

Magma source and evolution of granitoid rocks from the Palopo and Masamba granitoids in South Sulawesi Indonesia

sudirman -

sudirmantg@gmail.com

PT Tekindo Energi

A Wirdiansyah

PT. Bukit Makmur Istindo Nikeltama

Research Article

Keywords: Granitoids, Palopo, Masamba, Magma Source, Magmatic Evolution

Posted Date: August 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10393948/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Granitoid belts have been widely recognized as important hosts of mineralization prospects, and the characterization of granitoid geochemistry has provided valuable insights for identifying sources of economically significant mineral deposits. This study integrates field investigations with petrographic, major-element, and trace-element geochemical analyses of granitoid rocks from the South Sulawesi Granitoid Belt, encompassing the Palopo and Masamba areas. The results indicate that granodiorite and granite are the dominant lithologies in the study area. These rocks are characterized as I-type granitoids with high-K calc-alkaline to shoshonitic affinities and metaluminous to weakly peraluminous compositions. Geochemical data suggest that the granitoids were derived predominantly from partial melting of crustal sources with minor mantle contributions. The Palopo granitoids were generated from high-K mafic or metabasaltic source rocks, whereas the Masamba granodiorites were derived from high-K mafic or metabasaltic sources with minor contributions from metasedimentary material. In contrast, the Masamba granites were generated from tonalitic to metasedimentary source rocks. Dy/Yb ratios ranging from 1.87 to 2.17 indicate dominant amphibole fractionation with insignificant garnet influence during partial melting, suggesting magma generation at intermediate crustal depths. Magmatic evolution was controlled by both magma mixing and fractional crystallization. Evidence for magma mixing is supported by the occurrence of mafic enclaves observed in the field, as well as zoning and poikilitic textures identified petrographically. Fractional crystallization is reflected by decreasing MgO, Fe₂O₃, CaO, and TiO₂ contents with increasing SiO₂ concentrations, together with high LREE/HREE ratios, negative Eu anomalies (Eu/Eu*), and elevated La/Yb ratios ranging from 20.10 to 35.84. These findings indicate that the Palopo and Masamba granitoids were derived from relatively distinct source materials and subsequently underwent significant magmatic evolution through magma mixing and fractional crystallization, resulting in the enrichment of incompatible elements within the residual melt.

1. Introduction

Sulawesi, characterized by its distinctive K-shaped geometry, is located at the convergence zone of the Eurasian, Indo-Australian, and Pacific plates, which have undergone complex interactions and collisions throughout its tectonic evolution (Katili, 1978). These tectonic interactions have resulted in the development of four major tectonic provinces, including the West-North Arm, which is predominantly composed of magmatic and volcanic products (Sukanto, 1975; Katili, 1978; Hall, 2002; Satyana et al., 2011). In South Sulawesi, magmatic products are widely distributed along the southern arm of the island (Priadi et al., 1994; Polvé et al., 1997; Priadi et al., 2013), where granitoid rocks are extensively exposed in the Palopo and Masamba regions.

Previous studies have shown that the granitoids in Palopo are generally characterized by calc-alkaline (CAK) affinities, whereas those in Masamba exhibit calc-alkaline to high-K calc-alkaline (CAK–HK) characteristics (Maulana et al., 2016). By integrating whole-rock geochemical data with zircon U–Pb–Hf isotopic analyses, Zhang et al. (2020) identified a magmatic flare-up event at approximately 7–6 Ma. Furthermore, thermochronological data from the Masamba granitoids indicate an exhumation rate of

approximately 1.6 mm/yr, while granitoids from the Palopo area are inferred to have been exhumed from depths of approximately 8.2–10 km (Maulana et al., 2013).

Granitoid intrusions have been widely recognized as important indicators of magmatic processes and potential hosts of mineralization. Studies on multiphase granitoid intrusions by Cao et al. (2016) demonstrated that I-type, calc-alkaline, and metaluminous granitoids are commonly associated with mineralization systems. Similarly, Shen et al. (2015) reported that numerous mineral deposits are genetically related to calc-alkaline granites. Oxidation state has been considered a primary control on the fertility of granitoid-related mineralization (Shen et al., 2015; Richards, 2015), although Cao et al. (2016) suggested that certain reduced granitoid systems may also be favorable for mineralization.

Granitoid rocks provide valuable information regarding magma sources and magmatic evolution and may also record processes associated with ore-forming systems. Therefore, understanding the source characteristics and magmatic evolution of the granitoids in the Palopo and Masamba areas is essential for improving regional geological knowledge and contributing to future mineral exploration programs associated with granitoid-hosted mineralization.

2. Geological Setting

Geochemical data from the Palopo Granite indicate that the granitoid is characterized by high-K, magnesian, peraluminous, and calc-alkaline affinities. These results largely corroborate the findings of Priadi et al. (1994) and further confirm that the granitoid belongs to the high-K calc-alkaline (CAK) Miocene–Pliocene granitoid belt of Sulawesi as proposed by Polvé et al. (1997). Zircon U–Pb ages of 6.3 Ma obtained from deformed granodiorite and 5.0 Ma from undeformed granodiorite constrain the timing of mylonitization to between 6.3 and 5.0 Ma (White et al., 2014).

According to Van Leeuwen and Maulana (2025), the granitoid rocks in the Masamba area constitute the Masamba Complex, which is interpreted as a composite high-K calc-alkaline intrusive complex. Numerous studies have reported granodiorite as the dominant lithology within this complex. Maulana et al. (2016) similarly classified the Masamba Complex as belonging to the calc-alkaline to high-K calc-alkaline (CAK–HK) series. Furthermore, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data reported by Anderson and Smith (1995) indicate ages ranging from 9.5 to 4.3 Ma. The distribution of granitoid rocks can be seen in Fig. 1.

3. Analytical Methods

This study was conducted through two main stages: field sampling and laboratory analyses. Sampling was carried out at two granitoid bodies located in the Palopo and Masamba areas of South Sulawesi. In the Palopo area, samples were collected from the Babak River (BA-01A and BA-04) and the Siguntu River (SG-04). In the Masamba area, samples were collected from the Masamba River (SM-01, SM-17, and SM-26).

Laboratory analyses consisted of petrographic and geochemical investigations. Petrographic analyses were conducted on all samples at the Petrography Laboratory, Department of Geological Engineering, Hasanuddin University, Indonesia. Geochemical analyses of the Palopo samples were performed using X-ray fluorescence (XRF) at Intertek Laboratory, Jakarta, Indonesia. In contrast, geochemical analyses of the Masamba samples were carried out using XRF and inductively coupled plasma–mass spectrometry (ICP–MS) at Kyushu University, Japan.

Petrographic analysis was employed to determine rock classifications and identify textural features developed during rock formation. Geochemical analyses were undertaken to characterize the geochemical signatures of the granitoids, constrain their magma sources, and evaluate the magmatic evolution processes involved in their petrogenesis.

4. Result

4.1 Petrology and Petrographic Characteristic

The granitoid units examined in this study include the Palopo and Masamba granitoid complexes. The Palopo granitoids are represented by granodiorite, deformed granodiorite, and granite, with the occurrence of dioritic mafic enclaves. The Masamba granitoids are mainly composed of granodiorite and granite. The megascopic and petrographic features can be observed in Figure 2.

4.1.1 Palopo Granitoids

The granodiorite exhibits a phaneritic texture and is composed of andesine plagioclase (20%), pyroxene (10%), hornblende (12%), biotite (17%), orthoclase (13%), and quartz (20%), with minor opaque minerals (3%) and sericite (7%). The deformed granodiorite displays a phaneritic texture and consists of labradorite plagioclase (25–27%), pyroxene (10–12%), hornblende (5–8%), biotite (15–17%), and quartz (21–24%). Accessory minerals include opaque minerals, titanite, zircon, magnetite, and apatite, whereas alteration products comprise sericite, epidote, actinolite, chlorite, and diaspore. Both macroscopic and microscopic observations reveal a foliated fabric characterized by the preferred orientation of platy minerals, particularly biotite, and elongate quartz grains. Maulana (2019) classified this rock as exhibiting a palimpsest texture, in which the original igneous texture remains recognizable and corresponds to a blastoporphyratic type. Based on its mineralogical composition and deformation textures, this rock is classified as metagranodiorite. Sudirman et al. (2024) documented several deformation-related microstructures within the Palopo granodiorite, including feldspar porphyroblasts and partial grain fragmentation, quartz–biotite foliation, and quartz deformation features such as undulose extinction, bulging recrystallization, and lobate grain boundaries.

The granite is characterized by a porphyritic texture and consists of labradorite plagioclase (26–29%), pyroxene (5–7%), hornblende (5–7%), biotite (15–17%), orthoclase (25–27%), and quartz (18–20%), together with minor opaque minerals (1–3%). Accessory phases include titanite, zircon, magnetite, apatite, and rutile, whereas alteration minerals comprise sericite, adularia, epidote, actinolite, diaspore,

and anhydrite. The occurrence of hornblende indicates an igneous protolith source (Singtuen et al., 2023). Furthermore, the presence of magnetite and titanite suggests that hornblende crystallized under relatively oxidizing conditions (Wones, 1989).

The occurrence of foliation in the granitoid rocks indicates emplacement and deformation under collisional or compressional orogenic tectonic settings, whereas the undeformed granitoids are interpreted to have formed during late to post-orogenic tectonic stages (Kwayisi et al., 2023). Petrographic observations reveal several distinctive textures within the deformed granodiorite, including antiperthitic, myrmekitic, zoning, and poikilitic textures. The granite similarly exhibits antiperthitic, zoning, and poikilitic textures. The presence of poikilitic textures may indicate magma mingling and/or mixing between compositionally distinct magmas (Kazemi et al., 2018).

4.1.2 Masamba Granitoids

The granodiorite exhibits a phaneritic texture and is composed of quartz (30–35%), albite plagioclase (25–30%), hornblende (10–20%), orthoclase (10%), biotite (10–14%), and locally occurring muscovite (up to 14%), with zircon as an accessory mineral. The granite is characterized by a phaneritic texture and consists of K-feldspar (20%), quartz (35%), albite plagioclase (5%), hornblende (20%), and biotite (20%). Petrographic observations reveal the presence of distinctive textures within the granodiorite, including antiperthitic and poikilitic textures. In contrast, the granite is characterized by the occurrence of graphic texture. The megascopic and petrographic features can be observed in Figure 3.

4.2 Geochemistry Characteristic

Geochemical analyses indicate that the Palopo granitoids contain 64.31–67.37 wt% SiO_2 , whereas the Masamba granitoids contain 66.15–72.52 wt% SiO_2 . Based on the classification of Le Maitre et al. (1989, cited in Rollinson, 1993), these compositions are classified as felsic magmas. The results of major element geochemistry are presented in Table 1.

Rock classification based on the Total Alkali–Silica (TAS) diagram of Cox et al. (1976), using SiO_2 versus total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$), indicates that the Palopo and Masamba granitoids are composed of granodiorite and granite. Magmatic affinity was determined following the classification scheme of Peccerillo and Taylor (1976, cited in Rollinson, 1993), based on the relationship between SiO_2 and K_2O contents. The results show that the Palopo granitoids belong to the high-K calc-alkaline series, whereas the Masamba granitoids range from high-K calc-alkaline to shoshonitic affinity. The degree of alumina saturation was evaluated using the classification of Shand (1943, cited in Clarke, 1992), based on the molar ratios A/CNK [$\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$] and A/NK [$\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$]. The Palopo granitoids are characterized by metaluminous to weakly peraluminous compositions, whereas the Masamba granitoids are predominantly metaluminous. The results of the geochemical characteristic plots are shown in Figure 4.

The Palopo granitoids exhibit a high-K calc-alkaline affinity, whereas the Masamba granitoids range from high-K calc-alkaline to shoshonitic compositions. This variation suggests that the Masamba granitoids experienced a more advanced stage of magmatic evolution, resulting in the enrichment of potassium within the residual melt. Rompo et al. (2023) proposed that variations in magma series may reflect fractional crystallization processes operating after partial melting of metasomatized mantle and lower crustal sources. In general, high-K calc-alkaline granitoids are considered to originate from the partial melting of older crustal materials and/or mantle-derived sources (Gläser et al., 2022; Kwayisi et al., 2023).

5. Discussion

The granitoid rocks from the study area are classified as I-type granitoids, indicating derivation from the partial melting of igneous protoliths, as illustrated by the SiO_2 versus TiO_2 diagram. Their formation may be attributed to the partial melting of older mafic to intermediate igneous rocks within the deep crust or infracrustal levels (Chappell and White, 1992), or alternatively to the interaction and mixing of mantle-derived and crust-derived melts that contributed to continental crustal growth (Kemp et al., 2007). Geochemical investigations by Liu et al. (2020) on the Palopo granitoids revealed elevated Sr/Y ratios indicative of an adakitic geochemical signature. This suggests the involvement of lower-crustal thickening at depths exceeding approximately 50–80 km under pressures greater than 1.2–1.5 GPa, resulting in partial melting of basaltic to intermediate igneous source rocks. Such conditions are consistent with adakitic magmatism associated with crustal thickening and/or delamination processes in the lower crust.

The binary and ternary geochemical discrimination diagrams indicate that the Palopo granitoids were derived from the partial melting of high-K mafic rocks or metabasaltic source rocks. A similar source is inferred for the Masamba granodiorites, which appear to have originated from high-K mafic or metabasaltic protoliths with minor contributions from metasedimentary material. In contrast, the Masamba granites are interpreted to have been derived from tonalitic to metasedimentary source rocks. Moradi et al. (2021) attributed such geochemical characteristics to dehydration partial melting of metabasaltic–metatonalitic source rocks. Partial melting of metabasaltic rocks can generate tonalitic–trondhjemitic–granodioritic (TTG-like) magmas under optimal petrogenetic conditions of approximately 800–950°C and 10–18 kbar (Palin et al., 2016). In contrast, partial melting of metatonalitic protoliths commonly produces granitic melts, consistent with the inferred origin of the Masamba granites. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios range from 31.5 to 38.0 for the Palopo granitoids and from 27.4 to 62.0 for the Masamba granitoids. According to Sylvester (1998), relatively low $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (<100) indicate partial melting at temperatures approaching or exceeding approximately 875°C. These values therefore suggest that the parental magmas of both granitoid suites were generated under relatively high-temperature melting conditions. The results of geochemical data plots related to magma sources are presented in Figure 5.

The Mg# values of the studied granitoids range from 42.67 to 58.82, all exceeding 40. According to Rapp and Watson (1995), Mg# values greater than 40 indicate that granitoid magmas were generated through partial melting processes involving mantle-derived sources. This interpretation contrasts with the MgO versus FeO/(FeO + MgO) discrimination diagram, which suggests that the Palopo and Masamba granitoids were predominantly derived from crustal sources. This discrepancy may be explained by the different petrogenetic significance of the geochemical parameters. Mg# represents the proportion of Mg relative to Fe and is commonly regarded as an indicator of source characteristics. Therefore, elevated Mg# values may preserve evidence of mantle involvement in magma generation, whereas other geochemical indicators reflect the dominant crustal contribution. Furthermore, Liu et al. (2020) proposed that limited mixing with mantle peridotite, estimated at approximately 1–2%, contributed to the elevated Mg ratios observed in the Palopo granitoids. These results suggest that the Palopo and Masamba granitoids were primarily derived from crustal sources with a minor mantle contribution.

An alternative process that may account for these geochemical characteristics is magma mixing, as indicated by the $\text{Al}_2\text{O}_3/\text{CaO}$ versus $\text{Na}_2\text{O}/\text{CaO}$ and MgO versus Fe_2O_3 diagrams. Both diagrams support a magma mixing model followed by fractional crystallization of mafic minerals and plagioclase. This interpretation is evidenced by the progressive depletion of MgO and Fe_2O_3 contents from granodioritic to granitic compositions. The combined effects of magma mixing and subsequent fractional crystallization are further supported by systematic decreases in MgO, Fe_2O_3 , CaO, and TiO_2 contents with increasing SiO_2 concentrations. These trends are consistent with magmatic differentiation involving the removal of mafic minerals and plagioclase from the evolving melt. The results of geochemical data plots related to magma evolution are presented in Figure 6.

Additional evidence for magma mixing is provided by the occurrence of mafic enclaves within the granitoid bodies. These enclaves are characterized by elliptical to rounded shapes and mineral assemblages similar to those of the host granitoids, although with different modal proportions. They also exhibit relatively finer-grained textures and sharp contacts with the surrounding host rocks, features that are commonly associated with magma mixing processes. Petrographic observations of the host granitoids reveal the presence of poikilitic textures, which have been interpreted as evidence of mingling and/or mixing between compositionally distinct magmas (Kazemi et al., 2018). Zoning textures are also observed and are expressed as compositional zonation reflected by variations in the optical properties of individual mineral grains. According to Streckeisen (2024), such zoning records chemical variations during crystal growth related to changes in temperature, pressure, and magma composition, and may indicate fluctuations in magma replenishment. Evidence supporting magma mixing can be observed in Figure 7. The magma mixing model involves the interaction and homogenization of mafic magma, likely derived from mantle sources, with felsic magma generated within the continental crust (Kazemi et al., 2018; Teha et al., 2024). In this scenario, early crystallization and differentiation of the granitoid magma were followed by the rapid formation of mafic enclaves, probably as a result of thermal and pressure quenching. These enclaves were subsequently injected into the felsic host magma while both magmas remained partially molten. The elliptical to rounded morphology of the enclaves indicates that mixing

occurred under magmatic conditions prior to complete crystallization of the host granitoid (Kazemi et al., 2018; Moradi et al., 2021).

The SiO_2 versus $\text{Al}_2\text{O}_3/\text{CaO}$ diagram was used to evaluate magmatic evolution through fractional crystallization, particularly to distinguish between plagioclase and clinopyroxene fractionation trends (Moradi et al., 2021). The plotted data indicate that both the Palopo and Masamba granitoids were predominantly influenced by clinopyroxene fractionation. This interpretation is based on the behavior of clinopyroxene, a Ca–Mg–Fe silicate mineral, which preferentially incorporates Ca during crystallization, resulting in a decrease in CaO relative to Al_2O_3 in the residual melt. The observed trend is also consistent with adakitic magmatism, where plagioclase becomes unstable under high-pressure conditions in the lower crust. Experimental studies by Green (1967) demonstrated that plagioclase is progressively replaced by more stable mineral phases with increasing pressure, and that at pressures exceeding approximately 23 kbar and temperatures around 1100°C, plagioclase is no longer stable, whereas clinopyroxene remains stable and crystallizes together with other high-pressure mineral assemblages. The progressive increase in SiO_2 and Al_2O_3 contents from granodioritic to granitic compositions further reflects magmatic differentiation toward more evolved felsic melts. These geochemical trends suggest that fractional crystallization of clinopyroxene played an important role in the evolution of the Palopo and Masamba granitoid magmas.

Magmatic evolution is further reflected in the trace-element geochemistry of the granitoids from the study area. The rare earth element (REE) patterns are characterized by enrichment of light rare earth elements (LREEs) relative to heavy rare earth elements (HREEs), displaying a general decrease in concentration from La to Yb. The high LREE/HREE ratios indicate significant magmatic fractionation and progressive enrichment of incompatible elements within the residual melt (Koljonen and Rosenberg, 1974). This interpretation is consistent with the elevated La/Yb ratios, which range from 20.10 to 35.84. Such values indicate substantial fractionation and accumulation of incompatible elements during magma evolution. The Palopo granitoids exhibit higher La/Yb ratios than those from Masamba, suggesting a more evolved magmatic system, consistent with their derivation from high-K mafic source rocks and subsequent magmatic differentiation. Negative Eu anomalies are evident from Eu/Eu* values ranging from 0.093 to 0.287. According to Liu et al. (2025), such negative anomalies reflect plagioclase fractionation, during which Eu was preferentially incorporated into crystallizing plagioclase, resulting in Eu depletion within the residual melt. The Dy/Yb ratios are relatively low, ranging from 1.87 to 2.17. Davidson et al. (2013) suggested that such values are indicative of dominant amphibole fractionation with little to no significant garnet involvement. This interpretation implies that magma evolution and partial melting occurred predominantly under middle-crustal conditions, where amphibole remained stable while garnet was absent or only minimally involved in the residue. The results of trace element geochemistry are presented in Table 2.

Based on their geochemical characteristics, the Palopo and Masamba granitoids are classified as I-type, high-K calc-alkaline, and predominantly metaluminous granitoids. These rocks are interpreted to have originated mainly from igneous source rocks, with minor contributions from mantle-derived and

sedimentary materials. Magmatic evolution was dominated by fractional crystallization, as evidenced by the systematic decreases in MgO, Fe₂O₃, CaO, and TiO₂ contents with increasing SiO₂ concentrations, together with elevated LREE/HREE ratios. Such geochemical trends indicate progressive magmatic differentiation, which may have promoted the enrichment of volatiles and metals within the residual melt. The occurrence of magma mixing during the early stages of magma evolution may have introduced additional heat, sulfur, and metal-bearing components into the magmatic system. Subsequent intensive fractional crystallization would have further concentrated H₂O-rich fluids and metallic elements in the residual melt, thereby enhancing the potential for ore-forming processes. Petrographic evidence also supports this interpretation. The presence of alteration minerals indicates post-magmatic hydrothermal activity, while the occurrence of accessory magnetite and titanite suggests that hornblende crystallized under relatively oxidizing conditions. Previous studies have demonstrated that oxidized magmatic systems represent a key factor controlling magma fertility and the formation of hydrothermal mineralization (Shen et al., 2015; Richards, 2015). Therefore, the combined geochemical and petrographic characteristics of the Palopo and Masamba granitoids suggest that these rocks possess favorable magmatic fertility and may have significant potential for associated mineralization.

The geochemical characteristics indicate that the Palopo and Masamba granitoids were generated through interactions between mantle-derived magmas and crustal melts. This interpretation is supported by relatively high Mg# values (>40), which suggest minor mantle contributions, together with geochemical evidence for partial melting of metabasaltic to tonalitic crustal sources. Elevated Sr/Y ratios and adakitic signatures reported by Liu et al. (2020) suggest magma generation under thickened crustal conditions. The limited influence of garnet, as indicated by the relatively low Dy/Yb ratios (1.87–2.17), implies that melting likely occurred within the middle to lower crust rather than within a deep garnet-rich source. The Palopo and Masamba granitoids were emplaced during the Late Miocene–Early Pliocene magmatic flare-up recognized throughout South Sulawesi (Zhang et al., 2020). The timing of emplacement suggests that these granitoids formed as part of a regional magmatic event associated with intensified crust–mantle interactions along the southern arm of Sulawesi.

6. Conclusions

Based on field observations and laboratory analyses, the following conclusions can be drawn:

1. The granitoid rocks in the Palopo and Masamba areas are classified as I-type granitoids, consisting of granodiorite and granite. Geochemically, the Palopo granitoids are characterized by high-K calc-alkaline affinities and metaluminous to weakly peraluminous compositions, whereas the Masamba granitoids exhibit high-K calc-alkaline to shoshonitic affinities and are predominantly metaluminous.
2. The Palopo granitoids, including both granodiorite and granite, were derived from the partial melting of high-K mafic or metabasaltic source rocks. In contrast, the Masamba granodiorites originated from high-K mafic or metabasaltic sources with minor contributions from metasedimentary material, whereas the Masamba granites were derived from tonalitic to metasedimentary source rocks.

3. The Palopo and Masamba granitoids experienced significant magmatic evolution involving both magma mixing and fractional crystallization. Evidence for magma mixing is provided by the occurrence of mafic enclaves in the field and the presence of zoning and poikilitic textures observed petrographically. Fractional crystallization is reflected by systematic decreases in MgO, Fe₂O₃, CaO, and TiO₂ contents with increasing SiO₂ concentrations, together with elevated LREE/HREE ratios, pronounced negative Eu anomalies (Eu/Eu*), and high La/Yb ratios ranging from 20.10 to 35.84. These geochemical characteristics indicate progressive magmatic differentiation and enrichment of incompatible elements within the residual melt during magma evolution.

Declarations

Acknowledgments

The authors gratefully acknowledge the local authorities of the Palopo and Masamba regions for permitting this study. Appreciation is also extended to the Department of Geological Engineering, Hasanuddin University, for providing laboratory facilities and access to the Petrography Laboratory used in this research.

Funding statement: This research did not receive any specific funding from public, commercial, or not-for-profit funding agencies.

Clinical Trial Registration: Not applicable.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Consent to publish: Not applicable.

References

1. Altherr R, Holl A, Hegner E, Langer C, Kreuzer H (2000) High potassium, calc-alkaline I-type plutonism in the European Variscides: northern Vosges (France) and northern Schwarzwald (Germany). *Lithos* 50:51–73. [https://doi.org/10.1016/S0024-4937\(99\)00052-3](https://doi.org/10.1016/S0024-4937(99)00052-3)
2. Anderson JL, Smith DR (1995) The effect of temperature and fO₂ on the Al-in-hornblende barometer. *American Mineralogist* 80:549–559.
3. Cao M, Qin K, Li GM, Evans NJ, Hollings P, Jin LY (2016) Genesis of ilmenite-series I-type granitoids at the Baogutu reduced porphyry Cu deposit, western Junggar, NW China. *Lithos* 246–247:13–30. <https://doi.org/10.1016/j.lithos.2015.12.019>
4. Chappell BW, White AJR (1992) I- and S-type granites in the Lachlan Fold Belt. Published online by Cambridge University Press, 03 November 2011.

5. Clarke DB (1992) Granitoid rocks. Department of Earth Sciences, Dalhousie University, Halifax, Canada.
6. Cox KG, Bell JD, Pankhurst RJ (1979) The interpretation of igneous rocks. Springer Science+Business Media, Dordrecht.
7. Davidson J, Turner S, Plank T (2013) Dy/Dy*: variations arising from mantle sources and petrogenetic processes. *Journal of Petrology* 54(3):525–537. <https://doi.org/10.1093/petrology/egs076>
8. Gläser L, Grosche A, Voudouris PC, Haase KM (2022) The high-K calc-alkaline to shoshonitic volcanism of Limnos, Greece: implications for the geodynamic evolution of the northern Aegean. *Contributions to Mineralogy and Petrology* 177(8):73.
9. Green TH (1967) An experimental investigation of sub-solidus assemblages formed at high pressure in high-alumina basalt, kyanite eclogite and grosspydite compositions. *Contributions to Mineralogy and Petrology* 16:84–114.
10. Hall R (2002) Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, models and animations. *Journal of Asian Earth Sciences* 20(4):353–431. [https://doi.org/10.1016/S1367-9120\(01\)00069-4](https://doi.org/10.1016/S1367-9120(01)00069-4)
11. Katili JA (1978) Past and present geotectonic position of Sulawesi, Indonesia. *Tectonophysics* 45(4):289–322. [https://doi.org/10.1016/0040-1951\(78\)90166-X](https://doi.org/10.1016/0040-1951(78)90166-X)
12. Kazemi K, Kananian A, Xiao Y, Sarjoughian F (2018) Role of magma mixing in generating the Gheshlagh Aftabrow intrusions, SW Buin Zahra, Iran: evidence for a juvenile origin from geochemical and Sr–Nd isotopic data. *Geological Journal* 53:1–27.
13. Kemp AIS, Hawkesworth CJ, Foster GL, Paterson BA, Woodhead JD, Hergt JM, Gray CM, Whitehouse MJ (2007) Magmatic and crustal differentiation history of granitic rocks from Hf–O isotopes in zircon. *Science* 315:980–983.
14. Koljonen T, Rosenberg RJ (1974) Rare earth elements in granitic rocks. *Lithos* 7(4):249–261. [https://doi.org/10.1016/0024-4937\(74\)90046-2](https://doi.org/10.1016/0024-4937(74)90046-2)
15. Kwayisi D, Nyavor E, Dzikunoo EA, Fynn IEM, Kutu J, Nude PM (2023) Cryogenian–Ediacaran crustal growth and evolution of the active margin of the Dahomeyide Belt, Ghana. *Geological Magazine* 160:1914–1931. <https://doi.org/10.1017/S0016756823000808>
16. Langmuir CH, Vocke RD, Hanson GN, Hart SR (1978) A general mixing equation with applications to Icelandic basalts. *Earth and Planetary Science Letters* 37:380–392.
17. Laurent O, Martin H, Moyen JF, Doucelance R (2014) The diversity and evolution of Late Archean granitoids: evidence for the onset of modern-style plate tectonics between 3.0 and 2.5 Ga. *Lithos* 205:208–235.
18. Liu J, Zhang J, Hsia J, Xian WW, Yin C, Djoko FX, Cheng C, Zhao C, Liu X, Chen Y, Wang X (2020) Late Miocene to Pliocene crustal extension and lithospheric delamination revealed from the ~5 Ma Palopo granodioritic intrusion in Western Sulawesi, Indonesia. *Journal of Asian Earth Sciences* 201:104506.

19. Liu L, Duan M, Huang J, Song H, Lin X, Zhan Y (2025) Petrogenesis and tectonic implications of the Early Jurassic syenogranite in the northern section of Zhangguangcai Range, NE China: insights from geochronology, geochemistry, and Lu-Hf isotopes. *Frontiers in Earth Science* 13:1578301. <https://doi.org/10.3389/feart.2025.1578301>
20. Maulana A (2019) *Petrologi*. Penerbit Ombak, Yogyakarta.
21. Maulana A, Yonezu K, Watanabe K, Imai A (2013) Granitic magmatism and related ore deposit in Sulawesi, Indonesia. *Proceedings of the International Symposium on Earth Science and Technology*, Fukuoka, Japan, 3–4 December 2013.
22. Maulana A, Imai A, Van Leeuwen T, Watanabe K, Yonezu K, Takano N, Boyce A, Page L, Schersten A (2016) Origin and geodynamic setting of Late Cenozoic granitoids in Sulawesi, Indonesia. *Journal of Asian Earth Sciences* 124:102–125.
23. Moradi S, Jiang SY, Christiansen EH, Ghorbani MR (2021) Petrogenesis of Tertiary granitoid rocks from east of the Bidhand Fault, Urumieh-Dokhtar Magmatic Arc, Iran: implication for an active continental margin setting. *Lithos* 400–401:106422.
24. Palin RM, White RW, Green ECR (2016) Partial melting of metabasic rocks and the generation of tonalitic-trondhjemitic-granodioritic (TTG) crust in the Archaean: constraints from phase equilibrium modeling. *Precambrian Research*. <https://doi.org/10.1016/j.precamres.2016.11.001>
25. Polvé M, Maury RC, Bellon H, Rangin C et al. (1997) Magmatic evolution of Sulawesi (Indonesia): constraints on the Cenozoic geodynamic history of Sundaland active margin. *Tectonophysics* 272(1):69–92. [https://doi.org/10.1016/S0040-1951\(96\)00276-4](https://doi.org/10.1016/S0040-1951(96)00276-4)
26. Priadi B, Polvé M, Maury RC et al. (1994) Tertiary and Quaternary magmatism in Central Sulawesi: chronological and petrological constraints. *Journal of Southeast Asian Earth Sciences* 9(1–2):81–93. [https://doi.org/10.1016/0743-9547\(94\)90067-1](https://doi.org/10.1016/0743-9547(94)90067-1)
27. Priadi B, Surono, Hartono U (2013) *Geologi Sulawesi*. LIPI Press, Jakarta.
28. Rapp RP, Watson EB (1995) Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust–mantle recycling. *Journal of Petrology* 36:891–931.
29. Richards JP (2015) The oxidation state, and sulfur and Cu contents of arc magmas: implications for metallogeny. *Lithos* 233:27–45. <https://doi.org/10.1016/j.lithos.2014.12.011>
30. Rollinson HR (1993) *Using geochemical data: evaluation, presentation, interpretation*. Longman Group UK Ltd, London.
31. Rompo I, Ismail F, Santoso SB, Rosana MF, Yuningsih ET (2023) Petrogenesis of igneous complex of Iloa Nanasi gold deposit, Gunung Pani, Gorontalo, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology* 8(4).
32. Satyana AH, Faulin T, Mulyati SN (2011) Tectonic evolution of Sulawesi area: implications for proven and prospective petroleum plays. *Proceedings JCM Makassar 2011, The 36th HAGI and 40th IAGI Annual Convention and Exhibition*.
33. Shen P, Hattori K, Pan H, Jackson S, Seitmuratova E (2015) Oxidation condition and metal fertility of granitic magmas: zircon trace-element data from porphyry Cu deposits in the Central Asian

- Orogenic Belt. *Economic Geology* 110:1861–1878.
34. Singtuen V, Phajuy B, Wichaiya K (2023) Geochemical characteristics of arc fractionated I-type granitoids of eastern Tak Batholith, Thailand. *Open Geosciences* 15:20220528.
 35. Sudirman, Maulana A, Umar H (2024) Petrographic study of granitoid rocks of Latuppa Area, Palopo, South Sulawesi, Indonesia: implications for mineralization style. *Proceedings of the 2nd International Conference on Research in Engineering and Science Technology (IC-REST 2024)*.
 36. Streckeisen A (2024) Zoning. Available at: <https://www.alexstrekeisen.it> (accessed 15 Juni 2026).
 37. Sukanto R (1975) The structure of Sulawesi in the light of plate tectonics. *Proceedings of the Regional Conference on the Geology and Mineral Resources of Southeast Asia, Jakarta, 4–7 August 1975*.
 38. Sylvester PJ (1998) Post-collisional strongly peraluminous granites. *Lithos* 45:29–44.
 39. Tarney J (1977) Petrology, mineralogy, and geochemistry of the Falkland Plateau basement rocks, Site 330, Deep Sea Drilling Project.
 40. Teha KR, Pria KK, Brou KJ, Kouamelan AN, Allialy EM, M'Rabet S (2024) Magma mixing genesis of the mafic enclaves and related granitoids in the Kan Granite-Gneiss Complex of Central Côte d'Ivoire: evidence from geology, petrology and geochemistry. *Open Journal of Geology* 14:760–786.
 41. Van Leeuwen T, Maulana A (2025) *Geology of the Sulawesi Region*. Unhas Press, Makassar.
 42. White LT, Hall R, Armstrong RA, Barber AJ (2014) The geological history of the Latimojong Region of Western Sulawesi. *Journal of Asian Earth Sciences*.
 43. Wones DR (1989) Significance of the assemblage titanite + magnetite + quartz in granitic rocks. *American Mineralogist* 74:744–749.
 44. Zhang X, Tien CY, Chung SL et al. (2020) A Late Miocene magmatic flare-up in West Sulawesi triggered by Banda slab rollback. *GSA Bulletin* 132(11–12).
 45. Zorpi MJ, Coulon C, Orsini JB (1991) Hybridization between felsic and mafic magmas in calc-alkaline granitoids: a case study in northern Sardinia, Italy. *Chemical Geology* 92:45–86.

Tables

Table 1. Major-element geochemical compositions of granitoid rocks from the Palopo and Masamba areas.

Oksida Utama	Sampel Id					
	BA-01A (wt%)	BA-04 (wt%)	SG-04 (wt%)	SM-01 (wt%)	SM-17 (wt%)	SM-26 (wt%)
SiO ₂	65,02	64,31	67,37	66.96	66.15	72.52
Al ₂ O ₃	16,43	16,71	15,92	15.07	14.54	13.63
Fe ₂ O ₃	3,61	4,25	3,07	2.97	3.85	1.82
CaO	3,96	4,63	3,02	3.58	3.94	1.5
Na ₂ O	3,65	3,58	3,47	2.39	2.49	3.99
K ₂ O	3,61	2,83	3,93	4.32	4.59	4.96
MgO	2,57	2,42	1,81	2.38	2.44	0.76
MnO	0,05	0,07	0,04	0.05	0.08	0.05
P ₂ O ₅	0,17	0,174	0,15	0.13	0.22	0.05
TiO ₂	0,48	0,53	0,42	0.55	0.53	0.22

Table 2. Trace-element compositions of granodiorite samples from the Palopo and Masamba areas. Samples 18SS09-1, 18SS10-1, and 18SS11-1 are from Liu et al. (2020), whereas samples SM-01, SM-17, and SM-26 were analyzed in this study.

Sample	SM-01	SM-17	SM-26	18ss09-1	18ss10-1	18ss11-1
LREE						
La	29.3	64.5	39	45.9	40.5	34.2
Ce	58.5	112	75.6	85.1	78.3	67.3
Pr	6.72	11.2	8.67	9.01	8.51	7.67
Nd	23.6	40.3	32.5	32.2	30.1	29
Sm	4.42	7.38	6.45	5.33	4.91	5.26
HREE						
Gd	4.01	6.45	5.07	3.98	3.42	4.12
Tb	0.55	0.98	0.72	0.55	0.48	0.59
Dy	2.84	5.04	4.04	2.94	2.45	3.25
Ho	0.53	0.95	0.84	0.55	0.45	0.62
Er	1.52	2.76	2.21	1.5	1.22	1.69
Tm	0.21	0.4	0.31	0.22	0.17	0.24
Yb	1.33	2.69	1.94	1.42	1.13	1.59
Eu	1.21	1.56	0.53	1.13	0.96	1.11

Figures

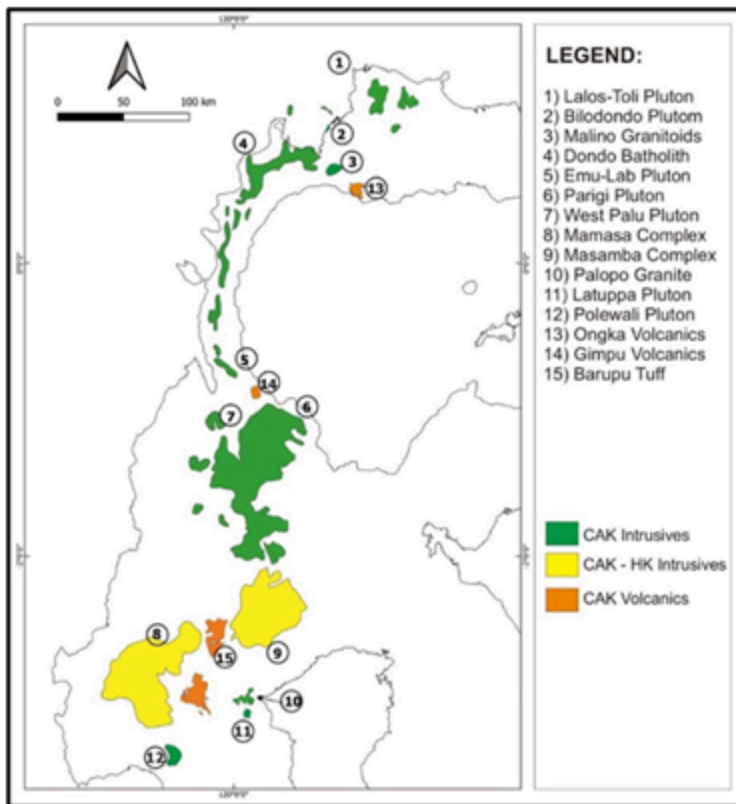


Figure 1

Distribution map of intrusive rocks, including the Masamba Complex and Palopo Granite (modified after Maulana et al., 2016).

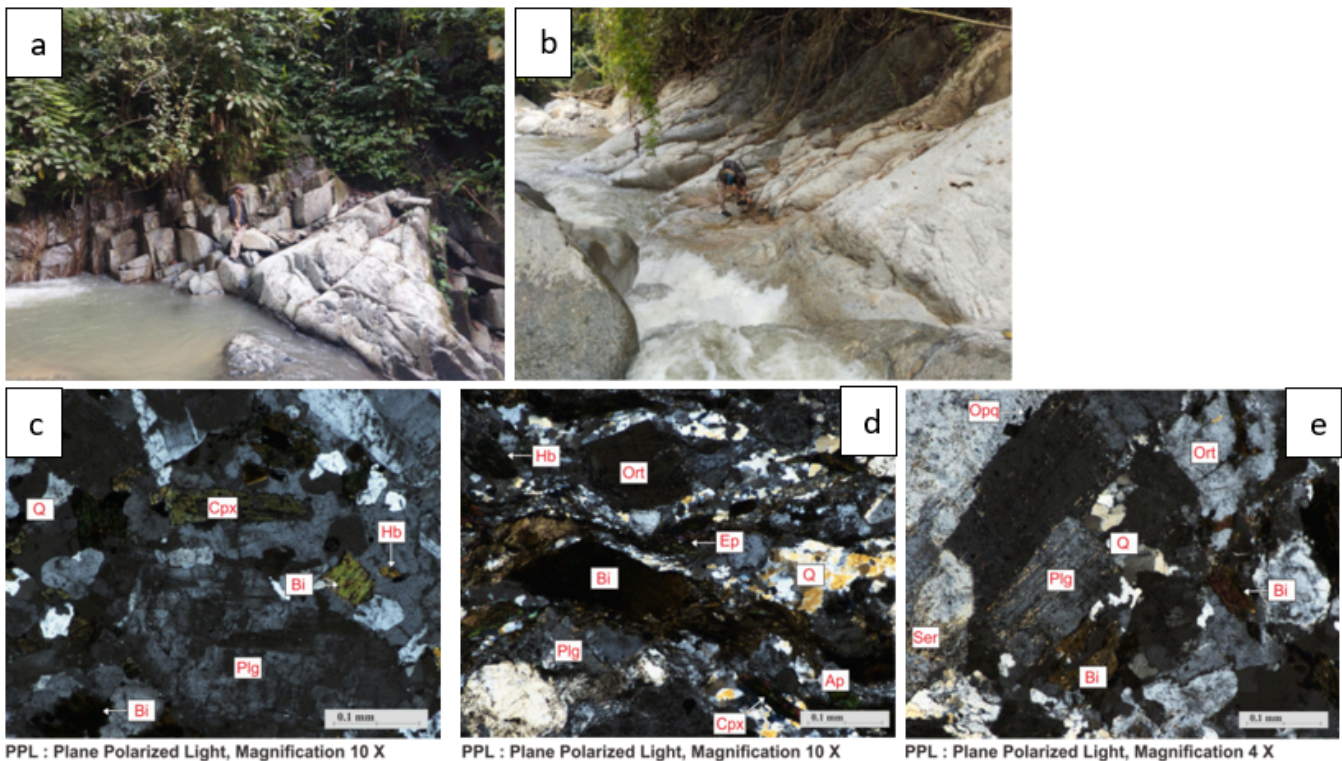


Figure 2

Representative outcrop and petrographic characteristics of the Palopo granitoids: (a) granodiorite outcrop, (b) granite outcrop, (c) photomicrograph of granodiorite, (d) photomicrograph of deformed granodiorite, and (e) photomicrograph of granite.

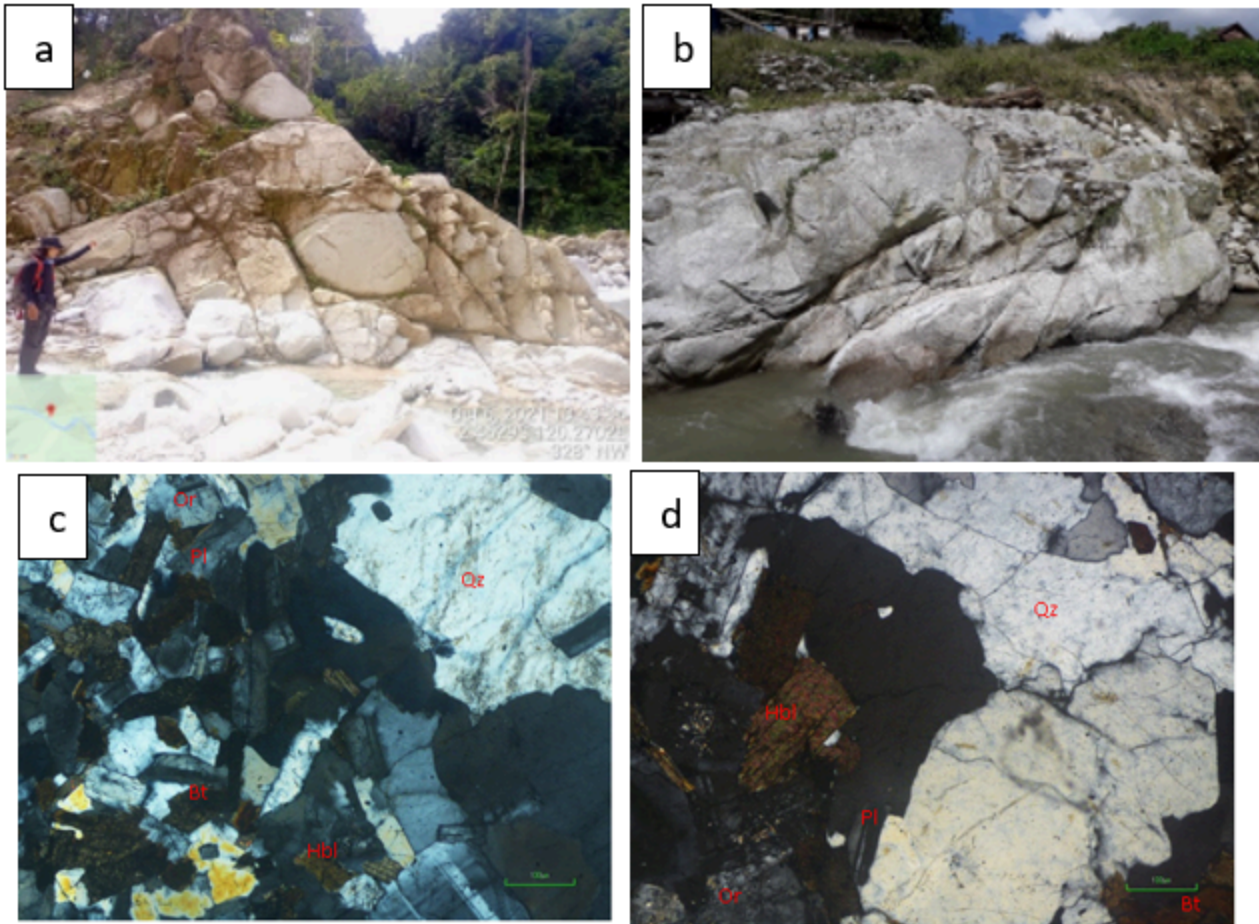


Figure 3

Field and petrographic features of the Masamba granitoids. (a) Granodiorite outcrop, (b) granite outcrop, (c) photomicrograph of granodiorite, and (d) photomicrograph of granite.

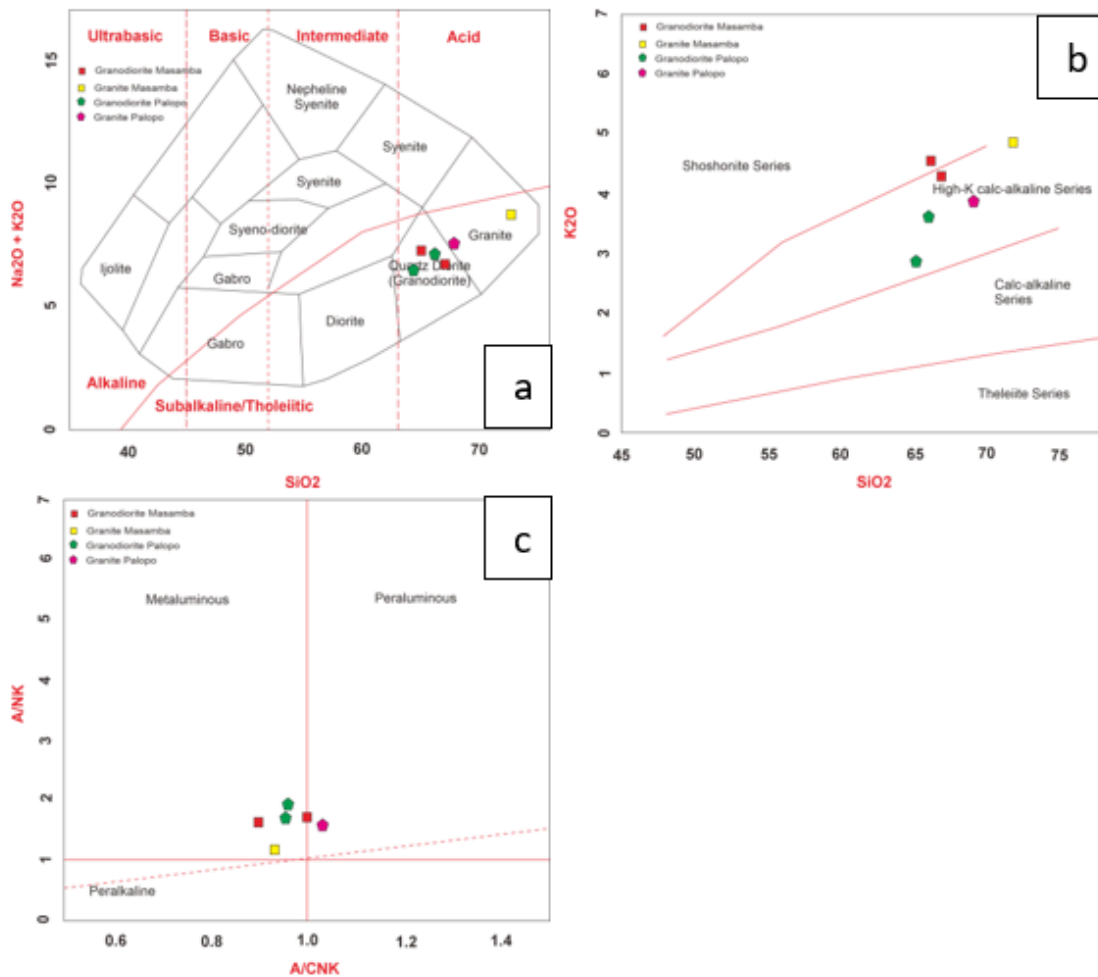


Figure 4

Geochemical characteristics of the granitoids from the study area: (a) rock classification diagram based on SiO_2 versus total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) using the TAS classification of Cox et al. (1979); (b) magma affinity diagram based on SiO_2 versus K_2O following the classification of Peccerillo and Taylor (1976, cited in Rollinson, 1993); and (c) alumina saturation diagram based on the A/CNK and A/NK ratios according to Shand (1943, cited in Clarke, 1992).

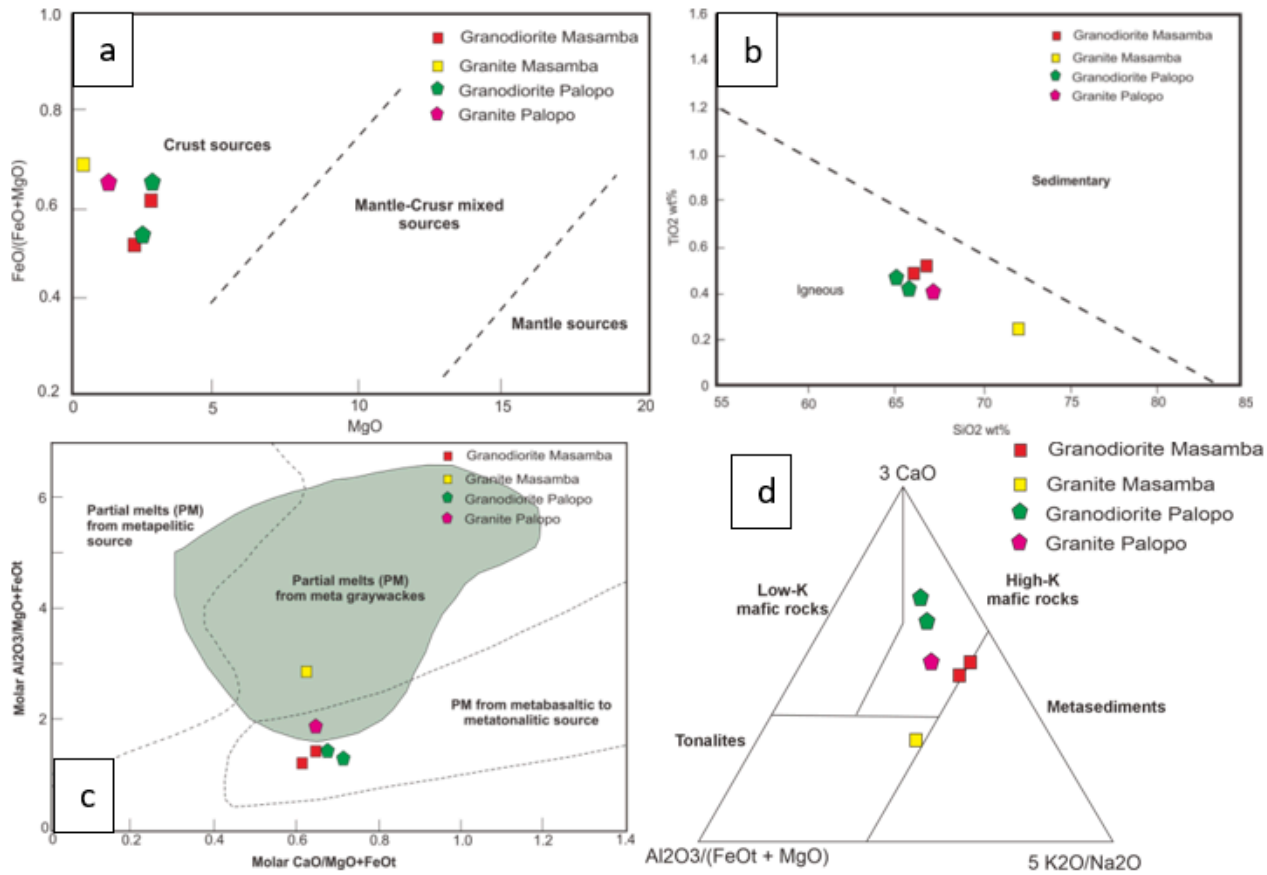


Figure 5

Magma source discrimination diagrams for the granitoids from the study area: (a) MgO versus FeO/(FeO + MgO) diagram (Altherr et al., 2000); (b) SiO₂ versus TiO₂ diagram (Tarney, 1977); (c) molar CaO/(MgO + FeO) versus Al₂O₃/(MgO + FeO) diagram (Altherr et al., 2000); and (d) ternary Al₂O₃/(FeO + MgO)–5K₂O/Na₂O–3CaO diagram (Laurent et al., 2014).

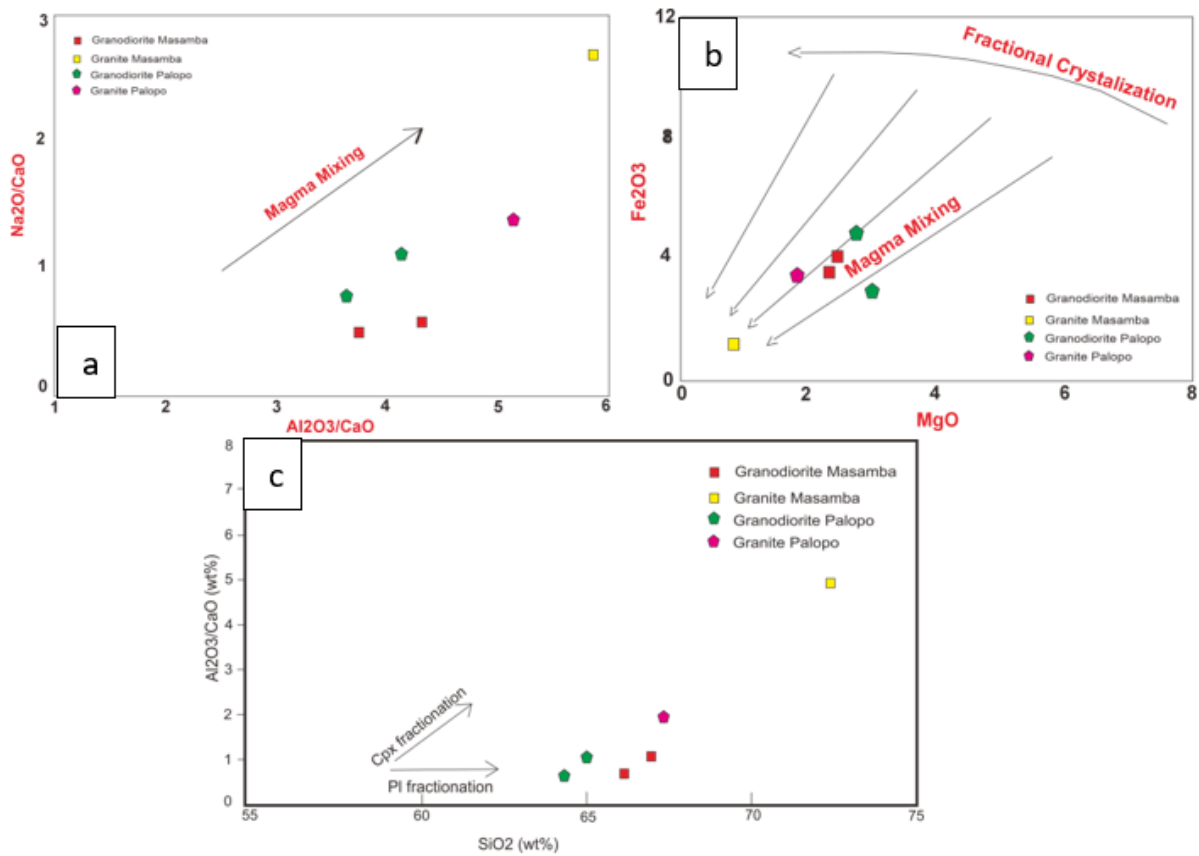


Figure 6

Geochemical diagrams illustrating the magmatic evolution of the granitoids from the study area: (a) $\text{Al}_2\text{O}_3/\text{CaO}$ versus $\text{Na}_2\text{O}/\text{CaO}$ diagram (Langmuir et al., 1978); (b) MgO versus Fe_2O_3 diagram (Zorpi et al., 1991); and (c) SiO_2 versus $\text{Al}_2\text{O}_3/\text{CaO}$ diagram (Moradi et al., 2021).

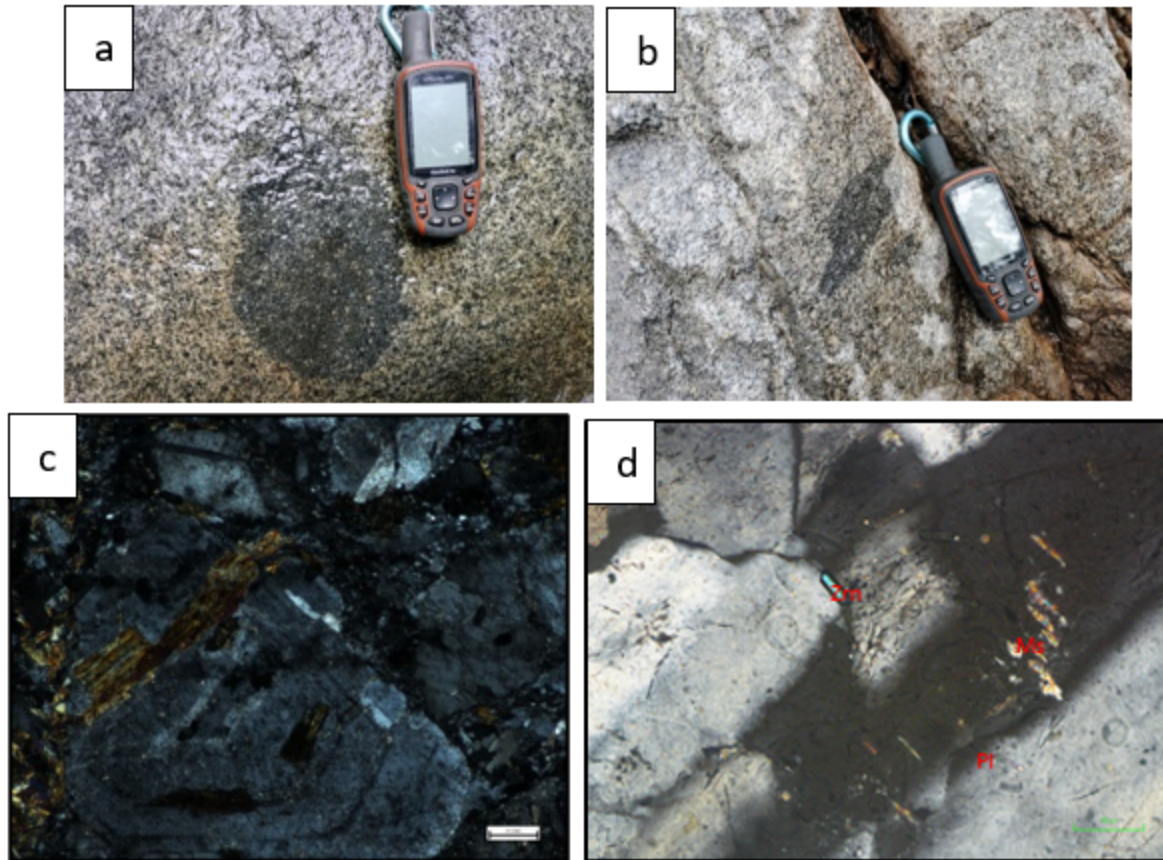


Figure 7

Evidence for magma mixing in the studied granitoids: (a) mafic enclave within the Palopo granodiorite, (b) mafic enclave within the Palopo granite, (c) photomicrograph showing zoning and poikilitic textures in the Palopo granite, and (d) photomicrograph showing poikilitic texture in the Masamba granodiorite.