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TEXTURAL VARIATION AND ALTERATION OF THE GUNUNG BULIGIR INTRUSIVE COMPLEX, BANTARUJEG, MAJALENGKA REGENCY, WEST JAVA: A PETROGRAPHIC APPROACH

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ABSTRACT

The Gunung Buligir Intrusive Complex in Bantarujeg, Majalengka Regency, West Java, is an andesitic to dioritic intrusive body that penetrates Tertiary sedimentary sequences of the Halang and Kaliwangu Formations, yet its petrographic variability and alteration evolution remain poorly constrained. This study aims to systematically characterize mineral assemblages, textures, and hydrothermal alteration patterns to better understand fluid-rock interaction during arc-related magmatism. This study presents revised and elaborated petrographic characterization of five thin-section samples (BTRJ1–BTRJ5), integrating modal point-counting data (1,000 points per sample), detailed alteration mineralogy, and systematic textural analysis. Four of five samples (BTRJ1, 2, 3, 5) are classified as porphyritic microdiorite with a microplagioclase groundmass, while BTRJ4 is classified as a diorite with a more equigranular texture (0.5 mm crystal size). The primary phenocryst assemblage is dominated by plagioclase (averaging ~28% as phenocrysts) and hornblende/amphibole (~11%), with clinopyroxene identified exclusively in BTRJ4 (~4%). Quartz ranges from <1% (BTRJ2) to ~5% (BTRJ3). Secondary alteration is dominated by a propylitic assemblage of chlorite, epidote, calcite, sericite, and secondary quartz. Alteration intensity, ranked by total secondary mineral content, follows BTRJ3 > BTRJ2 > BTRJ4 ≈ BTRJ5 > BTRJ1. The spatial variability in alteration intensity, together with the corona texture documented in BTRJ1, tentatively suggests a multi-stage hydrothermal system involving evolving fluid composition and temperature conditions. Distinctive features include the epidote–chlorite corona in BTRJ1, secondary biotite in BTRJ1 and BTRJ5 consistent with an early K-metasomatic overprint, intense silicification in BTRJ3, and elevated carbonate content in BTRJ5. These results provide new insights into the coupling between magmatic crystallization and hydrothermal processes in Neogene arc intrusions and contribute to a better understanding of alteration zoning and fluid evolution in the Bogor Zone, West Java.

Keywords: Bantarujeg, porphyritic microdiorite, diorite, petrography, propylitic alteration, silicification

ABSTRAK

Kompleks Intrusi Gunung Buligir di Bantarujeg, Kabupaten Majalengka, Jawa Barat, merupakan tubuh intrusi andesitik hingga dioritik yang menerobos urutan batuan sedimen Tersier dari Formasi Halang dan Formasi Kaliwangu. Studi ini menyajikan deskripsi petrografi yang telah direvisi dan diperluas dari lima sampel sayatan tipis (BTRJ1–BTRJ5), yang mengintegrasikan data point counting modal (1.000 titik per sampel), mineralogi ubahan secara rinci, dan analisis tekstur yang sistematis. Empat dari lima sampel (BTRJ1, 2, 3, 5) diklasifikasikan sebagai porfiri mikrodiorit dengan massa dasar mikroplagioklas, sedangkan BTRJ4 diklasifikasikan sebagai diorit dengan tekstur lebih equigranular (0,5 mm). Asosiasi fenokris primer didominasi oleh plagioklas (~28% fenokris) dan hornblenda/amfibol (~11%), dengan klinopiroksena hanya pada BTRJ4 (~4%). Kandungan kuarsa berkisar <1% (BTRJ2) hingga ~5% (BTRJ3). Ubahan sekunder didominasi asosiasi propilitik berupa klorit, epidot, kalsit, seriit, dan kuarsa sekunder. Intensitas ubahan, diurutkan berdasarkan total kandungan mineral sekunder, mengikuti pola: BTRJ3 > BTRJ2 > BTRJ4 ≈ BTRJ5 > BTRJ1. Fitur khas

meliputi tekstur korona epidot–klorit pada BTRJ1, biotit sekunder pada BTRJ1 dan BTRJ5 yang mengindikasikan overprint K-metasomatik awal, silisifikasi intensif pada BTRJ3, dan kandungan karbonat tinggi pada BTRJ5. Hasil ini memberikan wawasan baru mengenai keterkaitan antara kristalisasi magmatik dan proses hidrotermal pada intrusi busur berumur Neogen, serta berkontribusi pada pemahaman yang lebih baik mengenai zonasi ubahan dan evolusi fluida di Zona Bogor, Jawa Barat.

Kata Kunci : Bantarujeg, porfiri mikrodiorit, diorit, petrografi, ubahan propilitik, silisifikasi

INTRODUCTION

Textural variations in shallow intrusive igneous rocks encode a detailed record of magmatic crystallization history, cooling rates, and post-emplacement fluid-rock interaction. In sub-volcanic to shallow intrusive settings, these processes operate at the interface between magmatic, hydrothermal, and low-grade metamorphic regimes (Winter, 2010; Philpotts and Ague, 2022). Deciphering these textural and mineralogical signatures is therefore critical not only for reconstructing petrogenetic evolution, but also for constraining the development of hydrothermal systems associated with economically significant arc-related mineralization (Corbett and Leach, 1998).

The island arc of West Java preserves numerous examples of Neogene shallow intrusions that penetrate the Tertiary sedimentary basin fill of the Bogor Zone (van Bemmelen, 1949; Martodjojo, 1984), part of a broader belt of Tertiary arc magmatism across Java (Soeria-Atmadja et al., 1994). Among these, the Bantarujeg area in Majalengka Regency is notable for its isolated conical hills of intrusive rock ranging from andesite to diorite, cutting across deep-marine turbidite sequences of the Halang and Kaliwangu Formations. However, despite their clear field expression and regional significance, the internal petrographic variability of these intrusions—particularly in terms of textural heterogeneity, alteration mineral assemblages, and the extent of multi-stage hydrothermal overprinting—remains insufficiently constrained. This limitation hinders a more comprehensive understanding of fluid evolution and its coupling with magmatic processes in sub-volcanic arc systems.

Hydrothermal alteration in intermediate intrusive systems characteristically produces mineral assemblages indicative of propylitic, argillic, and phyllic zones, depending on temperature, salinity, and fluid chemistry (Corbett and Leach, 1998; Pirajno, 2009). Propylitic alteration defined by chlorite, epidote, and calcite, typically develops in the outer envelopes of porphyry-type systems and in sub-volcanic intrusions hosted in Tertiary sedimentary sequences (Seedorff et al., 2005). However, the identification of

overlapping alteration stages and their textural relationships at the thin-section scale remains a key challenge in distinguishing multi-phase fluid events and reconstructing hydrothermal evolution.

This study presents a refined petrographic investigation of the Gunung Bulagir Intrusive Complex in Majalengka Regency, based on thin-section analysis and 1,000-point modal counting of five samples (BTRJ1–BTRJ5). The addition of BTRJ5 to the earlier four-sample dataset significantly enriches the alteration record and reveals carbonate-rich fluid pathways not previously documented. The objectives are to: (1) characterize the primary mineralogy and textural fabric of the intrusive rocks; (2) document and compare the secondary alteration assemblages; (3) assess the intensity and multi-stage character of hydrothermal overprinting; and (4) discuss implications for the fluid-flow and crystallization history of the complex.

REGIONAL GEOLOGICAL SETTING

The Bantarujeg area is situated within the southern part of the Bandung Physiographic Zone as defined by van Bemmelen (1949), within the broader Bogor Basin framework of Martodjojo (1984). The regional structural grain trends broadly east–west, reflecting the dominant Tertiary to Quaternary subduction system to the south of Java (Hamilton, 1979; Clements et al., 2009). The Citanduy Fault System, trending east–west through this sector, is interpreted as a significant structural control on intrusive emplacement in the Bantarujeg sub-area (Haryanto and Ismawan, 2016), consistent with the local stratigraphic and structural framework documented for the adjacent Gununglarang area (Hastawan, 2022).

Stratigraphically, the area is underlain by the Cinambo Formation (Oligocene to Early Miocene), which consists of calcareous sandstone and claystone deposited in a deep-marine turbidite setting (Djuhaeni and Martodjojo, 1989), and is regionally characterized by mudstone-dominated successions with interbedded sandstones and volcanoclastic input within the Bogor Trough (Abdulkhaim and Haryanto, 2025). This is conformably overlain by the Halang Formation (Middle to Late Miocene), a complex succession of interbedded sandstone

and mudstone with volcanic breccia lenses (Djuri, 1995). In the Bantarujeg sub-area, the Halang Formation is directly overlain by the Kaliwangu Formation (Pliocene) in an unconformable contact, comprising clay with molluscs, conglomerate, and tuffaceous sandstone.

The term "Gunung Bulgir Intrusive Complex" is here informally introduced by the authors to describe a group of isolated conical hills interpreted as Neogene to early Quaternary andesitic to dioritic intrusions that cut the Tertiary sedimentary sequence (see Figure 1); this informal usage is adopted for descriptive convenience and does not constitute formal definition of a new lithostratigraphic unit under the Indonesian Stratigraphic Code, which would require separate procedural submission. Previous

studies did not explicitly recognize or name this intrusive complex as a distinct geological unit. However, the regional geological map depicts comparable bodies as hornblende andesite dykes with widths of approximately 20–30 m, indicating that these intrusions were previously identified but described in a more limited form (Djuri, 1995). Gunung Bulgir represents one of the most structurally well-preserved and accessible exposures within this intrusive system. The intersection of at least two fault sets at this locality likely acted as a structural control that facilitated magma emplacement and subsequently enhanced hydrothermal fluid circulation, consistent with the alteration patterns documented in this study.

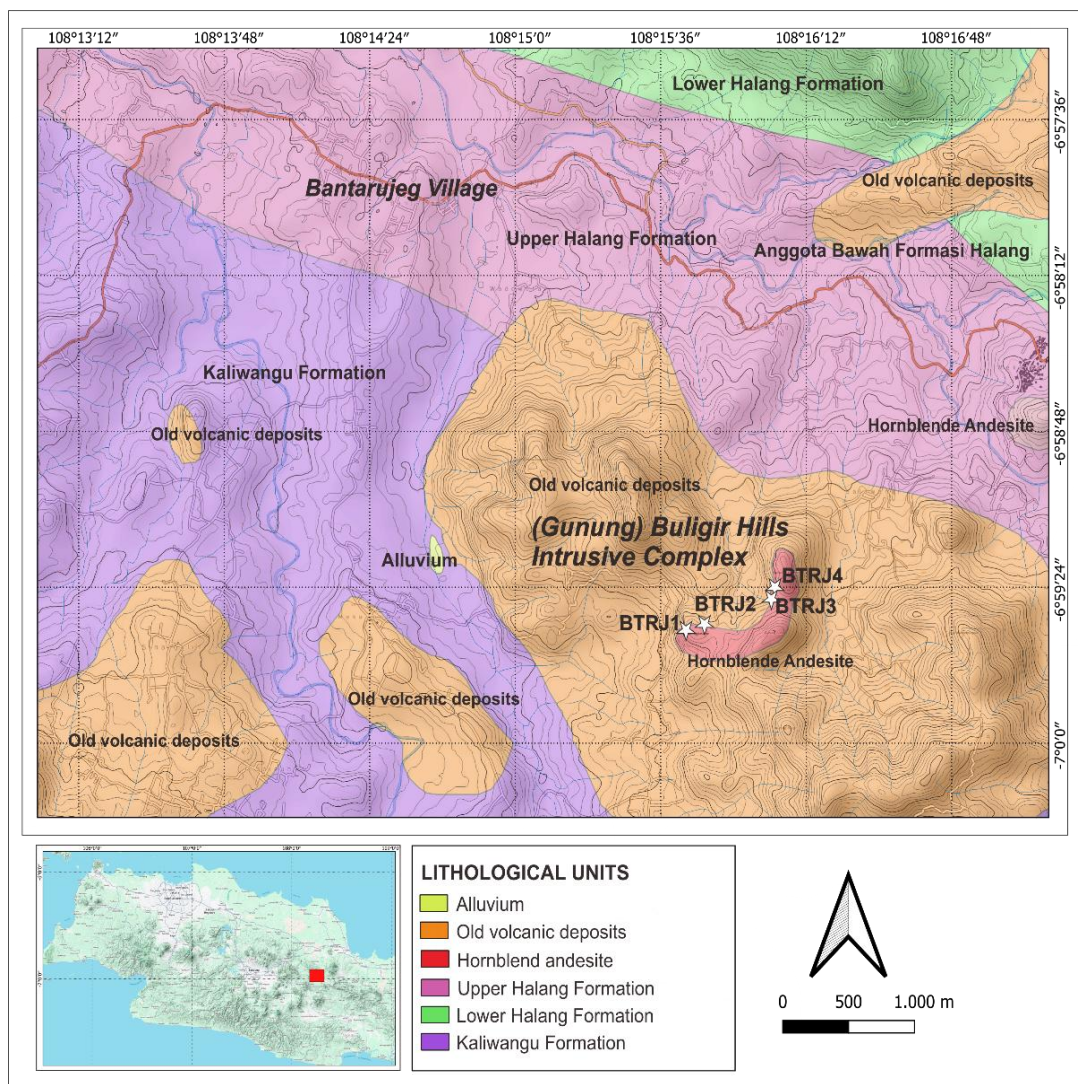


Figure 1. Simplified geological map of the Bantarujeg–Majalengka study area (modified after Djuri, 1995). Star symbol indicates the location of the Gunung Bulgir Intrusive Complex.

MATERIALS AND METHODS

Sample Collection

Rock samples BTRJ1–BTRJ5 were collected from different positions within the Gunung Bulgir outcrop, designed to capture textural

and mineralogical variation from the relatively fresh interior to the more altered marginal zones. BTRJ4 was specifically collected from a zone exhibiting a more equigranular fabric compared to the other four samples. All samples were prepared as standard petrographic thin sections (30 μm thickness) at the Geology Laboratory, Faculty of Geological Engineering, Universitas Padjadjaran.

Petrographic Analysis and Modal Point-Counting

Thin-section petrography was conducted using a Nikon Eclipse LV100POL polarizing microscope under both plane-polarized light (PPL) and crossed-polarized light (XPL). Thin sections were digitized using an EPSON V600 flatbed scanner configured for positive film scanning. During scanning, thin sections were placed between crossed polarizing films to simulate XPL conditions, enabling full-section imaging at high resolution in a single frame. Modal mineral abundances were quantified using the standard point-counting method (Chayes, 1956; Hutchison, 1974), with $\geq 1,000$ points per thin section collected on a randomized grid using JMicroVision software. Mineral identification followed standard optical criteria (MacKenzie and Guilford, 1980; Deer et al., 2013). Igneous rock classification was performed according to the IUGS QAP scheme (Streckeisen, 1976; Le Maitre, 2002), which was originally formulated for plutonic rocks; because the QAP scheme is applied here to porphyritic, subvolcanic rocks with a microcrystalline groundmass, modal phase proportions in the groundmass are subject to greater identification uncertainty than in coarser plutonic rocks, and this limitation is treated as a caveat on the classification rather than a source of geochemical control. A geochemical TAS classification (Le Bas et al., 1986) was not applied, as whole-rock geochemical data were not available for this study. Secondary alteration assemblages were described systematically, including their textural relationships to primary phases. Scanned thin-section images under transmitted light were obtained for macroscopic context.

RESULTS

Field and Sample Description

The Gunung Bulgir outcrop forms an isolated exposure with no observable internal layering, situated at an elevation of 620–673 m asl. The exposed body measures approximately 15 m in width and 7 m in height (azimuth 270–297°, slope 83°, see Figure 2A–B). The rock displays a grayish-black color in fresh condition and weathers to brownish-yellow, reflecting a mesocratic

composition with an estimated mafic mineral content of 30–60%. The absence of primary layering and the massive character of the outcrop suggest emplacement as a coherent intrusive body rather than volcanic flow units. Well-developed joint systems cut the outcrop, and several fracture planes are infilled by quartz veins, indicating brittle deformation and subsequent fluid infiltration along structural pathways. (Figure 2C). Texturally, it is porphyritic, inequigranular, and hypidiomorphic, with crystal sizes ranging from 1 to 5 mm and a predominantly massive structure (Figure 2D).

Modal Mineral Composition

Modal point-counting results for all five samples are summarized in Table 1, with their classification further constrained using the QAP diagram (Figure 5). Plagioclase is the dominant mineral phase in all samples, consistently the most abundant phase (combined phenocryst + groundmass: 44–52% depending on sample). Mafic mineral assemblages are generally dominated by hornblende/amphibole (7–15% across samples; mean $\sim 11\%$), indicating a hydrous magmatic system, except in sample BTRJ4, where clinopyroxene ($\sim 4\%$) occurs alongside reduced amphibole content ($\sim 10\%$). This variation suggests localized differences in crystallization conditions, potentially reflecting changes in water content or temperature during magma evolution. Chlorite is the dominant secondary mineral (10–20% modal), consistent with pervasive propylitic alteration across the intrusion. Calcite reaches its highest abundance in BTRJ5 ($\sim 5\%$), while quartz is most abundant in BTRJ3 ($\sim 5\%$), indicating localized enrichment associated with fluid-mediated alteration processes.

Petrographic Description by Sample

BTRJ1: Porphyritic Microdiorite

BTRJ1 is classified as a porphyritic microdiorite characterized by a microplagioclase-dominated groundmass exhibiting a pilotaxitic fabric (Figure 3A). Primary quartz is minor ($< 2\%$), occurring as isolated anhedral grains within the groundmass, suggesting limited late-stage silica saturation during crystallization. Plagioclase phenocrysts display well-developed polysynthetic (albite-law) twinning and pronounced oscillatory zoning, expressed as alternating extinction bands under XPL (Figure 4B). The presence of oscillatory zoning indicates fluctuating physicochemical conditions during crystallization, likely reflecting variations in temperature, water content, or magma composition. Amphibole phenocrysts (~ 1

mm; ~15% modal) exhibit characteristic green to brownish-green pleochroism in PPL and two-directional prismatic cleavage at ~56° and ~124°. The abundance of amphibole suggests crystallization under relatively hydrous conditions, consistent with arc-related magmatic systems.

BTRJ2: Porphyritic Microdiorite (Strongly Chloritized)

BTRJ2 is classified as a porphyritic microdiorite characterized by a microplagioclase-dominated groundmass that has undergone extensive chloritization (~20% modal chlorite), representing the highest alteration intensity among the porphyritic samples (Figure 3B). Primary quartz is very minor (<1%), indicating limited silica saturation during the late stages of crystallization. Plagioclase phenocrysts (~15% modal) exhibit polysynthetic twinning and compositional zoning (Fig. 4C, 4D). Amphibole phenocrysts (~1 mm) show more advanced chlorite replacement than in BTRJ1, with many grains largely pseudomorphed. The scanned thin section (Figure 3B) reveals a two-toned appearance consisting of a relatively pale interior and a darker, chlorite-enriched outer zone, possibly reflecting heterogeneous fluid pathways or a chilled margin effect. No corona texture or secondary biotite was observed, clearly distinguishing BTRJ2 from BTRJ1 and BTRJ5, suggesting a different alteration pathway or a lower degree of potassic overprinting in this sample.

BTRJ3: Porphyritic Microdiorite (Silicified)

BTRJ3 is a porphyritic microdiorite with the most significant silica enrichment among all samples (Figure 3C, 4E). Total quartz reaches ~5% (the highest in the suite): approximately 2% primary quartz and ~3% secondary quartz formed through hydrothermal silicification. The secondary quartz displays irregular grain shapes and interlocking boundaries under XPL, which are texturally consistent with hydrothermal precipitation rather than primary magmatic crystallization (Figure 4F). Amphibole phenocrysts are extensively pseudomorphed by chlorite (18% modal), indicating intense alteration of primary mafic phases. This degree of replacement suggests strong fluid-rock interaction under propylitic conditions, where ferromagnesian minerals are preferentially altered. Fe-Ti oxides are a notable accessory phase, visible as small cubic grains even at the macroscopic scan scale. The combination of intense silicification

and pervasive chloritization makes BTRJ3 the most altered sample in the suite.

BTRJ4: Diorite

BTRJ4 is classified as a diorite based on its equigranular grain size (~0.5 mm), clearly distinguishing it from the four porphyritic samples (Figure 3D). This texture indicates a more uniform crystallization history under relatively stable cooling conditions compared to the porphyritic counterparts. The groundmass comprises microplagioclase and micropyrroxene (>80%), with crystal sizes of ~0.5 mm. Modal composition: plagioclase phenocrysts ~28%, clinopyroxene ~4%, amphibole ~10%, quartz ~2% (Figure 4G). The relatively low proportion of phenocrysts compared to groundmass further supports a more equilibrated crystallization environment. Clinopyroxene crystals are subhedral, colorless to pale greenish under PPL, with extinction angles consistent with augite. The presence of clinopyroxene, uncommon in the other samples, indicates crystallization under comparatively higher temperature and/or lower water activity conditions. Incipient chloritization along clinopyroxene cleavage planes is noted, unique to this sample. The scanned thin section presents the most crystalline and uniformly bright appearance, reflecting the interlocking pyroxene-plagioclase fabric. The coexistence of clinopyroxene and amphibole in BTRJ4 may indicate a compositionally distinct or deeper-crystallized portion of the intrusive body.

BTRJ5: Porphyritic Microdiorite (Carbonate-bearing)

BTRJ5 is a porphyritic microdiorite with a microplagioclase groundmass. Modal composition: plagioclase phenocrysts ~27%, amphibole ~15%, quartz 3% (Table 1). Primary quartz is minor (~1%), and secondary quartz (~2%) is also present, together accounting for the ~3% total quartz reported in Table 1 and indicating limited but detectable silica addition during post-magmatic alteration. The most distinctive feature of BTRJ5 is its elevated calcite content (~5% modal), representing the highest abundance among all samples. This enrichment suggests a significant contribution of CO₂-rich hydrothermal fluids during alteration. Calcite occurs in two textural modes: as replacement of feldspar phenocrysts, and as interstitial secondary grains disseminated throughout the matrix (Figure 4H). Under XPL, calcite is readily identifiable by its characteristic high-order pearly birefringence and rhombic cleavage.

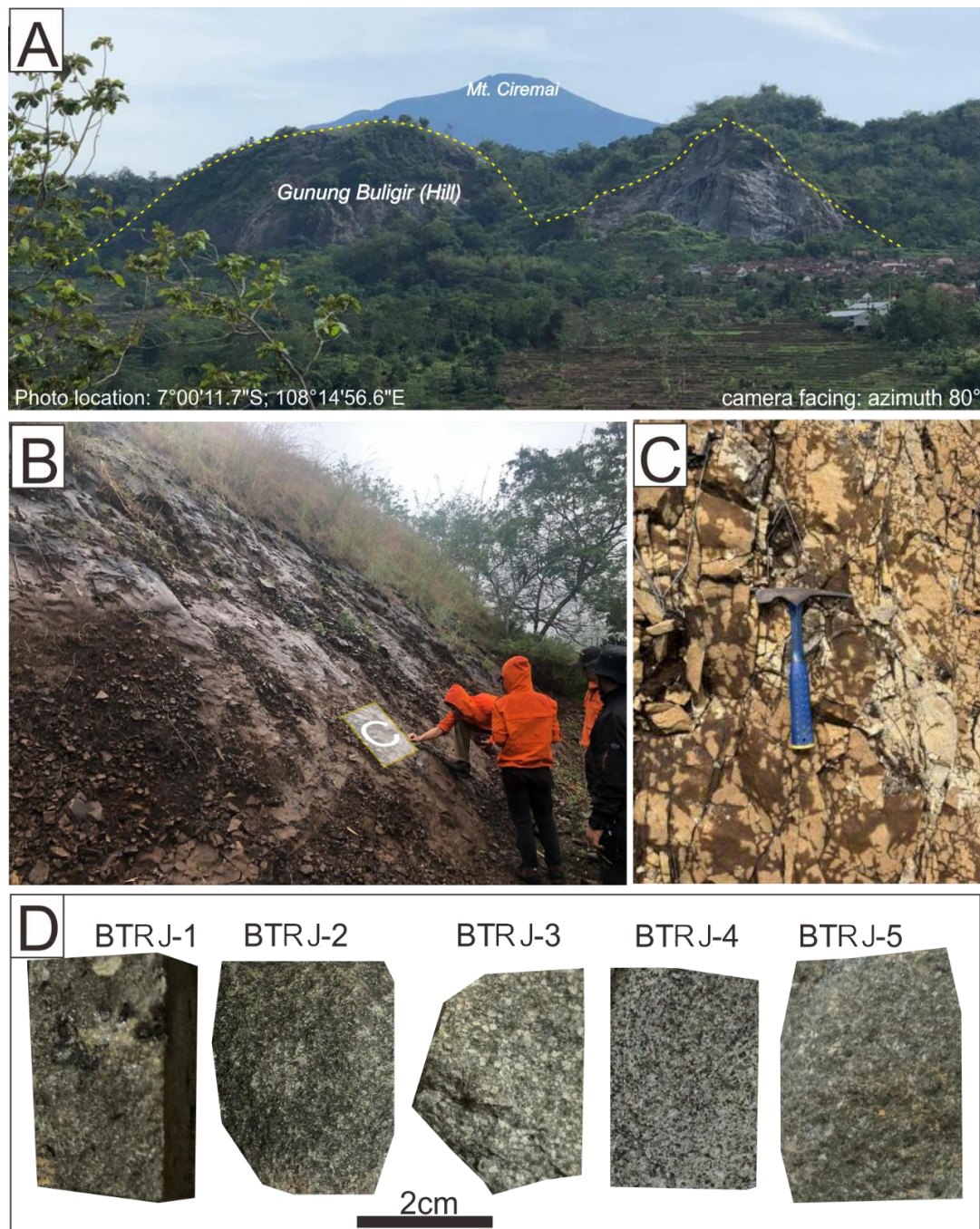


Figure 2. Field photographs and hand specimens from Gunung Buligir. (A) Panoramic view of Gunung Buligir hill (outlined in yellow dashes), with Mt. Ciremai visible in the background (photo location: 7°00'11.7"S; 108°14'56.6"E, camera facing azimuth 80°). (B) Outcrop exposure along the hillslope showing the intrusive body. (C) Close-up of the weathered outcrop surface with well-developed joints and quartz veins. (D) Hand specimens BTRJ-1 to BTRJ-5, showing porphyritic texture in most samples, with BTRJ-4 displaying a coarser, more equigranular texture (scale bar = 2 cm).

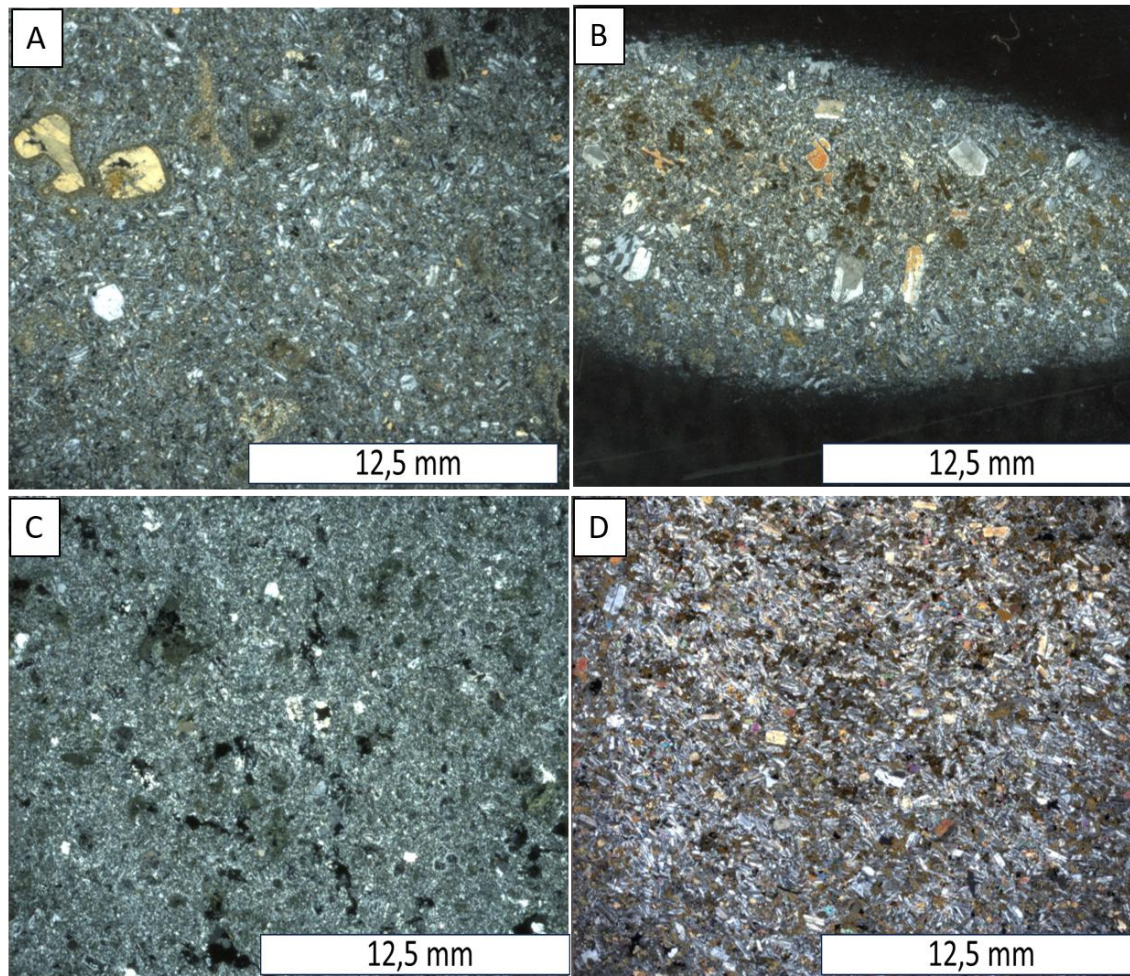


Figure 3. Photomicrographs and scanned thin sections of the Gunung Buligir Intrusive Complex. A–D: Scanned thin sections (transmitted light; scale bar = 12.5 mm). A: BTRJ1, inequigranular porphyritic fabric with brownish amphibole and pale plagioclase phenocrysts. B: BTRJ2, two-toned fabric with chlorite-enriched outer margin. C: BTRJ3, uniformly dark grey groundmass reflecting pervasive chloritization and silicification. D: BTRJ4, uniformly bright equigranular dioritic fabric.

Alteration Mineralogy and Textures

Secondary alteration is present in all five thin sections. Summing all secondary phases in Table 1 (chlorite, epidote, secondary biotite, sericite, and calcite), total secondary mineral content ranges from 20% (BTRJ1) to ~31% (BTRJ3). This variation indicates a heterogeneous distribution of hydrothermal processes across the intrusive body. The alteration assemblage comprises chlorite, epidote, secondary biotite, sericite, calcite, secondary quartz, and iron hydroxides, representing a spectrum of propylitic to locally overprinted alteration stages. Table 2 summarizes these phases, their parent minerals, textural characteristics, and intensities.

The corona texture observed in BTRJ1 represents one of the most petrographically

significant features in the dataset. An epidote–chlorite intergrowth has developed as a rim around amphibole phenocrysts, Chlorite (10–20% modal) is the dominant secondary phase in all samples, derived primarily from amphibole breakdown. In BTRJ2 and BTRJ3, groundmass chloritization is pervasive. In BTRJ4, incipient chloritization of clinopyroxene along cleavage planes is unique to that sample. Replacement of amphibole commonly produces pseudomorphic textures with preserved crystal outlines, reflecting mineralogical transformation under relatively low-grade hydrothermal conditions. Optically, chlorite shows pale green color in PPL and near-isotropic anomalously low birefringence under XPL, consistent with iron-rich chlorite (Deer et al., 2013).

significant features in the dataset. An epidote–chlorite intergrowth has developed as a rim around amphibole phenocrysts,

sharply bounded against both the amphibole core and the surrounding groundmass. This records disequilibrium breakdown of hornblende during low-temperature propylitic fluid infiltration and is characteristic of sub-greenschist conditions (Creasey, 1959).

Secondary biotite occurs in BTRJ1 (3%) and BTRJ5 (2%), as fine flakes at the same sites as chlorite; in BTRJ1 it also occurs at corona epidote sites, whereas the epidote–chlorite corona texture itself is documented only in BTRJ1 (Figure 4A) and was not observed in the BTRJ5 thin section. The presence of secondary biotite in both BTRJ1 and BTRJ5,

together with its absence in the three heavily chloritized samples (BTRJ2, BTRJ3, BTRJ4), may indicate an early K-metasomatic event preceding the main propylitic stage, although the corona texture recorded in BTRJ1 is not documented in BTRJ5. Sericite (1–2%) replaces plagioclase phenocrysts, producing turbid cores and obscured twinning under XPL. Calcite (2–5%) occurs as vein fill and interstitial grains. Secondary quartz is most concentrated in BTRJ3 (~3%), with irregular interlocking morphology confirming hydrothermal precipitation.

Table 1. Modal mineral composition (%) based on 1,000-point counting per thin section. BTRJ1–BTRJ3 and BTRJ5 are porphyritic microdiorite; BTRJ4 is diorite. (–) = absent or trace.

Mineral / Component	BTRJ1	BTRJ2	BTRJ3	BTRJ4	BTRJ5
Primary Phase					
Plagioclase (phenocryst)	14	28	16	28	27
Plagioclase (groundmass)	38	23	28	26	20
Hornblende / Amphibole	15	8	7	10	15
Clinopyroxene	–	–	–	4	–
Quartz (total)	2	1	5	2	3
Alkali Feldspar	<1	<1	<1	<1	<1
Fe-Ti Oxide	6	6	7	6	5
Volcanic Glass	3	3	3	–	3
Plagioclase Type	Andesine	Andesine	Andesine	Andesine	Andesine
Secondary phase					
Chlorite (secondary)	10	20	25	16	12
Epidote (secondary)	4	3	2	2	2
Biotite (secondary)	3	–	–	–	2
Sericite	1	2	2	2	1
Calcite	2	3	2	2	5
Groundmass (other)	2	3	5	2	5
Total	100	100	100	100	100

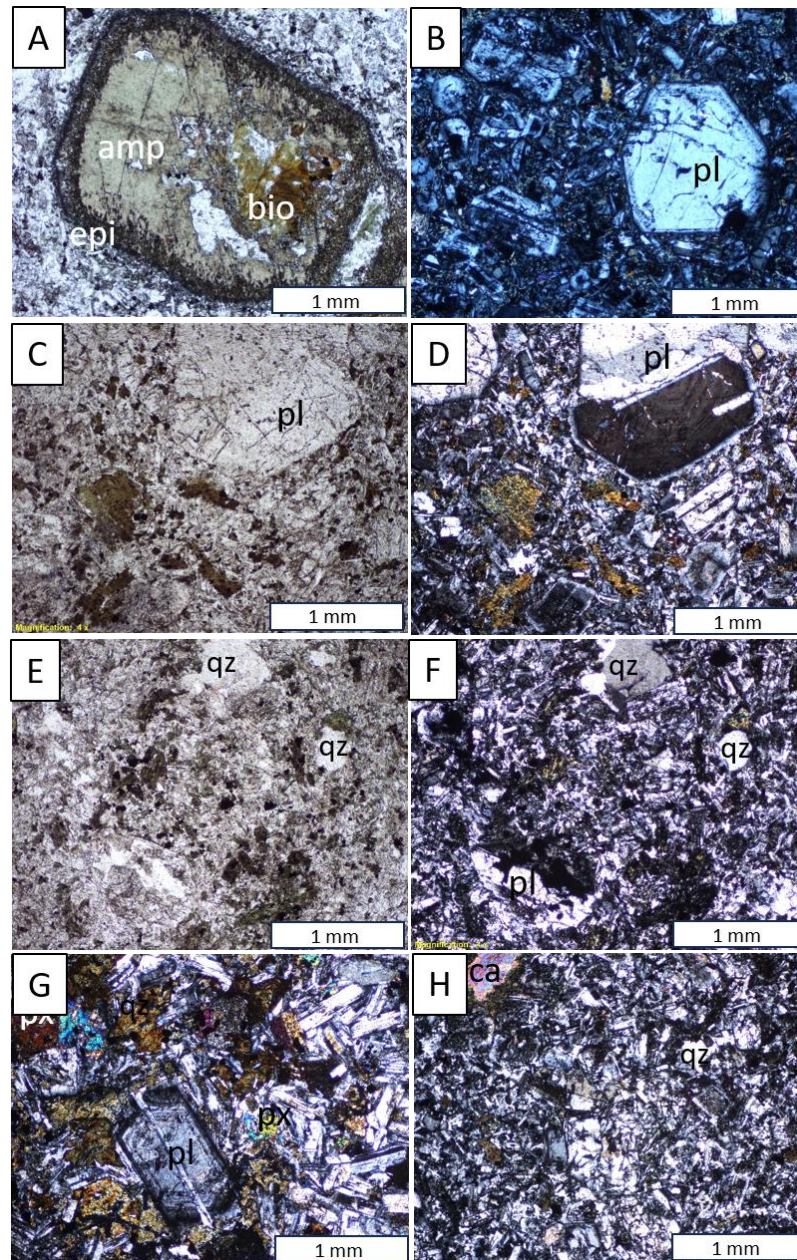


Figure 4. A–H: Photomicrographs at 40× magnification, each with a scale bar of 1 mm. (A) BTRJ1 in PPL displays a corona texture developed around amphibole phenocrysts (amp), characterized by an epidote–chlorite reaction rim (epi) accompanied by secondary biotite (bio). (B) BTRJ1 in XPL shows plagioclase phenocrysts (pl) exhibiting clear polysynthetic twinning and oscillatory zoning. (C) BTRJ2 in PPL contains plagioclase phenocrysts (pl) that have undergone strong sericitization within a chlorite-rich groundmass. (D) BTRJ2 in XPL presents euhedral plagioclase (pl) with well-defined polysynthetic twinning, while Fe-Ti oxides occur in the matrix. (E) BTRJ3 in PPL reveals secondary quartz grains (qz) with irregular shapes set within a silicified groundmass. (F) BTRJ3 in XPL highlights secondary quartz (qz) characterized by interlocking grain boundaries, together with partially preserved plagioclase microlites (pl). (G) BTRJ4 in XPL consists of subhedral clinopyroxene (px) and plagioclase (pl) distributed in an equigranular groundmass. (H) BTRJ5 in XPL shows interstitial calcite (ca) displaying high-order birefringence, associated with secondary quartz (qz) and plagioclase (pl). Abbreviations: amp = amphibole, bio = biotite, epi = epidote, pl = plagioclase, qz = quartz, px = clinopyroxene, ca = calcite; PPL = plane-polarized light, XPL = crossed-polarized light.

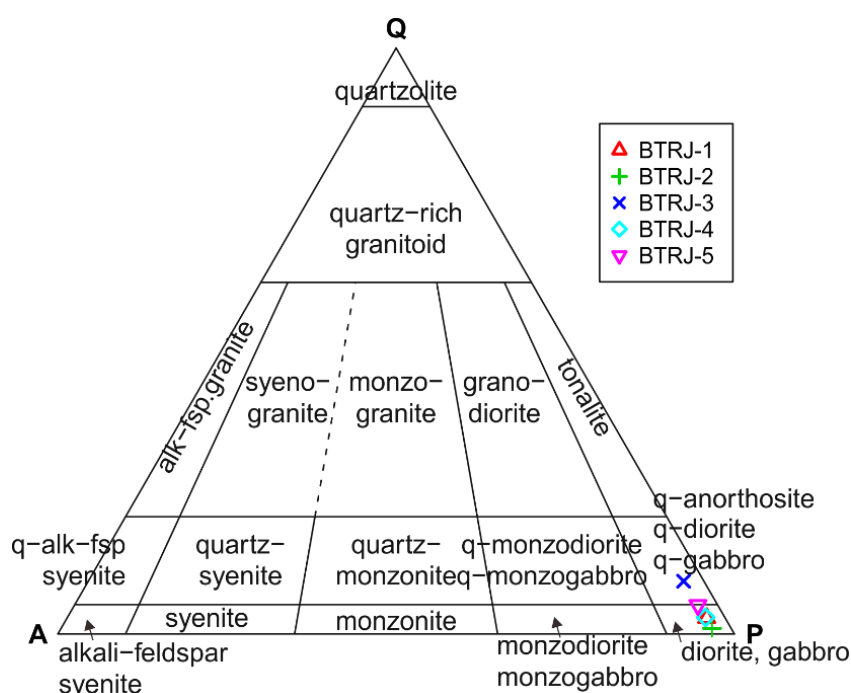


Figure 5. QAP ternary classification diagram (after Streckeisen, 1976) for the Gunung Buligir Intrusive Complex samples. All five samples plot within the plagioclase-dominated ($Q < 5\%$, $A < 10\%$) field of the QAP diagram corresponding to diorite/gabbro. Because QAP alone cannot discriminate diorite from gabbro without plagioclase compositional data, the measured andesine composition (An_{30-50}) of the plagioclase in all samples indicates that this field position corresponds to diorite rather than gabbro.

DISCUSSION

Rock Classification and Primary Mineralogy

The petrographic dataset reveals significant compositional and textural heterogeneity within the Gunung Buligir Intrusive Complex. All samples plot close to the plagioclase apex of the QAP diagram, with quartz contents of only 1–5% placing them well within the diorite field rather than tonalite or quartz diorite fields, consistent with the "porphyritic microdiorite" designation, which combines this QAP-based compositional field with the porphyritic texture and fine-grained (micro-) groundmass observed petrographically. The predominance of porphyritic microdiorite suggests emplacement at shallow crustal levels, where rapid cooling facilitated the formation of a fine-grained microplagioclase groundmass. Such textures are widely associated with disequilibrium crystallization under undercooled conditions, where nucleation rates exceed crystal growth rates in sub-volcanic environments (Cashman and Blundy, 2013).

In contrast, BTRJ4 exhibits an equigranular dioritic texture and contains clinopyroxene

(augite), indicating crystallization under relatively higher temperature and/or lower water content conditions. According to Putirka (2017), clinopyroxene stability is strongly controlled by pressure–temperature conditions, making it a useful indicator of crystallization environment. The coexistence of clinopyroxene with reduced amphibole abundance in BTRJ4 therefore suggests localized variations in magmatic conditions, which may also reflect differences in melt composition or emplacement depth (Mollo et al., 2021).

The dominance of plagioclase phenocrysts accompanied by amphibole as the primary mafic phase is consistent with a calc-alkaline affinity typical of subduction-related magmatism. Such mineral assemblages are indicative of hydrous magma systems commonly developed in volcanic arcs, including the Sunda Arc (Gill, 2010). Oscillatory zoning in plagioclase records fluctuations in physicochemical conditions during crystallization, including variations in temperature, magma composition, and volatile content. These zoning patterns are widely interpreted as evidence of open-

system magmatic processes, such as magma recharge, mixing, or decompression-induced crystallization (Ginibre et al., 2020; Ruprecht and Bachmann, 2010).

Table 2. Secondary alteration phases identified in the Gunung Buligir thin sections, with parent phases, textural characteristics, and relative intensities.

Secondary Mineral	Parent Phase	Textural Characteristics	Intensity
Chlorite	Hornblende / Amphibole; groundmass	Pseudomorphic aggregate along cleavage; most pervasive in BTRJ2	Moderate–Pervasive
Epidote	Hornblende rims; plagioclase	Pale pistachite grains; epidote–chlorite corona documented in BTRJ1 only; disseminated epidote (no corona) in BTRJ5	Minor–Moderate
Secondary Biotite	Hornblende alteration sites	Fine flakes at chlorite sites; BTRJ1 & BTRJ5 only	Minor
Sericite	Plagioclase phenocrysts	Turbid cores; twinning obscured under XPL	Weak–Moderate
Calcite	Fractures; interstitial	Veinlets and disseminated grains; highest in BTRJ5 (5%)	Weak–Moderate
Secondary Quartz	Groundmass (silicification)	Irregular interlocking grains; dominant in BTRJ3 (~3%)	Weak–Strong (BTRJ3)
Limonite / Goethite	Fe-Ti Oxides	Yellow-brown rims on opaque grains	Weak
Chlorite (on pyroxene)	Clinopyroxene (BTRJ4 only)	Incipient along cleavage planes	Weak

Textural variations across the samples further constrain crystallization dynamics and emplacement conditions. The porphyritic and inequigranular textures observed in BTRJ1, BTRJ2, BTRJ3, and BTRJ5 indicate a two-stage crystallization history, involving early phenocryst growth followed by rapid groundmass crystallization during ascent or emplacement at shallow depths. The development of pilotaxitic textures in the groundmass reflects rapid undercooling, which promotes dense nucleation of microlites (Cashman and Blundy, 2013). By contrast, the equigranular texture in BTRJ4 reflects slower cooling and more stable crystallization conditions, allowing crystals to grow to relatively uniform sizes. Experimental and natural observations demonstrate that lower degrees of undercooling favor crystal growth over nucleation, resulting in coarser-grained, equigranular textures (Holness, 2014; Shea and Hammer, 2013). The coexistence of these contrasting textures within a single intrusive complex indicates spatial and temporal variability in cooling rates, which may be controlled by emplacement depth, intrusion geometry, and episodic magma input. Such heterogeneity is characteristic of dynamic magmatic plumbing systems in arc environments, where repeated injections of magma and variable heat

transfer conditions influence final rock textures (Annen et al., 2015; Edmonds et al., 2019).

The consistently low abundance of primary quartz (<5%) across all samples supports an overall intermediate bulk composition. Taken together, the mineralogical and textural characteristics indicate that the Gunung Buligir intrusion represents a hydrous, evolving arc magma system emplaced at shallow crustal levels, with textures recording the interplay between cooling rate, undercooling, and magma recharge processes.

Alteration Style and Tentative Multi-Stage History

The secondary mineral assemblage — chlorite + epidote + calcite + sericite ± secondary quartz ± secondary biotite — is most consistent with a propylitic-style alteration system, typically developed at temperatures of ~150–300°C in the outer zones of shallow intrusive complexes (Corbett and Leach, 1998; Seedorff et al., 2005). Within this framework, chlorite replacing amphibole, epidote forming corona rims, and calcite infilling brittle fractures represent diagnostic mineralogical and textural expressions of propylitic alteration. Alteration intensity ranks as BTRJ3 > BTRJ2 > BTRJ4 > BTRJ5 > BTRJ1,

indicating spatial heterogeneity in fluid flux and fluid–rock interaction within the intrusive body.

The presence of secondary biotite in both BTRJ1 and BTRJ5 — with the epidote–chlorite corona texture documented only in BTRJ1 — introduces complexity beyond simple propylitic overprinting. Secondary biotite is more commonly associated with potassic-style alteration at higher temperatures (>350°C) in porphyry systems (Beane and Titley, 1981), and its association with the epidote–chlorite corona in BTRJ1, together with its occurrence without a documented corona texture in BTRJ5, tentatively suggests either (a) an early K-metasomatic event overprinted by later propylitic alteration, or (b) localized infiltration of K-rich fluids during the transition toward propylitic conditions. Similar overprinting relationships have been documented in arc-related intrusive systems, where evolving magmatic–hydrothermal fluids produce temporally overlapping alteration assemblages. Distinguishing between these scenarios would require microprobe characterization of biotite and chlorite compositions and stable isotope data. The intense silicification of BTRJ3 (~3% secondary quartz with irregular interlocking morphology) suggests exposure to silica-saturated hydrothermal fluids distinct from those responsible for the chlorite-dominated alteration in BTRJ2, with silica precipitation commonly associated with fluid cooling, pressure changes, or fluid mixing (Fournier, 1999). BTRJ3 also retains high chlorite (18%), consistent with the most fluid-intensive conditions in the suite, possibly reflecting proximity to a structurally controlled fluid conduit. The elevated calcite in BTRJ5 (~5% modal), occurring as both vein fill and interstitial grains, indicates preferential channeling of CO₂-bearing, late-stage hydrothermal fluids through that portion of the intrusion (Pirajno, 2009).

Collectively, these observations tentatively suggest a multi-stage hydrothermal evolution for the Gunung Buligir Intrusive Complex, provisionally outlined as: (1) a possible early K-metasomatic event, hypothesized on the basis of secondary biotite (2–3% modal) in BTRJ1 and BTRJ5 and the corona-forming texture documented in BTRJ1, tentatively indicating localized high-temperature fluid–rock interaction during the initial stages of system development — this stage is treated as a working hypothesis given the limited biotite abundance and its confirmation would require mineral–chemical verification; (2) a main propylitic stage producing the pervasive chlorite–epidote–calcite assemblage in all five samples, reflecting widespread circulation of relatively low-temperature hydrothermal

fluids; and (3) a late silicification overprint most intensely expressed in BTRJ3, representing a focused fluid pulse of elevated silica activity. This sequence is broadly consistent with alteration evolution models proposed for porphyry-related hydrothermal systems, where early high-temperature metasomatism is progressively overprinted by lower-temperature assemblages (Seedorff et al., 2005). However, the relatively small scale of the Gunung Buligir intrusion and the absence of mineralization data preclude direct classification within a formal porphyry framework; the system is more appropriately interpreted as a sub-volcanic intrusive complex exhibiting porphyry-style hydrothermal characteristics. Further constraints from whole-rock geochemistry, mineral chemistry, and geochronology will be required to quantify the timing, duration, and physicochemical conditions of each alteration stage.

CONCLUSIONS

Petrographic analysis and 1,000-point modal counting of five samples from the Gunung Buligir Intrusive Complex yield the following conclusions:

1. Four samples (BTRJ1, 2, 3, 5) are classified as porphyritic microdiorite; BTRJ4 is a diorite with equigranular texture (~0.5 mm) and the only sample containing clinopyroxene (augite, ~4%). The primary phenocryst assemblage is dominated by plagioclase (~28%) and hornblende/amphibole (~11%), consistent with a calc-alkaline, hydrous arc magma. Textural and mineralogical heterogeneity across samples suggests multiple or differentiated intrusive pulses.
2. Secondary alteration is propylitic throughout, comprising chlorite, epidote, calcite, sericite, secondary quartz, secondary biotite, and iron hydroxides. Chlorite (10–25% modal) is the dominant secondary phase in all samples, derived mainly from amphibole breakdown. Secondary biotite occurs in BTRJ1 (3%) and BTRJ5 (2%) only, while the epidote–chlorite corona texture is documented in BTRJ1 alone. BTRJ3 shows the strongest silicification (~3% secondary quartz), and BTRJ5 has the highest calcite content (~5%), together indicating spatially heterogeneous alteration assemblages across the intrusive body.
3. Total secondary mineral content (chlorite + epidote + secondary biotite + sericite + calcite from Table 1) ranks alteration intensity as BTRJ3 (31%) > BTRJ2 (28%) > BTRJ4 ≈ BTRJ5 (22% each) > BTRJ1 (20%). This pattern, together with the restriction of the corona texture and

secondary biotite to BTRJ1 (and biotite additionally to BTRJ5), tentatively suggests a multi-stage hydrothermal overprint — a possible early, localized K-metasomatic pulse followed by a pervasive propylitic stage and a late, more focused silicification event in BTRJ3 — although this staging remains a working hypothesis pending mineral-chemical and isotopic verification.

4. The coexistence of porphyritic (BTRJ1, 2, 3, 5) and equigranular (BTRJ4) textures indicates spatial variability in cooling rate and emplacement depth within the complex, while the joint- and quartz-vein-controlled fabric observed in outcrop implies that brittle structures exerted a first-order control on hydrothermal fluid pathways. The spatial coupling between textural domains and alteration intensity supports a model in which fluid flux was channeled along structurally permeable zones during and after magmatic crystallization. Further constraints from whole-rock geochemistry, mineral chemistry, and geochronology are needed to quantify the timing, duration, and physicochemical conditions of each proposed alteration stage.

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