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Magnetic petrofabric and petrographic evidence for late- to post-tectonic emplacement of the Kalpetta Granite, Nilgiri Block, Southern Granulite Terrain, India

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ABSTRACT

Anisotropy of Magnetic Susceptibility (AMS) provides an ideal methodology for identifying subtle internal deformations in rocks that lack visible macro-scale strain markers. This study investigates the petrographic and magnetic petrofabric characteristics of the Neoproterozoic alkaline-subalkaline Kalpetta Granite, an oval-shaped pluton located in the western portion of the Nilgiri Block within the Southern Granulite Terrain. The Kalpetta granite is a medium to coarse-grained body primarily composed of quartz, plagioclase, and alkali feldspar, with significant mafic contributions from biotite and hornblende. Detailed petrographic analysis reveals a complex crystallisation history, notably including chessboard patterns in quartz, indicative of solid-state deformation at high temperatures near the solidus. AMS analysis reveals a high degree of magnetic anisotropy in the Kalpetta granite, predominantly controlled by ferrimagnetic minerals, notably magnetite. The resulting AMS ellipsoids exhibit an oblate shape, corresponding to the weak alignment of these magnetite grains within the rock matrix. Magnetic lineation and foliation trends within the pluton align obliquely to the general trend of the regional Bavali-Moyar shear zone. These findings suggest that the granite experienced significant magmatic flow and high-temperature deformation before its final solidification. Yet, it strikingly lacks the low-temperature deformation features found in surrounding lithologies. The associated host rocks, including hornblende-biotite gneiss, charnockite, and pyroxene granulite, display a range of intense deformation textures, moving from high-temperature grain boundary migration to low-temperature, high-strain conditions. This sharp disparity supports a post-tectonic emplacement model for the Kalpetta granite, distinguishing its relatively stable cooling history from the syntectonic deformation of the surrounding terrain. Thus, this research underscores the need to distinguish between high- and low-temperature deformation textures to accurately reconstruct the timing and tectonic setting of granite emplacement within the Southern Granulite Terrain.

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1. Introduction

The study of granitoid bodies is fundamental to understanding the evolution, differentiation, and stabilization of the continental crust. Granites constitute a major component of the upper continental crust. They are closely linked to processes such as crustal anatexis, magma generation, ascent, and emplacement, which are often synchronous with regional deformation and tectonic events (Solar et al., 1998; Pressley and Brown, 1999; Jaupart et al., 2014). These processes are commonly associated with

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large-scale geodynamic phenomena, including continental collision, crustal reworking, and supercontinent assembly (D'Lemos et al., 1992; Ingram and Hutton, 1994; Leblanc et al., 1996; Brown and Solar, 1998; Pressley and Brown, 1999; Greiling and Verma, 2001). Consequently, the internal fabric preserved within granitic rocks provides critical insights into magma dynamics, deformation history, and regional tectonic evolution (Bouchez et al., 1990; Vernon et al., 2004). Despite their geological significance, most granitoids lack well-developed macroscopic planar and linear structures across the scale of an entire pluton or batholith. This limitation makes conventional field-based structural analysis insufficient for deciphering their internal fabric. Although microstructural studies can document solid-state deformation features, such as recrystallization and grain boundary migration, these features are not always uniformly developed or easily interpretable. Therefore, alternative approaches are required to quantify the internal fabric and understand the relationship between emplacement and deformation processes.

In this context, Anisotropy of Magnetic Susceptibility (AMS) has emerged as a powerful and widely used technique for investigating rock fabric. AMS is a specialized magneto-fabric method that illustrates the preferred orientation of magnetic minerals within rocks or unconsolidated sediments. The technique is non-destructive and applicable to nearly all rock types, as it does not require the presence of visible strain markers such as deformed fossils, lineation, or ooids (Tarling and Hrouda, 1993; Borradaile and Henry, 1997). A key advantage of AMS is its ability to detect subtle deformation even in rocks where no macroscopic fabric is evident. In rocks exhibiting well-defined tectonic fabrics, the principal magnetic directions often correspond closely with structural elements such as folds, faults, foliation, and lineation (Hrouda and Janák, 1976; Borradaile, 1988; Averbuch et al., 1992; Borradaile and Jackson, 2010; Robion et al., 2014). AMS data from granitoids demonstrate that magnetic fabrics are effective proxies for interpreting pluton kinematics, regional tectonic strain fields, and magma ascent/emplacement mechanisms in granitic bodies (Burton-Johnson et al., 2022; Knight et al., 2024; Gonçalves et al., 2025).

The detection of crystal orientation via magnetic properties was first demonstrated by Ising (1942), who observed anisotropic behaviour in sediments. Subsequently, Graham (1954) established that magnetic fabric reflects petrofabric, thereby validating the geological relevance of magnetic measurements. Balsley and Buddington (1960) further demonstrated that magnetic methods could surpass conventional microscopic techniques in detecting subtle fabrics. Today, AMS is recognised as an interdisciplinary tool that integrates mineral magnetism, structural geology, and petrology (Borradaile, 2001). AMS has proven particularly effective in granitoid studies, where it provides a quantitative description of the internal crystalline fabric. This allows for the interpretation of magma flow patterns, identification of emplacement mechanisms, and reconstruction of stress regimes during and after solidification. Additionally, AMS can detect post-emplacement deformation that may not be visible in the field, thereby offering a more comprehensive understanding of tectonic processes. As such, it serves as an indispensable tool for linking magmatic processes with regional tectonics.

The present study focuses on the Kalpetta granite, a prominent intrusive body within the Southern Granulite Terrain (SGT), located in the Nilgiri Block of southern India. The SGT represents a deeply exhumed segment of the Precambrian continental crust and preserves a complex history of tectonothermal events associated with the assembly of the Gondwana during the Pan-African Orogeny (Santosh et al., 2009; Collins et al., 2014). The Kalpetta granite, classified among the "Younger Granites" of Kerala, has been extensively studied for its geochronology, petrochemistry, and tectonic setting (Nair and Santosh, 1984; Santosh, 1989). However, its magnetic fabric characteristics and internal deformation patterns remain largely unexplored. This study aims to address this gap by applying AMS techniques to the Kalpetta granite. The primary objective is to generate the first comprehensive magnetic fabric dataset for this pluton, which can be used to infer magma emplacement processes, deformation history, and tectonic conditions. Particular emphasis is placed on understanding the relationship between the granite emplacement and regional structural features, including the Bavali-Moyar Shear Zone. The integration of AMS data with petrographic and structural analyses is expected to provide new insights into the origin, emplacement mechanism, and tectonic evolution of the Kalpetta granite, thereby contributing to a broader understanding of crustal processes within the Southern Granulite Terrain.

2. Geologic Setting

The Kalpetta granite, located within the southern segment of the Indian Shield, specifically in the Southern Granulite Terrain (SGT), is one of the most extensive exposures of deep continental crust worldwide (Janardhan, 1999; Yellappa and Rao, 2018). The SGT preserves a long and complex geological history ranging from the Paleoarchean to the Neoproterozoic (~3.5-0.55 Ga) and records multiple episodes of crustal growth, reworking, high-grade metamorphism, and magmatism (Santosh et al., 2009; Plavsa et al., 2012). It represents a classic example of exhumed lower crust, characterized by granulite-facies rocks and widespread tectonothermal overprinting associated with continental assembly. Tectonically, the SGT extends southward from the Dharwar Craton and is separated from it by the Fermor Line, which marks a transition from granite-greenstone terrains to high-grade granulitic rocks (Naqvi and Rogers, 1987; Fig. 1). The terrain comprises several crustal blocks that were amalgamated during successive tectonic events from the Neoarchean to the Neoproterozoic-Cambrian. These blocks are delineated by major crustal-scale shear zones and suture systems, reflecting a history of subduction, collision, and crustal accretion (Santosh et al., 2003, 2009, 2015; Plavsa et al., 2012; Collins et al., 2014; Praveen et al., 2014; Kröner et al., 2015).

The principal tectonic blocks within the SGT include the Coorg, Nilgiri, Salem, Madras, Madurai, Trivandrum, and Nagercoil blocks, each exhibiting distinct lithological assemblages, metamorphic grades, and tectono-thermal histories (Clark et al., 2009). Among these, the Nilgiri Block hosts the present study area and represents a granulite-grade lower-crustal segment characterized by high-temperature metamorphism and complex deformation. The Nilgiri Block is geographically defined as an uplifted crustal segment forming a triangular massif, with elevations reaching ~2500 m above mean sea level. It is bounded by two major tectonic discontinuities: the Moyar Shear Zone to the north and the Bhavani Shear Zone to the south. These shear zones are part of a broader network of crustal-scale deformation zones that played a significant role in accommodating tectonic strain and controlling magmatic emplacement within the region. The lithological assemblage of the Nilgiri Block is dominated by granulite-facies rocks, including charnockites, hornblende-biotite gneisses, pyroxene granulites, and associated migmatitic and granitoid units (Samuel et al., 2014; Santosh et al., 2015).

3. Study Area

The study area, located in the Kalpetta region of Wayanad district, is characterized by a diverse geological framework comprising the Peninsular Gneissic Complex, Migmatite Complex, Charnockite Group, and supracrustal sequences of the Wayanad Group (Fig. 2). These units represent varying metamorphic grades from amphibolite to granulite facies and occur as linear belts and massive bodies within the terrain. The Peninsular Gneissic Complex, consisting mainly of hornblende-biotite gneiss and granitic gneiss, occupies a significant portion of the region. At the same time, charnockites and pyroxene granulites form the high-grade metamorphic basement. Intrusive bodies such as granites, dolerites, and gabbros are emplaced within these older rocks, indicating multiple phases of magmatic activity (Nambiar, 1982).

Within this geological framework, the Kalpetta granite represents a prominent intrusive body and is classified among the "Younger Granites" of Kerala. These granites are interpreted to have formed during the late Neoproterozoic to early Palaeozoic, corresponding to the Pan-African Orogeny, a major tectonic event associated with the assembly of the Gondwana (Santosh et al., 2009; Nair and Santosh, 1984). The Pan-African event in southern India is marked by high-grade metamorphism, deformation, and widespread granitic magmatism, reflecting crustal thickening followed by extensional collapse.

Santosh and Masuda (1991) conducted extensive isotopic studies, revealing that the granites likely originated from a mixed source involving mantle-derived and crustal components. These findings were integral in understanding the petrogenesis of alkali granites in the region. The petrochemistry and petrogenesis of the Kalpetta granite have been examined by Kumar et al. (1998). Geochemical studies suggest that the Kalpetta granite is an alkaline to calc-alkaline felsic intrusive body derived from differentiated crustal melts, reflecting significant fractional crystallization during magma evolution (Kumar et al., 1998).

Geochronological studies based on K-Ar dating indicate that the Kalpetta granite cooled between 502 and 512 Ma, suggesting emplacement during

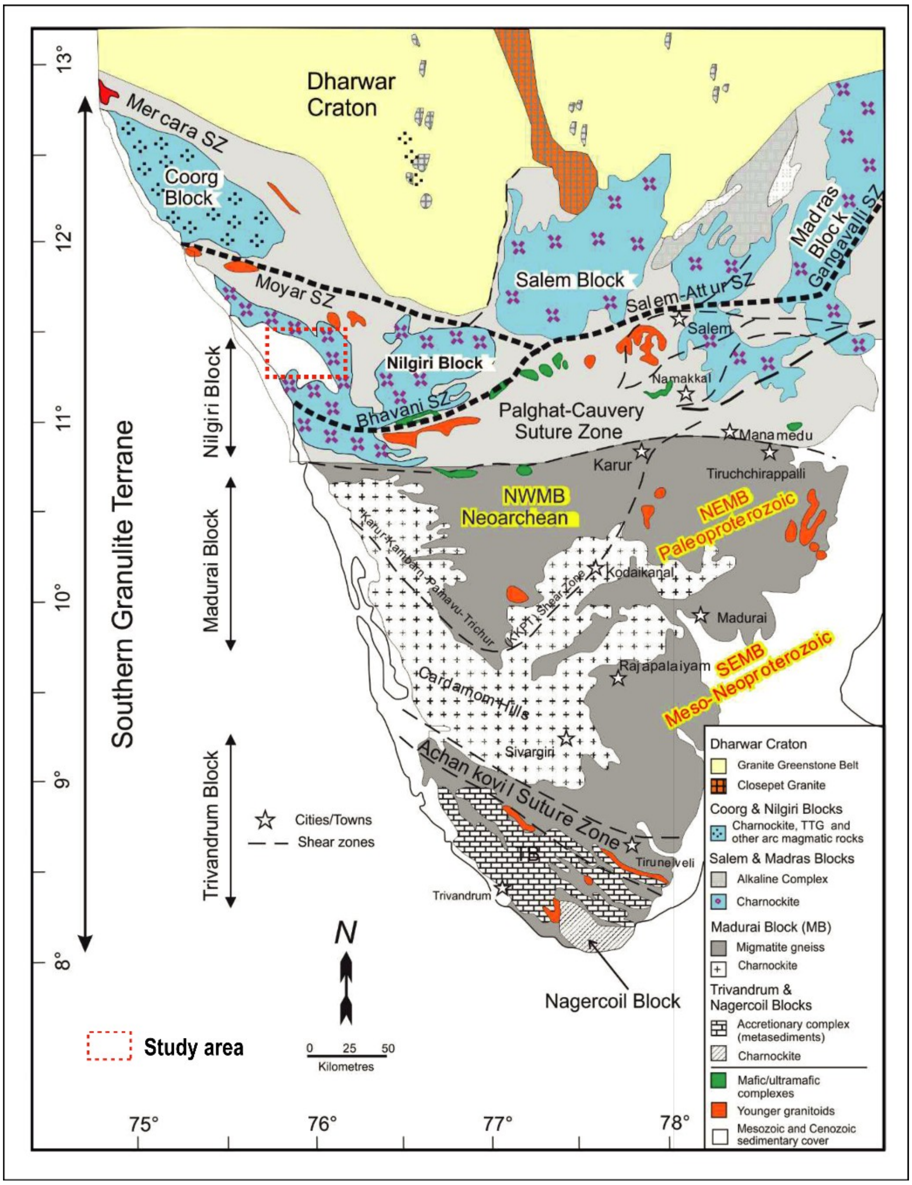

Fig. 1. Geological and tectonic framework of the Southern Granulite Terrain, with an inset indicating the location of the study area (modified after Santosh et al., 2009; Collins et al., 2007).

the waning stages of the Pan-African orogeny (Nair et al., 1985; Shamil et al., 2024). The granite lies immediately north of the Palghat-Cauvery Suture Zone, a fundamental tectonic boundary that separates Archean granulite terrains from Proterozoic domains (Collins et al., 2007; Santosh et al., 2003). This suture zone represents a major zone of crustal convergence and plays a critical role in understanding the tectonic evolution of southern India.

The Kalpetta granite intrudes high-grade metamorphic country rocks, including hornblende-biotite gneiss, charnockite, and pyroxene granulite, indicating emplacement at deep crustal levels. Field relationships and petrographic evidence suggest that the granite experienced magmatic crystallization followed by high-temperature solid-state deformation, with limited evidence for low-temperature deformation, supporting a post-tectonic to late-tectonic emplacement history. Structurally, the emplacement of the Kalpetta granite appears to be closely controlled by regional lineaments and shear zones. Major structural features, such as the Bavali lineament and the Moyar-Bhavani shear system, likely served as conduits for magma ascent. These crustal-scale discontinuities provided pathways for the emplacement of granitic magmas during a tectonically active regime. The spatial relationship between the granite and these structural features highlights the im-

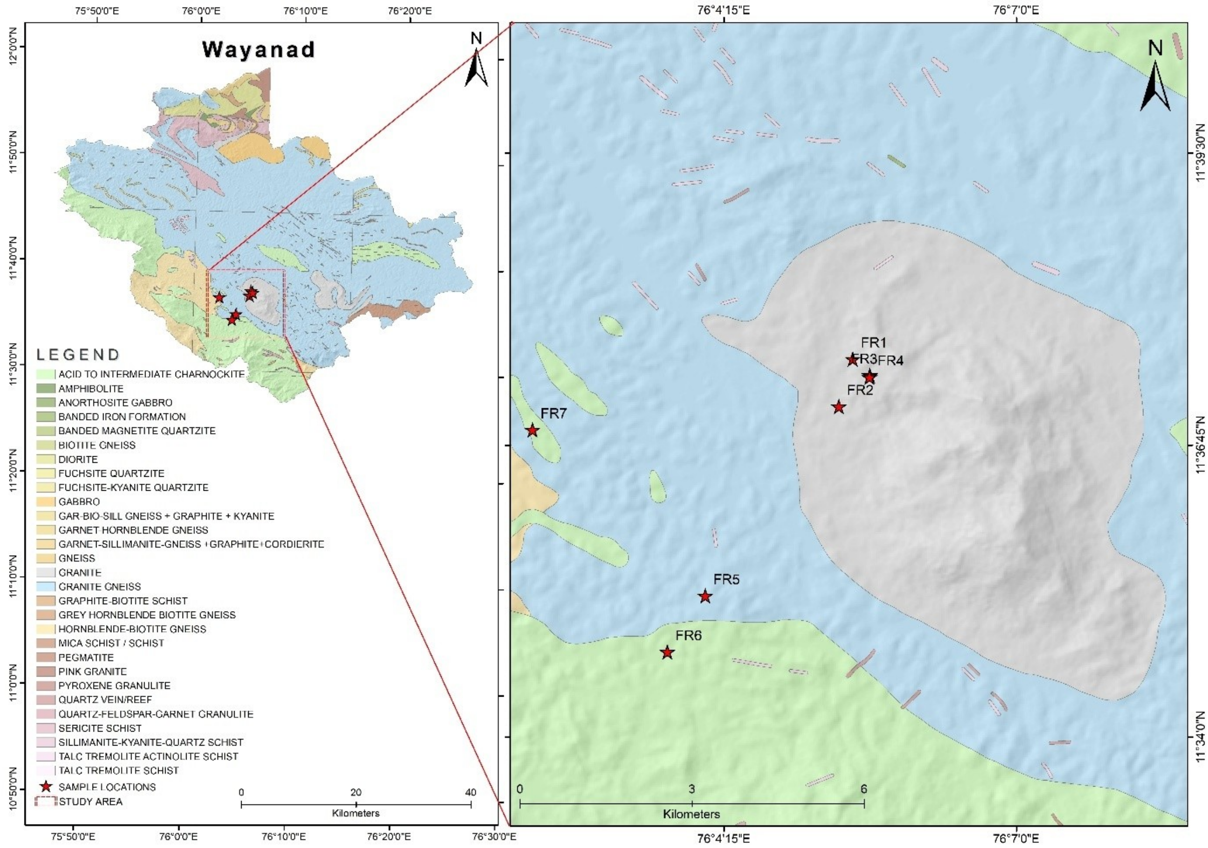

Fig. 2. Geological map of the study area showing the spatial distribution of lithological units and locations of sampling points (Map Source: Bhukosh, Geological Survey of India).

portance of tectonic control in the emplacement and evolution of granitoid bodies within the SGT.

As a whole, the geological setting of the Kalpetta granite reflects a complex interplay of high-grade metamorphism, magmatism, and deformation associated with the Pan-African tectonic cycle. The integration of regional tectonic architecture with local lithological and structural variations is essential for understanding the emplacement mechanisms, deformation history, and magnetic fabric development of the granite. This framework forms the basis for interpreting the AMS results and reconstructing the tectonic evolution of the study area.

4. Methodology

The investigation of the Kalpetta granite was conducted using a multidisciplinary approach that integrated detailed fieldwork, laboratory-based magnetic studies, and petrographic analysis (Fig. 3). This combined methodology was adopted to comprehensively understand the emplacement history, internal fabric, and deformation characteristics of the granite body, as well as its relationship with regional tectonic structures.

4.1. Field Investigations and Sampling Strategy

Field investigations were carried out in the Kalpetta region of Wayanad district using Survey of India toposheet No. 58A/02 (1:50,000 scale) as the base map. Detailed geological mapping was conducted at key locations, including Mayiladippara, Maniyamkode, Chundale, and Vengappally. Systematic observations were made to document lithological variations and structural features, including intrusive contacts, faults, microfaults, joints, and foliations. Structural measurements, including strike and dip, were recorded using a Brunton compass. For the AMS study, oriented core sampling was carried out using an onsite drilling technique to preserve the insitu fabric orientation. Cylindrical core samples (2.5 cm diameter) were extracted using a portable hand drill (Stihl MS-261) with a continuous water supply to minimize thermal effects. Each core was oriented with respect to geographic north before extraction. A total of seven core samples were collected from three representative sites for magnetic analysis (Table 1).

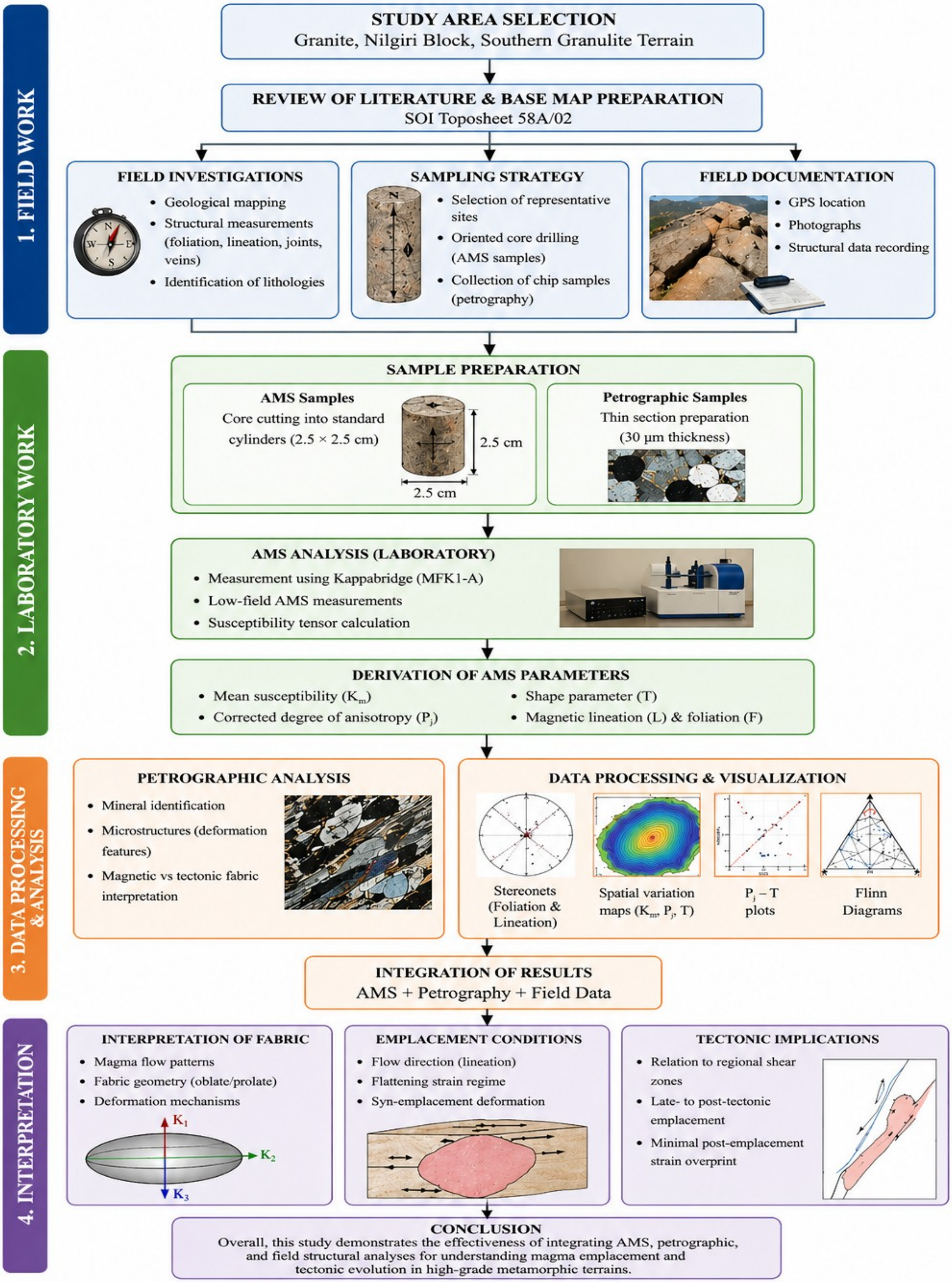

Fig. 3. Flowchart illustrating the methodology adopted in the study, including field investigations, sampling, laboratory analyses, and data interpretation.

Table 1. Details of sampling locations, geographic coordinates, and lithology of the Kalpetta granite and associated rocks in the study area.

Sl. No.	Location name	Sample name	Latitude	Longitude	Rock type
1	Mayiladippara Kalpetta	FR1	11°37'33.72" N	76°5'27.60" E	Granite
2	Mayiladippara Kalpetta	FR2	11°37'6.84" N	76°5'19.80" E	Granite
3	Mayiladippara Kalpetta	FR3	11°37'24.42" N	76°5'37.27" E	Granite
4	Mayiladippara Kalpetta	FR4	11°37'23.44" N	76°5'37.10" E	Granite
5	Maniyamkode Kalpetta	FR5	11°35'19.92" N	76°4'4.44" E	Pyroxene Granulite
6	Chundale	FR6	11°34'48.18" N	76°3'43.02" E	Hornblende Biotite Gneiss
7	Vengappally	FR7	11°36'53.70" N	76°2'26.88" E	Hornblende Biotite Gneiss and Charnockite

4.2. AMS Laboratory Techniques

4.2.1. Sample Preparation

In the laboratory, the oriented cores were cut into standard cylindrical specimens measuring 2.5 cm in diameter and 2.5 cm in height using a Buehler Isomet 1000 precision cutter. Care was taken to ensure parallel end surfaces to achieve accurate magnetic measurements.

4.2.2. Instrumentation and Measurement Procedure

AMS measurements were performed using an AGICO MFK1-A Kappabridge. Before measurements, the instrument was stabilized for approximately 15 minutes, followed by a zero calibration to eliminate background magnetic noise and a standard calibration to ensure accuracy. Magnetic susceptibility was measured in 15 different orientations following Jelinek's (1981) rotational scheme. Data acquisition and control were carried out using Safyr6 software, while Anisoft42 software was used for data processing and graphical representation.

4.2.3. Derived Magnetic Parameters

Magnetic susceptibility was treated as a second-order tensor and represented by a triaxial ellipsoid defined by three principal axes: maximum (k_1), intermediate (k_2), and minimum (k_3), where k_1 k_2 k_3 (Jelinek, 1981). From these, several parameters were derived, including mean susceptibility (K), degree of anisotropy (P or P), and shape parameter (T), which ranges from prolate (−1) to oblate (+1). Magnetic lineation (L) and foliation (F) were also calculated to quantify the linear and planar components of the magnetic fabric.

4.3. Petrographic Methodology

Petrographic analysis was carried out to distinguish between magmatic and tectonic fabrics. Representative samples of the Kalpetta granite and associated lithologies, including hornblende-biotite gneiss, charnockite, and pyroxene granulite, were prepared at the National Centre for Earth Science Studies (NCESS). Sample preparation involved sectioning using a diamond wafering saw (Isomet 1000), followed by vacuum impregnation with low-viscosity epoxy resin (EPO-THIN) to stabilize the samples. Grinding and lapping were performed using silicon carbide abrasives to achieve a smooth surface. The samples were then mounted on glass slides and ground to a standard thickness of 30 m. A total of seven granite thin sections, along with several sections of associated rocks, were examined under an Olympus Petrological Microscope and a Leica DM 2700P polarizing microscope. Mineral assemblages, textures, grain boundaries, and deformation features such as undulose extinction, recrystallization, and preferred mineral alignment were analyzed to infer deformation conditions.

4.4. Statistical and Graphical Analysis

The AMS and structural data were subjected to statistical and graphical analyses to interpret the magnetic fabric and deformation patterns. P-T and Jelinek plots were used to evaluate the intensity and shape of anisotropy. Flinn diagrams were employed to classify fabric types based on strain geometry (Flinn, 1965; Borradaile, 2001). Lower hemisphere equal-area stereographic projections (stereonets) were used to represent the spatial orientation of magnetic foliations and lineations. Additionally, rose diagrams were constructed to illustrate the frequency distribution and dominant orientations of structural features such as joints and magnetic axes. These analyses provided insights into magma flow patterns, deformation regimes, and tectonic controls on granite emplacement.

5. Field Relationships

The Kalpetta granite forms a prominent intrusive body within the Nilgiri Block of the Southern Granulite Terrain, covering an approximate area of

44 km^2. Field investigations reveal that the pluton is oval in shape and exhibits sharp, well-defined contacts with the surrounding country rocks, which are predominantly hornblende-biotite gneiss. These intrusive contacts are particularly evident along the margins of the pluton, where the granite clearly truncates the pre-existing metamorphic fabric of the host gneisses. The cross-cutting relationship indicates that the granite postdates the regional deformation and metamorphism, thereby suggesting a post-tectonic emplacement history.

Detailed field observations at Mayiladippara, which provide excellent exposures along road cuttings and hill slopes, indicate that the granite is medium- to coarse-grained and grey in colour (Fig. 4a). Hand specimen studies indicate a typical mineral assemblage consisting of quartz, plagioclase feldspar, K-feldspar, and biotite. Textural variations are evident across the study area, reflecting differences in cooling conditions and emplacement environments. Marginal zones locally exhibit finer-grained textures, suggesting relatively rapid cooling near the contact with country rocks. In contrast, the interior portions display coarse-grained, massive bluish-grey varieties with conspicuous feldspar phenocrysts, indicative of slower crystallization within the plutonic core.

A notable feature of the Kalpetta granite is the presence of multiple generations of intrusive veins, which traverse the pluton extensively and record a complex history of magmatic differentiation and late-stage processes. Pegmatite veins are widespread and represent an early phase of residual melt intrusion. These veins are typically composed of coarse quartz, orthoclase, and biotite (Fig. 4b, c), and are interpreted to have formed from volatile-rich late-stage magmatic fluids. Their irregular geometry and variable thickness reflect localized emplacement conditions. Many of these pegmatite veins exhibit deformation features such as fracturing and faulting, indicating that the pluton experienced tectonic stresses during its cooling and solidification.

In contrast, aplite veins represent a later intrusive phase and are commonly observed cutting across the earlier-formed pegmatites. These veins are fine-grained and composed predominantly of quartz and feldspar, reflecting crystallization from more evolved, silica-rich residual melts. The cross-cutting relationship between aplite and pegmatite veins (Fig. 4d) provides clear field evidence for a multiphase intrusive history. In several locations, aplite veins infill fractures within pegmatites, suggesting that brittle deformation preceded or accompanied the emplacement of these late-stage melts.

The occurrence of xenoliths within the Kalpetta granite further substantiates its intrusive nature. Near the margins of the pluton, enclaves of amphibolite and hornblende-biotite gneiss are commonly observed. These xenoliths represent fragments of the country rock that were incorporated into the magma during its ascent and emplacement. Their presence indicates incomplete assimilation of the host rocks and provides valuable information regarding magma-country rock interaction processes. The sharp boundaries between xenoliths and the granitic host suggest limited chemical equilibration, reinforcing the interpretation of relatively rapid emplacement.

The structural relationship between the Kalpetta granite and the surrounding country rocks provides important insights into the tectonic evolution of the region. While the host rocks, particularly the hornblende-biotite gneiss (Fig. 4e) exposed at locations such as Vengappally quarry, exhibit pronounced banding and well-developed gneissosity indicative of intense deformation under high-grade metamorphic conditions, localized zones of mylonitic fabric (Fig. 4f) are also observed within the country rocks, particularly in proximity to regional shear zones. These mylonitic rocks record intense ductile shearing under lower-temperature, high-strain conditions. In contrast, the granite itself shows minimal evidence of such pervasive deformation. The absence of significant low-temperature solid-state deformation features within the granite suggests that its emplacement occurred after the main phase of regional metamorphism and tectonic deformation.

6. Petrography

Petrographic analysis of the Kalpetta granite and its associated lithologies provides critical insights into the crystallization history, deformation mechanisms, and metamorphic evolution of the western Nilgiri Block within the Southern Granulite Terrain.

6.1. Petrography of Kalpetta Granite

The Kalpetta granite is a holocrystalline, phaneritic rock characterised by a well-developed interlocking granular texture, with grains typically exceeding 0.5 mm. The rock exhibits a mineral assemblage dominated by quartz, alkali feldspar (orthoclase and

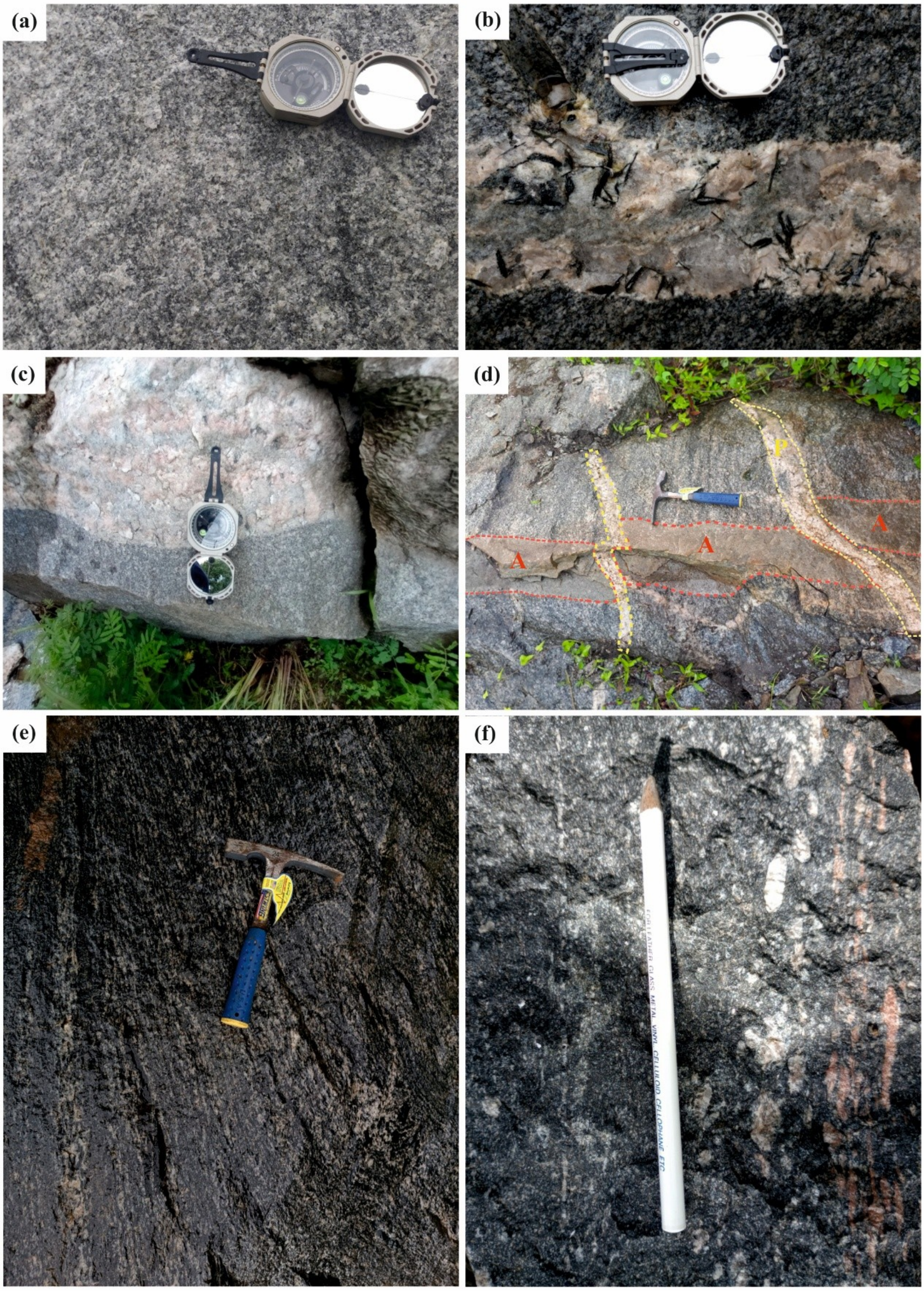

Fig. 4. **(a)** Field view of typical Kalpetta granite showing medium- to coarse-grained texture, **(b)** Pegmatite vein intruding the granite at Mayiladippara, **(c)** Boulder exhibiting a prominent pegmatitic contact within the granitic host, **(d)** Aplite and pegmatite veins cutting across the granite body at varying orientations, indicating multiphase intrusion, **(e)** Exposure of hornblende-biotite gneiss in a quarry section, showing well-developed foliation, **(f)** Mylonitic rock associated with a shear zone near Pulpally, displaying intense deformation and grain-size reduction.

microcline), and plagioclase, with biotite and hornblende constituting the principal mafic phases. Accessory minerals include magnetite, zircon, apatite, and sphene (titanite), which play important roles in both petrogenetic interpretation and magnetic fabric analysis (Fig. 5a).

Quartz occurs predominantly as anhedral interstitial grains between feldspar crystals. Grain sizes vary considerably, ranging from coarse grains (up to ~551 m × 121 m) to finer interstitial forms. The quartz grains commonly display undulose extinction, indicative of intracrystalline deformation under stress (Fig. 5a). Additionally, the presence of sutured grain boundaries suggests Grain Boundary Migration (GBM) during dynamic recrystallization at elevated temperatures (Fig. 5c). A particularly diagnostic microstructural feature observed in several samples is chessboard extinction, characterised by the formation of subgrains with boundaries parallel to both the prism and basal planes (Fig. 5d). This feature is widely regarded as evidence of high-temperature plastic deformation under near-solidus conditions, suggesting that the granite underwent deformation during the late stages of crystallisation.

Alkali feldspars, including orthoclase, microcline, and perthitic intergrowths, occur both as early-formed phenocrysts and as interstitial xenomorphic grains. Microcline is identified by its characteristic cross-hatched (tartan) twinning (Fig. 5b), which may result from the inversion of orthoclase during cooling or from solid-state deformation processes. The presence of perthitic textures (Fig. 5e) indicates exsolution phenomena during slow cooling, reflecting subsolidus re-equilibration. These features collectively suggest a prolonged cooling history with significant thermal and chemical evolution.

Plagioclase feldspar occurs as subhedral to euhedral laths with compositions ranging from albite to anorthite. The crystals exhibit well-developed twinning patterns, including polysynthetic (albite) twinning and, in some cases, mechanical twins. Under conditions of high-temperature deformation, the twin lamellae show bending, tapering, and local distortion (Fig. 5f), particularly near grain boundaries. These features are indicative of crystal-plastic deformation and suggest that the rock underwent deformation at elevated temperatures.

Biotite occurs in multiple textural forms, including elongated flakes aligned along preferred orientations, bladed interstitial grains, and equant fragmented grains. The alignment of biotite flakes contributes to the development of a weak foliation within the granite. Deformation features (Fig. 5g) such as kinking, bending, and fracturing of biotite grains are commonly observed, indicating the influence of mechanical stress during or shortly after crystallization. Hornblende, though less abundant, occurs as subhedral grains and contributes to the mafic mineral assemblage.

The accessory mineral suite is dominated by magnetite, which serves as the principal carrier of magnetic susceptibility and is therefore critical for AMS studies. Zircon occurs as euhedral, often elongated crystals, frequently displaying zoning that reflects magmatic growth (Fig. 5h). Apatite and sphene (titanite) are also present as minor phases, contributing to the overall mineralogical complexity of the granite.

6.2. Petrography of Associated Rocks

The country rocks surrounding the Kalpetta granite exhibit a more complex and intense deformational history, as evidenced by their varied microstructures and mineral assemblages. These rocks record a transition from high-temperature metamorphic conditions to lower-temperature, high-strain deformation regimes, reflecting prolonged tectonic activity in the region.

Hornblende-biotite gneiss is characterized by a medium- to coarse-grained texture with a well-developed foliation defined by the parallel alignment of hornblende and biotite. Feldspar grains within the gneiss commonly exhibit marginal granulation and recrystallization textures, while hornblende may display sieve textures (Fig. 6a, b) indicative of partial resorption or recrystallization under metamorphic conditions. These features point to high-grade regional metamorphism accompanied by significant ductile deformation.

Charnockites within the study area exhibit a granoblastic, inequigranular texture composed predominantly of quartz, feldspar, and orthopyroxene (hypersthene). The orthopyroxene displays characteristic pleochroism, ranging from pink to green, and occurs as subhedral grains. Grain boundaries are often curved or irregular (Fig. 6b), suggesting deformation at high temperatures. The overall texture reflects equilibration under granulite-facies conditions followed by tectonic modification.

Pyroxene granulites are melanocratic and display a granoblastic texture composed mainly of clinopy-

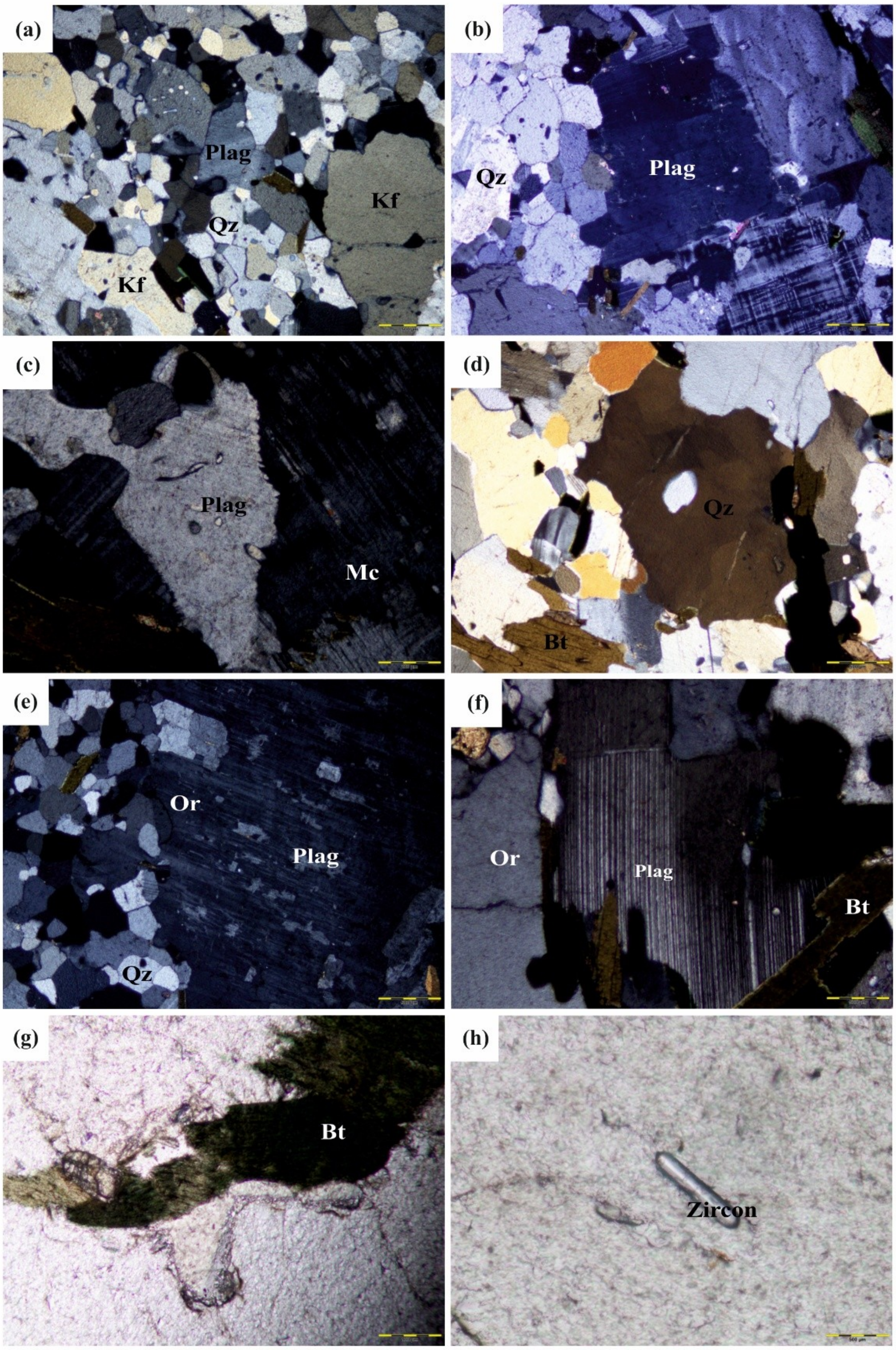

Fig. 5. Petrographic images of Kalpetta Granite **(a)** Photomicrograph showing interlocking texture of quartz and feldspar in the granite, **(b)** Undulose extinction in plagioclase along with cross-hatched (tartan) twinning in microcline, **(c)** Sutured grain boundary between plagioclase and K-feldspar, indicating dynamic recrystallization, **(d)** Chessboard extinction in quartz, indicative of high-temperature solid-state deformation, **(e)** Perthitic exsolution textures observed near the aplite-granite contact, **(f)** Bending of polysynthetic twin lamellae in feldspar, reflecting crystal-plastic deformation, **(g)** Kink bands developed in biotite grains due to deformation, **(h)** Occurrence of accessory zircon within the granitic matrix.

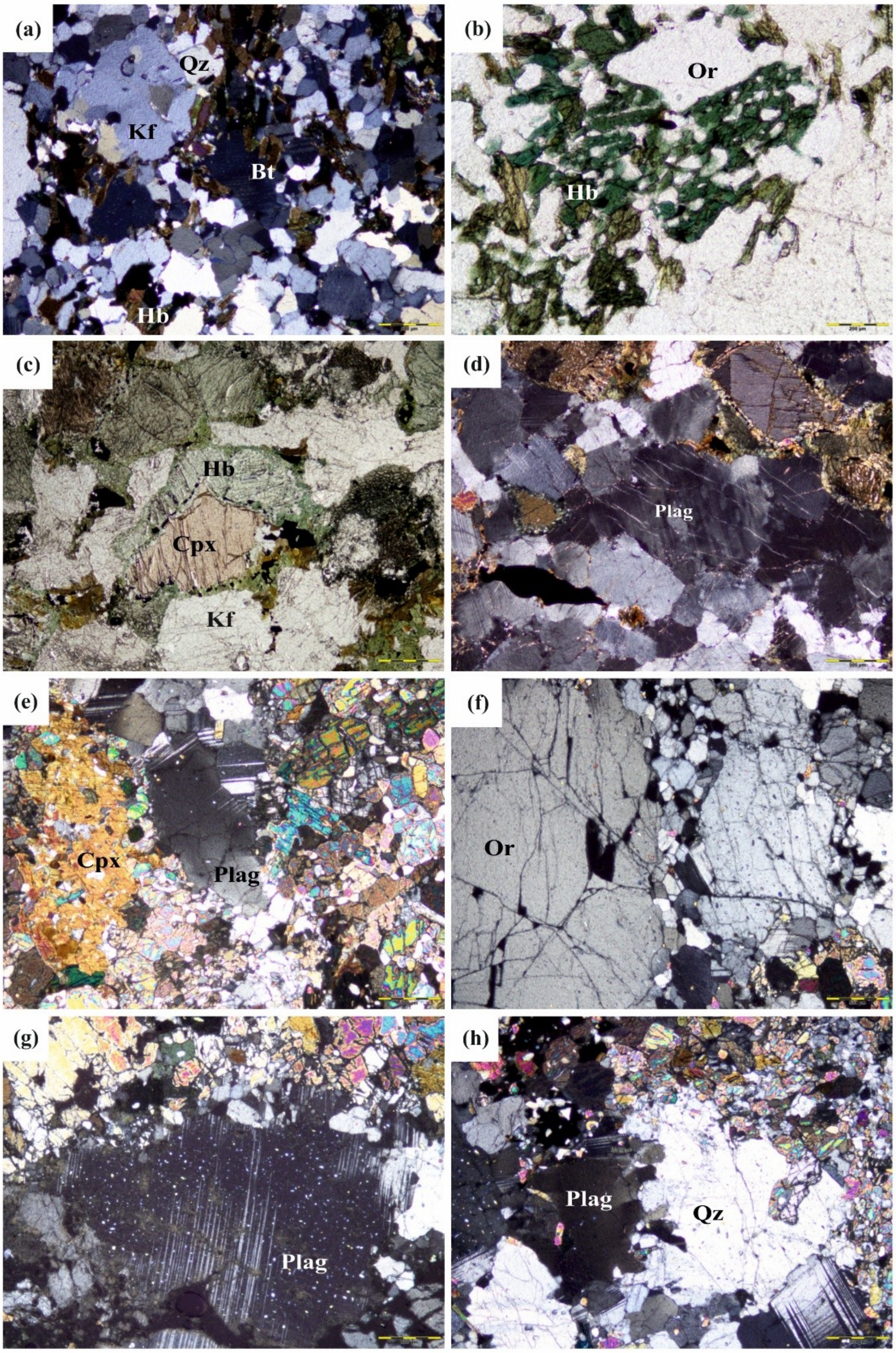

Fig. 6. Petrographic images of associated rocks of Kalpetta Granite **(a)** General mineral assemblage of hornblende-biotite gneiss showing foliated texture, **(b)** Sieve texture in hornblende indicative of metamorphic recrystallization, **(c)** Granoblastic texture of charnockite under plane-polarized light, **(d)** Curved grain boundaries in charnockite reflecting deformation under stress, **(e)** General assemblage of pyroxene granulite showing melanocratic composition, **(f)** Subgrain formation and recrystallization features indicating dynamic deformation, **(g)** Bending of twin lamellae and sericitization in plagioclase within pyroxene granulite, **(h)** Grain boundary migration between quartz and plagioclase, indicating high-temperature recrystallization.

roxene, orthopyroxene, and plagioclase. Evidence of deformation includes fractured pyroxene grains and deformation twins within large plagioclase crystals. In addition, bending of twin lamellae and sericitization in plagioclase (Fig. 6c, g), along with grain boundary migration between quartz and plagioclase (Fig. 6d, h), further reflect deformation and recrystallization under varying metamorphic conditions.

6.3. Petrographic Implications

A comparison between the Kalpetta granite and its host rocks reveals a clear contrast in deformation history. While the surrounding gneisses and granulites exhibit pronounced high-strain features, including mylonitic textures and low-temperature deformation structures, the granite lacks such pervasive deformation. Instead, it preserves evidence of magmatic flow and high-temperature plastic deformation, as indicated by features such as chessboard extinction in quartz and bent twin lamellae in feldspars.

This petrographic disparity strongly supports the interpretation that the Kalpetta granite was emplaced during a late- to post-tectonic phase, after the peak of regional metamorphism and deformation. The granite appears to have crystallized under high-temperature conditions and subsequently underwent limited deformation before cooling and stabilization. These observations are consistent with the regional tectonic framework of the Pan-African Orogeny, during which late-stage granitic magmatism followed major crustal deformation events.

7. Results of AMS study

The analysis of Anisotropy of Magnetic Susceptibility (AMS) in the Kalpetta granite provides quantitative constraints on the internal fabric, mineral alignment, and deformation history of the pluton. AMS is a robust technique for characterizing rock fabric, particularly in granitoids where macroscopic structural features are often poorly developed (Tarling and Hrouda, 1993; Borradaile and Henry, 1997). The magnetic fabric is represented by a triaxial susceptibility ellipsoid defined by three principal axes (k_1 k_2 k_3), corresponding respectively to magnetic lineation, intermediate orientation, and magnetic foliation (Jelinek, 1981). The derived scalar parameters:mean magnetic susceptibility (K), corrected degree of anisotropy (P), and shape parameter (T)-collectively provide insights into the intensity and geometry of deformation as well as the processes governing magma emplacement (Table 2).

7.1. Magnetic Susceptibility and Degree of Anisotropy

The bulk magnetic susceptibility (K) of the Kalpetta granite samples ranges from 1340 × 10 SI to 3200 × 10 SI (Fig. 7a). The relatively high bulk susceptibility values, together with petrographic observation of magnetite, suggest that ferrimagnetic phases, particularly magnetite, are likely to be the dominant contributors to the AMS signal. In granitoids, susceptibility values exceeding ~1000 × 10 SI are generally interpreted to reflect a dominant contribution from ferromagnetic phases, whereas lower values typically indicate paramagnetic control by minerals such as biotite and hornblende (Ishihara, 1977; Borradaile, 2001). The presence of magnetite as an accessory phase in petrographic observations further supports this interpretation, suggesting that the AMS fabric primarily reflects the alignment of magnetite grains during magma flow and crystallization.

The corrected degree of anisotropy (P) for the analyzed samples ranges between 1.20 and 1.29, indicating a moderately to strongly developed magnetic fabric (Fig. 7b). Such values are significantly higher than those expected for undeformed or weakly deformed granites, where P values typically remain close to unity (Jelinek, 1981; Hrouda, 1982). The observed range therefore, suggests a well-developed internal fabric, likely associated with magmatic flow processes. The consistency of these values across the study area implies a relatively uniform deformation regime during emplacement.

Spatial variations in P values reveal that the highest degrees of anisotropy are concentrated in the southern part of the study area. This spatial pattern closely matches field observations of more pronounced foliation and biotite-flake alignment, suggesting that deformation intensity was not uniform across the pluton. Instead, it appears to have been locally enhanced, possibly due to variations in magma viscosity, cooling rates, or proximity to structural controls such as shear zones.

7.2. Orientation of Magnetic Fabric

The orientation of the magnetic fabric in the Kalpetta granite is defined by the spatial distribution of the principal susceptibility axes, derived from lower-hemisphere equal-area stereographic projections. The magnetic foliation, represented by the plane containing K_1 and K_2 axes, exhibits dominant

Table 2. Summary of Anisotropy of Magnetic Susceptibility (AMS) results, including mean magnetic susceptibility (K), principal susceptibility axes (K_1, K_2, K_3), corrected degree of anisotropy (P), shape parameter (T), and derived magnetic fabric parameters for the Kalpetta granite samples.

ID	Orientation	K_m $(E)^{-6}$	L	F	P	P_j	T	U	K_{max} Dec	K_{max} Inc	K_{int} Dec	K_{int} Inc	K_{min} Dec	K_{min} Inc
FR1	335/17	2050	1.03	1.14	1.18	1.20	0.61	0.59	119.59	23.67	89.70	20.42	247.44	56.30
FR2	338/18	3200	1.07	1.19	1.27	1.29	0.40	0.36	122.57	23.25	135.33	49.88	269.51	27.02
FR3	355/44	1340	1.07	1.14	1.22	1.23	0.29	0.25	106.62	16.60	199.69	10.33	205.12	69.23

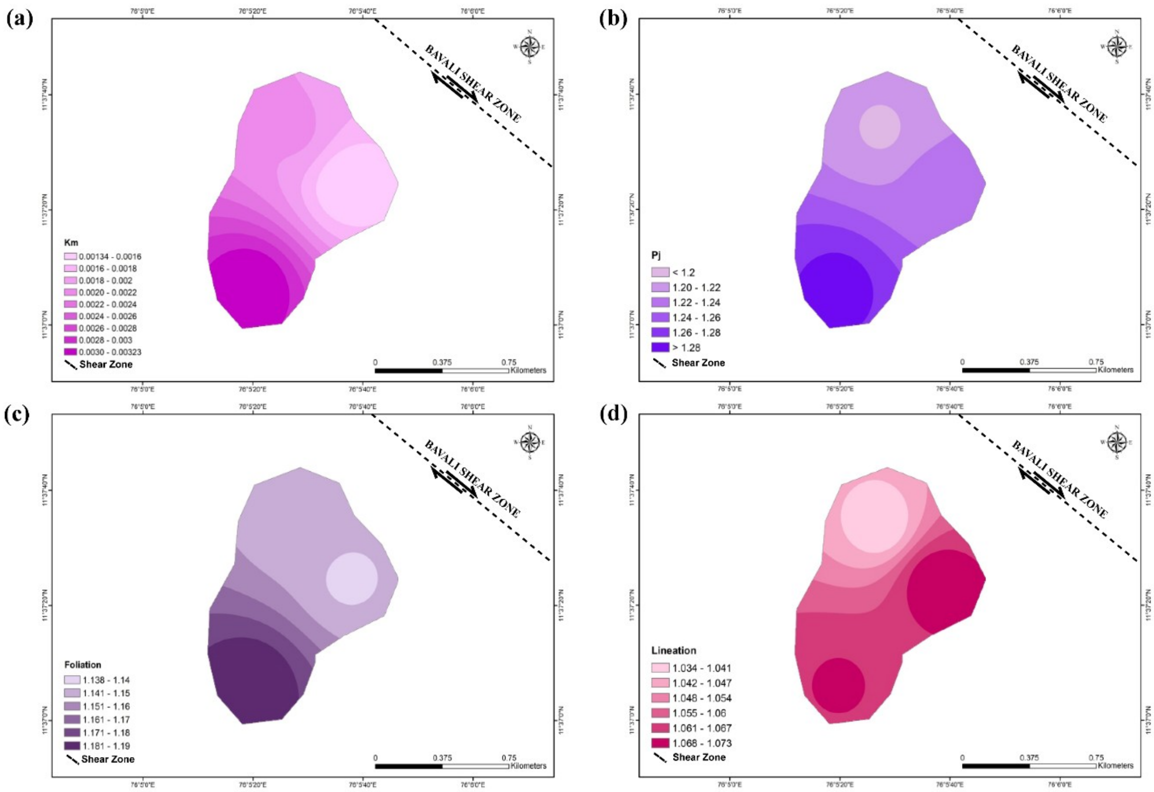

Fig. 7. **(a)** Spatial variation of mean magnetic susceptibility (K), **(b)** Spatial variation of corrected degree of anisotropy (P), **(c)** Spatial distribution of magnetic foliation, **(d)** Spatial distribution of magnetic lineation.

strike orientations of approximately N30°, N357°, and N350°, indicating a general NNW-SSE to NNE-SSW trend across the study area (Fig. 7c; Fig. 8a).

Magnetic lineation, defined by the maximum susceptibility axis (K_1), shows a consistent NNE-SSW orientation (Fig. 7d; Fig. 8b). This uniformity suggests a coherent internal alignment of magnetic minerals, reflecting a stable and directed magma flow regime during emplacement. The clustering of lineation directions further indicates limited post-emplacement reorientation, preserving the primary fabric signature. Notably, the magnetic fabric orientation is oblique to the regional Bavali-Moyar Shear Zone, a major tectonic feature within the Nilgiri Block. This obliquity implies that the development of the magnetic fabric was not directly controlled by the final stages of regional shear deformation. Instead, it likely records primary magmatic flow patterns established during emplacement and early crystallization.

The close correspondence between magnetic foliation and field-observed biotite foliation further supports this interpretation. The alignment of biotite flakes observed in hand specimens and thin sections is consistent with the orientation of the AMS fabric, indicating that both magnetic and mineral fabrics were formed under similar conditions. This relationship suggests that the AMS fabric represents a primary magmatic fabric, modified to a limited extent by high-temperature deformation during the last stages of crystallization (Kruhl, 1996; Vollbrecht et al., 1997; Sahamieh, 2021).

7.3. Shape of the Magnetic Fabric

The shape parameter (T), which describes the geometry of the susceptibility ellipsoid, varies from 0.29 to 0.61 for the Kalpetta granite samples. All values

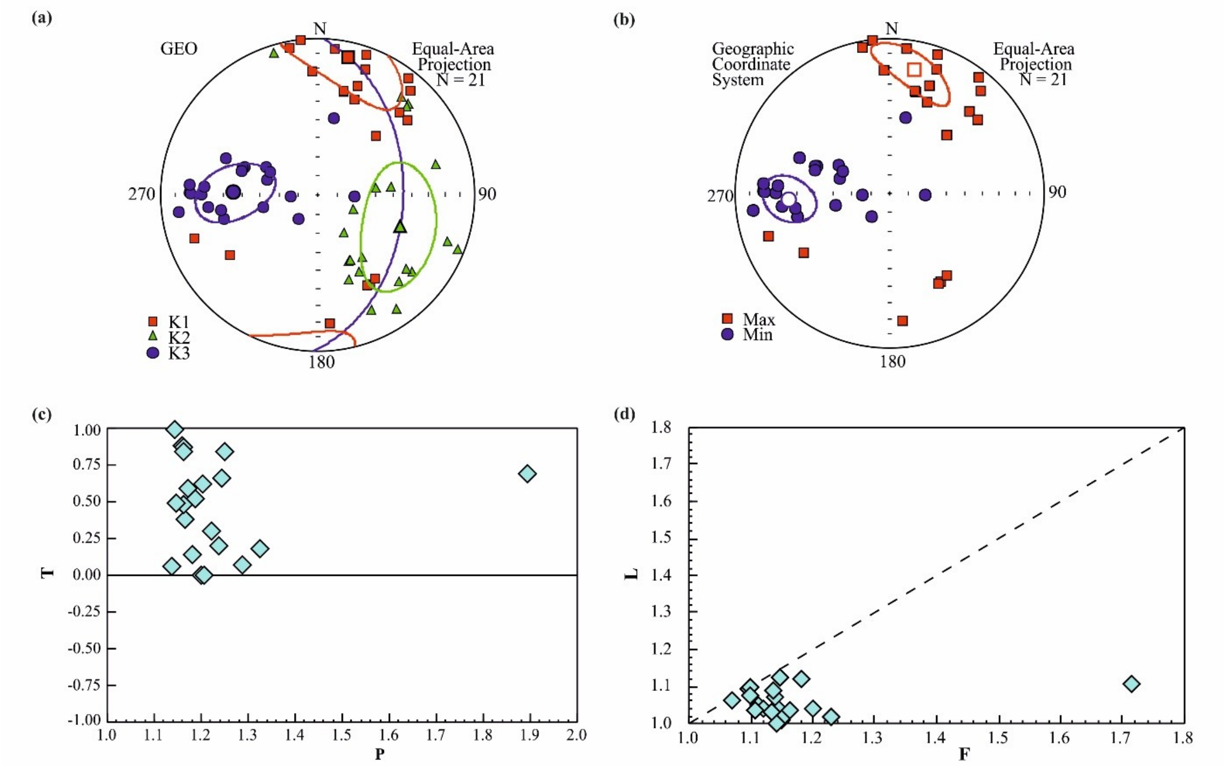

Fig. 8. **(a)** Lower hemisphere equal-area projection of magnetic foliation (K_1-K_2 plane), **(b)** Lower hemisphere equal-area projection of magnetic lineation (K_1 axis), **(c)** P -T plot illustrating the relationship between anisotropy and shape of the susceptibility ellipsoid, **(d)** magnetic lineation–foliation (L–F) plot/Flinn-type AMS diagram showing dominance of planar magnetic fabric.

are positive, indicating that the magnetic fabric is dominantly oblate. Oblate ellipsoids are characterized by two nearly equal principal axes ($K_1 \approx K_2$) and a shorter minimum axis (K_3), producing a flattened, disk-like geometry. This type of fabric is typically associated with planar structures such as foliations developed under flattening strain conditions (Jelinek, 1981; Borradaile and Henry, 1997).

The predominance of oblate fabrics suggests that deformation within the Kalpetta granite was largely controlled by flattening processes, such as magmatic flow, compaction, or syn-emplacement deformation under compressive stress regimes. Although the degree of anisotropy (P = 1.20-1.29) indicates a well-developed fabric, the moderate range of T values implies that the ellipsoids are not perfectly planar but exhibit slight triaxiality.

The relationship between anisotropy and shape is further illustrated in the P-T plot (Fig. 8c), which confirms the dominance of oblate fabrics across the study area. In addition, the magnetic lineation–foliation (L–F) plot, or Flinn-type AMS fabric diagram, shows that most samples plot within the foliation-dominated field, while a few samples lie near the triaxial boundary, indicating minor variations in fabric symmetry. These results collectively suggest that the magnetic fabric of the Kalpetta granite is primarily governed by planar alignment of minerals, consistent with magmatic flow-induced foliation rather than strong linear stretching.

7.4. Implications for Emplacement and Deformation

The combined AMS results indicate that the Kalpetta granite preserves a well-developed, magnetite-controlled magnetic fabric characterized by moderate to strong anisotropy and predominantly oblate geometry. The orientation of magnetic foliations and lineations suggests that the pluton records a coherent magmatic flow pattern, likely influenced by regional structural features but not strictly controlled by them.

The absence of strongly prolate fabrics and the dominance of oblate ellipsoids imply that flattening processes, rather than simple shear or unidirectional stretching, played a major role in fabric development. This is consistent with emplacement under a compressive or transpressional regime, where magma flow and deformation occur simultaneously (Bouchez, 1997; Borradaile, 2001). Furthermore, the oblique relationship between the AMS fabric and the regional shear zone, combined with petrographic evidence of high-temperature deformation and the lack of pervasive low-temperature strain features, supports a late- to post-tectonic emplacement model. The granite appears to have been emplaced during the waning stages of regional tectonic activity, recording magmatic flow and early deformation, but remaining largely unaffected by subsequent tectonic overprinting.

8. Discussion

The integrated analysis of petrographic observations and Anisotropy of Magnetic Susceptibility (AMS) data provides a coherent framework for understanding the emplacement history and deformational evolution of the Kalpetta granite within the Southern Granulite Terrain. The combined datasets indicate that the granite preserves evidence of magmatic crystallization accompanied by high-temperature solid-state deformation, but lacks significant low-temperature tectonic overprinting. This distinction is critical for constraining the timing of emplacement relative to regional deformation events.

Petrographic evidence, particularly the presence of chessboard extinction in quartz, sutured grain boundaries, and undulose extinction, indicates deformation under high-temperature conditions close to the solidus. These microstructures are widely interpreted as indicators of crystal-plastic deformation during the last stages of magma crystallization, when the rock transitions from a partially molten to a fully solid state (Hirth and Tullis, 1992; Passchier and Trouw, 2005). The deformation features observed in feldspars, including bent and tapered twin lamellae, further support the interpretation of deformation under elevated temperatures. Such microstructures suggest that the granite experienced internal strain during emplacement and cooling, likely associated with magmatic flow and syn-emplacement stress conditions.

In contrast, the surrounding country rocks, including hornblende-biotite gneiss, charnockite, and pyroxene granulite, exhibit pronounced low-temperature, high-strain deformation features, including recrystallisation textures, grain-size reduction, and mylonitic fabrics. These features reflect prolonged tectonic deformation under subsolidus conditions and are characteristic of regional shear zones within the Nilgiri Block (Santosh et al., 2015). The absence of such features in the Kalpetta granite indicates that it was not subjected to the same intensity of post-solidification deformation, thereby suggesting that its emplacement postdated the main phase of regional tectonism.

The AMS results further reinforce this interpretation by providing quantitative constraints on the internal fabric of the granite. The relatively high corrected degree of anisotropy (P = 1.20-1.29) indicates a well-developed magnetic fabric, which is typically associated with magmatic flow processes in granitoids (Jelinek, 1981; Bouchez, 1997). The dominance of magnetite as the primary carrier of magnetic susceptibility ensures that the AMS fabric reliably reflects the alignment of magnetic grains during magma fractionation and crystallization (Borradaile and Henry, 1997; Borradaile, 2001; Borradaile and Jackson, 2004).

The shape parameter (T) values, ranging from 0.29 to 0.61, indicate a predominantly oblate magnetic fabric. Oblate fabrics are generally associated with flattening strain regimes and are commonly interpreted as the direction of magmatic flow or compaction during emplacement (Bouchez, 1997). This suggests that the internal fabric of the Kalpetta granite developed primarily under conditions of planar flow, rather than unidirectional stretching or shear. The alignment of platy and elongate minerals such as biotite and magnetite within this flow regime contributes to the observed magnetic foliation.

The orientation of the magnetic fabric provides additional insights into the relationship between magma emplacement and regional tectonics. The magnetic foliations and lineations exhibit consistent orientations, with lineations trending predominantly NNE-SSW. However, these orientations are oblique to the regional Bavali-Moyar Shear Zone, which represents a primary tectonic feature controlling deformation within the Nilgiri Block. This obliquity indicates that the last stages of regional shear deformation did not directly control the magnetic fabric.

Instead, the AMS fabric appears to record primary magmatic flow patterns established during emplacement, with only limited influence from subsequent tectonic events. The close correspondence between magnetic foliation and biotite alignment observed in petrographic analysis further supports the interpretation that the AMS fabric represents a primary magmatic fabric rather than a tectonically overprinted one. Similar relationships have been documented in other granitoid bodies, where AMS fabrics preserve emplacement-related flow patterns even in tectonically active shear (Bouchez, 1997; Vernon et al., 2004).

The combined petrographic and AMS evidence strongly supports a late- to post-tectonic emplacement model for the Kalpetta granite. The granite appears to have intruded into an already deformed and metamorphosed crust, as indicated by the well-developed gneissosity and high-strain features in the surrounding rocks. Its emplacement likely occurred during the waning stages of regional tectonic activity associated with the Pan-African Orogeny, when the crust was transitioning from a compressional to an extensional or relaxation regime (Santosh et al., 2009; Collins et al., 2014).

In this context, the granite records a snapshot of magmatic flow and high-temperature deformation that was effectively preserved due to the absence of significant post-emplacement tectonic reworking. The oblate magnetic fabric, moderate to high anisotropy, and consistent lineation trends collectively indicate a coherent emplacement process influenced by regional stress fields but not dominated by them. The integration of AMS data with petrographic and field observations provides a comprehensive understanding of the emplacement dynamics and tectonic setting of the Kalpetta granite. The study demonstrates that the pluton preserves a primary magmatic fabric formed under high-temperature conditions, with minimal subsequent tectonic overprinting, thereby offering valuable insights into the late-stage evolution of the Nilgiri Block within the Southern Granulite Terrain.

9. Conclusion

The integrated petrographic and magnetic petrofabric investigation of the Kalpetta granite provides robust constraints on its emplacement history and tectonic significance within the Southern Granulite Terrain. The results demonstrate that the granite represents a late- to post-tectonic pluton emplaced at deep crustal levels within the Nilgiri Block during the late Neoproterozoic to early Palaeozoic. This timing corresponds to the terminal stages of the Pan-African Orogeny, associated with the assembly of Gondwana.

Petrographic analysis reveals that the internal fabric of the granite is governed by a combination of magmatic crystallization and high-temperature solid-state deformation. Microstructural features such as chessboard extinction in quartz, undulose extinction, and deformed feldspar twins indicate crystal-plastic deformation under near-solidus conditions. These features, together with field evidence of magmatic flow, record the last stages of magma emplacement, cooling, and the development of internal strain before complete solidification.

AMS results further substantiate these interpretations by demonstrating that the magnetic fabric is dominantly controlled by magnetite. The relatively moderate to high degree of anisotropy ($P = 1.20$--1.29) and consistently oblate susceptibility ellipsoids indicate a well-developed, planar fabric associated with magmatic flow and flattening strain. The orientation of magnetic foliations and lineations, trending predominantly NNE-SSW, is oblique to the regional Bavali-Moyar Shear Zone, suggesting that the internal fabric of the pluton developed independently of the final stages of regional deformation.

A key outcome of this study is the clear petrographic and structural contrast between the Kalpetta granite and its host rocks. While the surrounding hornblende-biotite gneiss and charnockite exhibit pervasive low-temperature, high-strain deformation features such as mylonitization and intense recrystallization, the granite lacks this overprinting. This indicates that the pluton stabilized after the peak of regional tectonism and was not significantly affected by subsequent deformation.

Thus, the Kalpetta granite preserves a primary magmatic fabric modified by high-temperature deformation, but largely free of tectonic overprinting. The study highlights the importance of integrating AMS data with petrographic and field observations to distinguish between magmatic and tectonic fabrics. Such an approach is essential for accurately constraining the timing, emplacement mechanisms, and tectonic setting of granitoid bodies within high-grade metamorphic terrains like the Southern Granulite Terrain.

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CRediT statement

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

AI usage statement

The authors declare that generative AI tools were used solely to assist in language refinement, formatting, and improvement of clarity during manuscript preparation. These tools were not employed for data generation, analysis, interpretation, or deriving scientific conclusions. All scientific content, results, interpretations, and conclusions in this study are the original work of the authors. The manuscript has been thoroughly reviewed and edited by the authors to ensure accuracy, integrity, and adherence to journal standards. The authors assume full responsibility for the content of this manuscript.

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