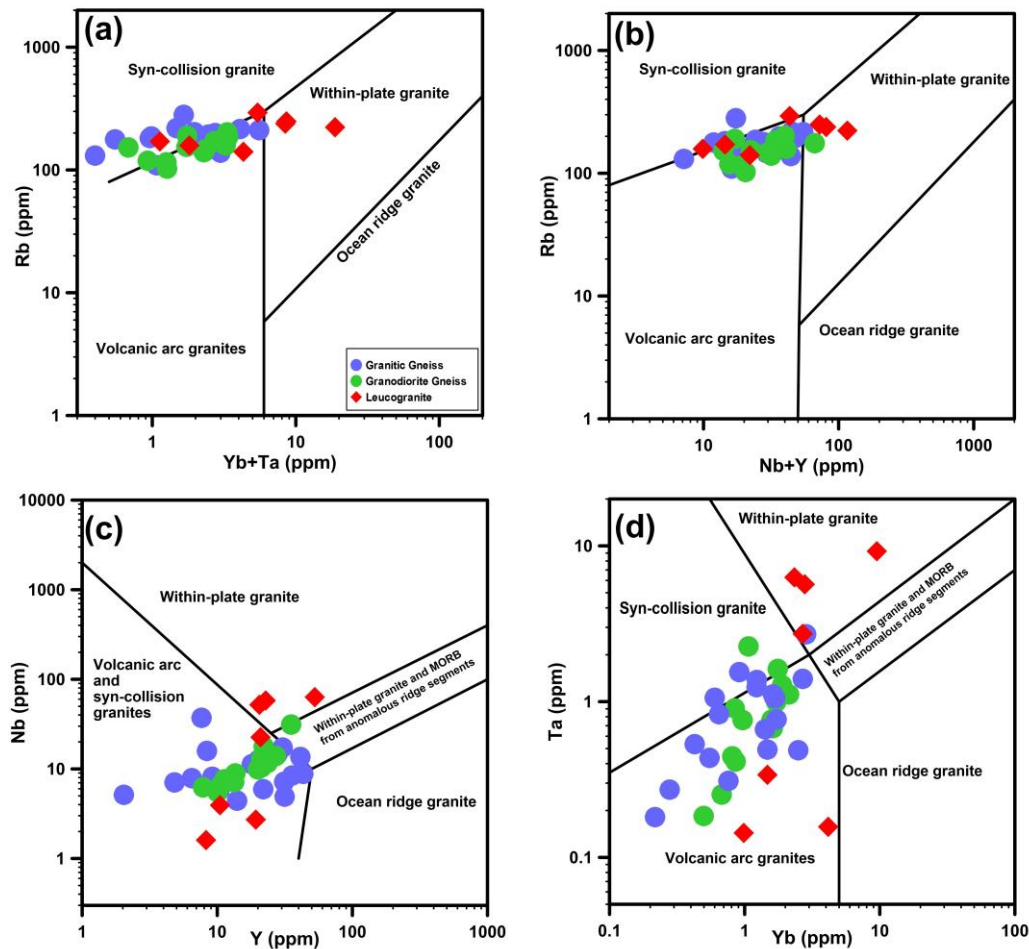


Figure 9. (a-d) Tectonic discrimination diagrams for granitoids based on trace element compositions after Pearce et al. (1984).

CONCLUSIONS

- (i) The Ghanapur area preserves a coherent record of the late Archean crustal growth, reworking, and progressive crustal maturation within the EDC.
- (ii) The studied rocks are classified into three suites on the basis of their field relationships, petrographic features, and geochemical characteristics: granitic gneisses, granodiorite gneisses, leucogranites.
- (iii) The older granitic gneisses (2697–2607 Ma) record early crust-forming events dominated by melting of heterogeneous crustal protoliths, including metasedimentary, tonalitic and high-K mafic sources.
- (iv) The younger granodiorite gneiss (2560–2545 Ma) show sanukitoid affinity, indicating derivation from melting of a mantle wedge metasomatized by subduction-derived fluids and melts.
- (v) The leucogranites represent terminal high-temperature crustal anatexis, formed as small-volume late anatectic melts.
- (vi) The geochemical and geochronological constraints are consistent with a broadly convergent-margin setting in which repeated episodes of crustal melting, mantle wedge metasomatism, and thermal reworking contributed to late Archean crustal evolution in the Ghanapur region over a protracted period of ~150 Ma.

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Author Credit statement

Namrata Khadke: Conceptualization, methodology, investigation, formal analysis, data curation, visualization, funding acquisition, software, writing original draft, writing

review & editing. Sarbajit Dash: Validation, writing, review & editing. T. Vijaya Kumar: Formal analysis. E.V.S.S.K. Babu: Supervision, writing, review & editing. Y.J. Bhaskar Rao: supervision and resources

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Compliance with Ethical Standards

The authors declare no conflict of interest. The manuscript complies with all applicable copyright requirements and ethical standards for publication.

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