

Mineral Geochemical Implications in the Thermo-Barometric Conditions and Petrogenesis of the Bougouni Plutonic Complex, in Southern Mali (Léo-Man Shield, West African Craton)

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Abstract: The Bougouni Pegmatite Province is recognized as the largest in west Africa. It comprises lithium-bearing pegmatites, which are associated with Paleoproterozoic rock lithology of Bougouni unit. In west Africa, the Paleoproterozoic rocks show alternation between metasedimentary units, greenstone belt and intrusive plutons. Plutonic intrusions are well distributed across the Léo-Man Shield and essential for understanding the evolution of Paleoproterozoic crust. This study highlight new petrographic and minerals chemical data of Bougouni unit. In this Unit, the metasedimentary rocks comprise two main types of metasedimentary sequence: coarse-grained (metagreywacke, schist and conglomerate) and fine-grained (siltstones and argillites). The Bougouni plutonic complex comprises a wide variety of rocks, range from diorite to two-mica monzogranites. They contain calcic amphibole, magnesium-rich biotite, plagioclase (albite to labrador), alkali feldspar (perthite, microcline), quartz, primary muscovite, and accessory minerals (e.g., titanite, magnetite, epidote, apatite, zircon etc.) in varying proportions. The chemical compositions of amphiboles, biotites and feldspars control the substitution relationships within these minerals and lithologies. Plutonic rocks are subalkaline (calc-alkaline) and range from metaluminous to slightly peraluminous in composition. They are crystallized under conditions of high fO_2 ($\Delta NNO = 1.13 \pm 0.65$ with pressure 2.75 ± 1.47 kbar and temperature $757 \pm 44^\circ\text{C}$). These are thought mostly of type I with a low S tendency in composition. They seem have formed during the subduction setting near-collisional.

Keywords: Mineral Chemistry; Crystallization; Magma Source; Thermometry; Barometry, Fugacity; Geodynamic Setting; WAC.

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I. INTRODUCTION

To understand the main geological processes (particularly magmatic processes) behind chemical variation in plutonic rocks requires evaluating parameters such as pressure, temperature and fugacity.

The most widely used thermobarometers are the QUILF (quartz-ulvospinelle-ilmenite-fayalite) program of Andersen et al. (1993), the titanium in calcium amphibole (Ti-Amp) of Liao et al. (2021) and the two-phase titanomagnetite-ilmenite (Anderson and Lindsley, 1988), muscovite - biotite (Hoisch, 1989 and Wu, 2020) and amphibole-plagioclase (Holland and Blundy, 1994) thermometers. However, these geothermobarometers, calibrated on the equilibrium of two or

more phases, are difficult to apply to hybrid and/or rehomogenized magmas (Devine et al., 2003 and Ridolfi et al., 2008). Empirical barometers that use aluminum content have been calibrated using experimental results on calc-alkaline granitoid or rhyolitic rocks (Johnson and Rutherford, 1989a and Ridolfi et al., 2010). These barometers are commonly used to estimate the pressure, and, consequently, the depth, of felsic and intermediate magmas (Ridolfi et al., 2010 and Mutch et al., 2016).

Amphiboles are often been regarded as "chemical dustbins" due to their wide range of compositions (Cawthorn and O'Hara, 1976). Studies by Raase (1974), Laird and Albee (1981), Spear (1981), Ellis and Thompson (1986), Holland and Blundy (1994), Ridolfi et al., (2008), Ridolfi et al. (2010), Ridolfi and Renzulli (2012) and Liao et al. (2021), have clarified the relationship between the chemical composition of amphiboles and their crystallization conditions. These studies have also clarified the relationships between pressure, temperature and oxygen fugacity on the one hand, and the chemical composition of the magma from which the amphiboles crystallized. Nearly all of these authors have demonstrated that the total aluminum content (Al_{tot}) of amphiboles reliably indicates the conditions (temperature, pressure, fugacity etc.) of igneous systems. According to these authors, barometers can only be applied correctly if the following prerequisites are met: i) a critical mineral assemblage of quartz, plagioclase, alkali feldspar, hornblende, biotite, apatite, zircon, titanite and Fe-Ti oxide; ii) the presence of Tschermakite substitution; iii) the presence of Edenitic substitution, and iv) high oxygen fugacity. And Anderson, (1996) recommends to use only hornblende with $Fe^{\#} = (Fe / (Fe + Mg)) \leq 0.65$ for geobarometry. As with the geobarometers, the aforementioned authors have proposed geothermometers to estimate granitoid temperatures. Oxygen fugacity (fO_2) or nickel-nickel-oxide (ΔNNO) are the parameter that control the redox state of magma. It depends on the magmatic source, which affects mineral composition, magmatic process control, crystallization sequence, and crystallized mineral types (Ishihara, 1977; Loiselle and Wones, 1979; Abbott and Clarke, 1979; Gill, 1981; Abbott, 1985; Wones, 1989; Botcharnikov et al., 2005; France et al., 2010).

Similar to amphiboles, the chemical composition of biotite enables us to study the physicochemical characteristics of its parent magma, including temperature, pressure, and oxygen fugacity (Munoz, 1984; Munoz, 1992; Henry et al., 2005 and Uchida et al., 2007a). Biotite is a major Ti-bearing mineral phase in igneous rocks. The replacement of this element in the structure of biotite is directly linked to temperature. Henry et al. (2005) propose using the Ti content of biotite as a geothermometer for graphitic and peraluminous metapelites containing ilmenite or rutile at a pressure of 4 to 6 kbar and Cesare et al. (2008) and Wu and Chen (2015) have applied this method to granitoids and pegmatitic rocks. Uchida et al. (2007a) proposed an empirical equation to estimate the solidification pressure of barren and fertile intrusions in Japan based on the aluminum content of biotite. Their study revealed a correlation between the Al content of biotite and that of the Al content of hornblende (i.e. the

hornblende geobarometer), implying that the Al^{IV} content of biotite can be used as a geobarometer. According to the calibration by Wones (1989), the oxygen fugacity (fO_2) of intrusions can be estimated based on the $Fe^{2+}/(Fe^{2+} + Mg^{2+})$ content of biotite associated with magnetite and alkali feldspar..

The Bougouni Formation is located in the center of the Paleoproterozoic formations in southern Mali, Baoulé-Mossi domain, the Léo-Man Shield, West African Craton (Figure 1). The Baoulé-Mossi domain are characterized by basin-shaped greenstone belts and dome-shaped granitic batholiths. These rock units were formed during the growth and collision of the Eburnean crust, between 2.2 and 1.8 Ga (Abouchami et al., 1990; Liégeois et al., 1991; Eisenlohr and Hirdes, 1992; Feybesse et al., 2006; Baratoux et al., 2011; De Kock et al., 2012; Block et al., 2016; Tshibubudze et al., 2013; Petersson et al., 2016; Wane et al., 2018; Grenholm et al., 2019; Blenkinsop et al., 2020; Masurel et al., 2022; Traoré et al., 2022 and Sanogo, 2022). The number of deformation phases observed and interpreted in the Eburnean cycle varies considerably depending on the author and the region studied (Liégeois et al., 1991; Milési et al., 1992; Hein, 2010; Lompo, 2010; Baratoux et al., 2011; Block et al., 2016; Wane et al., 2018; Masurel et al., 2022; Traoré et al., 2022) and Sanogo et al., 2026).

This paper presents new detailed fieldwork, petrographic and mineral chemistry data on the plutonic rocks of the Bougouni Pegmatite Province. These data are combined with a set of data from the literature. Integrating the data, particularly that obtained on the amphiboles, plagioclases and biotite of the intrusive will help constrain the intensive parameters (pressure, temperature and oxygen fugacity) acting during magma crystallization. The data also provide relevant information on the affinities and nature of plutonic rocks series.

➤ Geological Setting

The Bougouni town, the capital of the region with the same name, is located in southern Mali. The Bougouni unit covers the center of the southern Mali's Paleoproterozoic domain (Figure 1). It's part of the Baoulé-Mossi domain of the Léo-Man Shield of the West African Craton (WAC), which forms the bedrock of West Africa (Bessoles, 1977 and Rocci et al., 1991).

The WAC comprises 1.5 million km² of Archean rock and 3 million km² of Paleoproterozoic rock covering 4.5 million km² (Grenholm et al., 2019). It stabilized around 1.7 Ga (Grenholm et al., 2019; Black and Fabre, 1983 and Ikenne et al., 2017). It is bounded to the east by the Pan-African Dahomeyid, Gourma and Pharusid Ranges (Tuareg Shield and Benin Nigeria Shield), to the north by the High Atlas (continuity of the Reguibat Shield) (Ennih and Liégeois, 2008), to the west by the Mauritanides-Rokelides chain, and to the south by the Atlantic Ocean (Figure 1). The Léo-Man Shield exhibit a western Archean domain (3.6–2.6 Ga) and an eastern Paleoproterozoic domain (2.3–1.96 Ga) (Cahen et al., 1984; Boher et al., 1992; Potrel et al., 1996; Kouamelan et al., 1997; Thiéblemont et al., 2004; Wane et al., 2018 and

Grenholm et al., 2019). The Baoulé-Mossi domain consists of Paleoproterozoic rocks. It includes elongated greenstone belts, expansive volcanic sedimentary basins, and significant amounts of plutonic and gneissic rocks (Bessoles, 1977; Milési et al., 1992a; Liégeois et al., 1991; Feybesse et al., 2006; Baratoux et al., 2011; Tshibubudze et al., 2013; Petersson et al., 2016; Wane et al., 2018; Masurel et al., 2022 and Traoré et al., 2022). The Eburnean orogeny, which occurred from 2.27 to 1.96 Ga affected the Paleoproterozoic units of the Baoulé-Mossi domain (Wane et al., 2018; Grenholm et al., 2019 and Traoré et al., 2022).

The Eburnean orogeny was accompanied by green schist and amphibolite-type metamorphism, as well as by the juxtaposition of crustal domains with varying degrees of deformation, and the emplacement of large volumes of calc-alkaline to locally alkaline granitoids (Grenholm et al., 2019).

The region southern Mali within the Baoulé-Mossi domain is structured by three major shear zones (Yanfolila, Banifing and Syama) and four major basins (Siguiri-Kangaba, Yanfolila, Bougouni-Kékoro and Bagoé) (Feybesse, J.-L. et al., 2006 and Wane et al., 2018). The shear zones crosscut the greenstone belts according to the latter authors. The Bougouni Pegmatite Province (Sanogo et al., 2025) is framed by the Banifing and Yanfolila Shear Zones (Sanogo et al., 2026). The Paleoproterozoic Bougouni plutonic complex area, which are the subject of the present study, are located on the northern margin of the Leo-Man Shield (Figure 1). These units are hosted by the Bougouni-Kékoro metasedimentary basin (BKB) (Feybesse, J.-L. et al., 2006; Sanogo et al., 2025 and Sanogo et al., 2026). The BKB is characterized by the spectacular development of lithium-rich spodumene pegmatites (Wilde et al., 2021; Sanogo et al., 2025; Traore et al., 2026 and Sanogo et al., 2026).

Plutonic complex and pegmatite dykes are currently the focus of much industrial exploration, yet few fundamental studies have been devoted to them. The thermobarometric conditions and petrogenesis relationships of these magmatic units remain largely undiscussed.

II. MATERIALS AND METHODS

➤ Sampling and Analysis Techniques

Outcrop identification was based on various project reports, including those from mapping and prospecting reports, as well as a village survey. Samples were taken from and freshest parts of the outcrops. A macroscopic description was made of each outcrop observation area (Table 1), including those that were not sampled. Samples were taken from all lithology varieties of plutonic rocks in our study. More than 40 samples for polished thin sections at the lithogrinding workshop at the Earth Sciences Department at University of Lille (see Appendix I: List of Outcrops and Samples). All thin sections were observed and described in detail (Table 2) using an Olympus BX 60 polarizing optical microscope equipped with a high-resolution SPOT Flex camera controlled by SPOT Advanced software. This setup, located in the Earth Sciences Department at the University of Lille, was used to define the mineralogical paragenesis of

each sample and classify the samples into lithology groups. Representative samples from each lithology group were selected for further analysis. Representative samples (19 thin sections in total) of each lithology group were analyzed using a Labram HR800/Jobin Yvon/UV-532 nm Raman microspectrometry, driven by Lab-Spec 5 software. The analyses were performed at the Earth Sciences Department, University of Lille using on an optical platform with the frequency range of 100 to 1,500 cm^{-1} . The goal was to refine paragenesis and identify accessory phases. Some of the thin sections (8 thin sections in total) were also analyzed using a Quanta 200 scanning electron microscope equipped with an energy dispersive spectrometer at the electronic platform at the Earth Sciences Department at the Lille University. To characterize the chemical compositions and variations, 607 analyses were conducted. These included 200 analyses of amphiboles, 130 analyses of black ferromagnesian micas, 130 analyses of plagioclases, 36 analyses of alkali feldspars, 14 analyses of white micas (see Appendix II). Minerals were analyzed from the center to the periphery of the mineral sections (two to four analyses per section).

➤ Calculating the Structural Formulas of Solution Minerals

All microprobe results are available in Appendix II. A summary table of the geochemical compositions are provided for each mineral group (Tables 3–7).

• Amphiboles

The amphibole are geochemistry classified after Hawthorne et al. (2012). This classification categorizes amphibole chemical analyses into groups, subgroups and species (Hawthorne et al., 2012). The classification system is based on recommendations approved by the International Mineralogical Association (IMA) Commission on the Nomenclature and Classification of New Minerals (CNMNC), and published by Hawthorne et al., (2012). Elements are assigned to the general amphibole formula, $\text{A}_0\text{B}_2\text{C}_5\text{T}_8\text{O}_{22}\text{W}_2$. The T set corresponds to the elements Si, P, Be, Al, and Ti. The C set corresponds to $\text{Mg}^{2+} > \text{Fe}^{2+} > \text{Mn}^{2+} > \text{Li}^+$, Fe^{3+} , and Al^{3+} . The B set corresponds to Mn^{2+} , Fe^{3+} , Mg^{2+} , Li^+ , and Al^{3+} . The A set corresponds to the remaining cations Ca^{2+} , Li^+ , Na^+ , Pb^{2+} , and K^+ . The W set corresponds to OH^- , F^- , Cl^- , and O^{2-} . All formula calculations are based on 24 anions (OH^- , F^- , Cl^- , and O^{2-}) and there are no vacant anion sites. All amphibole chemical compositions and structural formulas are presented in Appendix II, and a summary is provided in Table 3.

Almost all of the calculated analyses in Table 3 indicate that $(\text{Ca} + \text{Na})^{\text{B}} \geq 1.00$ and $\text{Ca}^{\text{B}} \geq 1.50$ for all amphibole-bearing lithologies. These results suggest that our amphiboles are monoclinic calcic amphiboles (Leake et al., 1997). The $\text{Fe} / (\text{Mg} + \text{Fe})$ ratios are all below 0.65.

• Micas

✓ Black Micas (Biotite)

The structural formula calculation for black micas is based on the classification, nomenclature and notation system developed and approved by the International Mineralogical Association. This is a Microsoft Excel spreadsheet was

created by Dymek (1983). The general formula for black micas is $XY_{2-3}Z_4O_{10}(OH, F, Cl)_2$. The X set corresponds to K, Na, Ca, Rb, Cs and Ba. The Y set corresponds to Mg^{2+} , Fe^{2+} , Al^{3+} , Li^+ , Ti^{4+} , Mn^{2+} , Zn^{2+} , Cr^{3+} , V^{4+} , Ni^{2+} , etc. The Z set corresponds to Si^{4+} , Al^{3+} , and Fe^{3+} . The formula is calculated based on 11 oxygen atoms.

Black micas were analyzed in all lithologies containing them. The chemical compositions and structural formulas of the black micas are presented in the Appendix II, and a summary is provided in Table 4.

✓ White Micas (*Muscovite*)

The calculation of the structural formulas for white micas is based on the nomenclature and notation classification system developed and approved by the International Mineralogical Association (Rieder et al., 1999). The general formula is: $IM_{2-3}\square_{1-0}T_4O_{10}W_2$. The I set corresponds to K^+ , Na^+ , Ca^{2+} , Rb^+ , Cs^+ , Ba^{2+} , NH_4^+ , etc. The M set corresponds to Mg^{2+} , Fe^{3+} , Al^{3+} , Li^+ , Ti^{4+} , Mn^{2+} , Zn^{2+} , Cr^{3+} , V^{4+} , etc. The $\square$ set corresponds to the lacuna. The T set corresponds to Si^{4+} , Al^{3+} , and Fe^{3+} . The W set corresponds to OH-, F-, Cl-, O2-, and S2-. This formula is calculated based on 11 oxygen atoms.

White micas have been identified in a single group of plutonic lithology corresponding to two-mica monzogranites. The chemical compositions and structural formulas of the white mica are presented in Appendix II, and a summary is provided in Table 5.

• Feldspars

Feldspar is present in all Bougouni plutonic rock lithologies. Analyses have been conducted on feldspar minerals in nearly all of these lithologies. The general formula for feldspar is calculated from the general formula XY_4O_8 , where X and Y represent different cations. X corresponds to Ca^{2+} , Na^+ , and K^+ . The Y corresponds to Al^{3+} and Si^{4+} .

✓ Plagioclases

All of the plagioclase chemical compositions and structural formulas are presented in Appendix II, and a summary is provided in Table 6. The compositions range from labrador ($An = 58.02$) to albite ($An = 0.01$) and span the range of mafic to felsic lithology varieties (Table 5). The range of compositions within each lithology is less extensive. Only the plagioclases of granodiorites exhibit a broader range of compositions, due to the existence of three varieties in this rock group.

✓ Alkali Feldspars

Alkali feldspar was only identified in four granitoid rock lithologies. The synthesized analytical results are presented in Table 7.

• Process for Calculating Temperature (T), Pressure (P) and Oxygen Fugacity (ΔNNO)

Amphiboles with Si values below 7.50 apfu are considered magmatic (Leake et al., 1997). Six equations, established by different studies were used and compared to

calculate the emplacement pressures of the Bougouni plutonic complex rocks: i) $P (+0.6 \text{ kbar}) = -3.01 + 4.76 \cdot Al_{tot}$ (Schmidt, 1992); ii) $P = 0.5 + 0.3318 \cdot Al_{tot} + 0.9954 \cdot (Al_{tot})^2$ (Mutch et al., 2016); iii) $P (\pm 3 \text{ kbar}) = -3.92 + 5.03 \cdot Al_{tot}$ (Hammarstrom and Zen, 1986); iv) $P (\pm 1 \text{ kbar}) = -4.76 + 5.64 \cdot Al_{tot}$ (Hollister et al., 1987); v) $P (\pm 0.5 \text{ kb}) = -3.46 + 4.23 \cdot Al_{tot}$ (Johnson and Rutherford, 1989b); vi) $P = 19.209 \cdot \exp(1.438 \cdot Al_{tot})$ (Ridolfi et al., 2010). To estimate the temperature of the Bougouni lithologies, we used the Hollister et al. (1987), calibration eg., $T (^{\circ}C) = 1781 - 132.74 \cdot Si + 116.6 \cdot Ti_{tot} - 69.41 \cdot Fe_{tot} + 101.62 \cdot Na_{tot}$. Fugacity values are calculated using the calibration of Ridolfi et al. (2010) ($\Delta NNO = 1.644 \cdot (Mg + Si/47 - {}^CAl/9 - 1.3 \cdot {}^CTi + {}^BFe/3.7 + {}^CFe/5.2 + {}^BCa/20 - {}^ANa/2.8 + A/[9.5] - 4.01)$).

The exchange temperature for biotite is calculated using the following equation: $T (^{\circ}C) = \{[\ln(Ti) - a - c(XMg)^3] / b\}^{0.333}$ (Henry et al., 2005). Ti (apfu) was recalculated based on 22 oxygen atoms; $a = -2.3594$; $b = 4.6482 \times 10^{-9}$ et $c = -1.7283$; $XMg = Mg/(Mg+Fe)$. The equation for estimating solidification pressure with Al-in biotite method is as follows: $P (\text{kbar}) = 3.03 \cdot Al^{IV} - 6.33$ (Uchida et al., 2007b).

III. PETROGRAPHIC CHARACTERIZATION OF THE BOUGOUNI LITHOLOGIES

➤ Field Observations and Macroscopic Characterization of Bougouni Rocks

The Bougouni Pegmatite Province (BPP) consists of three rock groups: metasediments, intrusive plutonic rocks and following pegmatite dykes (Figure 2). In this section, we describe metasediments and plutonic rocks. The macroscopic description of dykes has already been carried out in (Sanogo et al., 2025).

• Metasedimentary Rocks.

The metasedimentary rocks of the Bougouni area comprise two main types of metasedimentary sequence. There are: coarse-grained and fine-grained. They exhibit subvertical to vertical schistosity (Figure 3a).

✓ Coarse-Grained Metasediments.

Coarse-grained metasediments (Figure 3) are highly resistant to weathering, and therefore prevalent as outcrops. This formation is present in many locations around the Baoulé River. It consists of metagreywacke, schist and conglomerate. The metagreywacke is dark gray in color and is generally poorly classified. It is medium to coarse-grained and barely discernible to the naked eye (Table 1). It consists of lithic debris sandstones and feldspathic sandstones. Their matrix consists of small grained of the same lithic composition. The schists are dark gray in color and consist of a fine-grained polyolithic material. Polygenic conglomerates composed of quartz pebbles and sandstones and present only in the Sogola area (Table 1). The angular pebbles are generally angular and range from centimeters to decimeters in size and have a sandy matrix metagreywackes (Figure 3b). A microconglomerate similar in nature to the Sogola conglomerate is also found at the Boundio-Kologo area.

The bedding of this metasedimentary formation is characterized by the alternating presence of decametric metagreywackes and metric schists. The S0 stratification and the first S1 deformation phase are locally subparallel (Figure 3a).

✓ *Fine-Grained Metasediments*

The main facies at the edges of the Bougouni-Kékoro basin (Figure 2) are fine-grained metasedimentary sequences. This formation is predominant in the Yanfolila-Kalana-Manankoro basin, in the western area adjacent to Bougouni. It is visible in the pits of a gold-panning area at Tiéouléna, located to the southwest of the region. It has undergone significant alteration. It consists mainly of flyschoids, dominated by fine sediments (siltstones and argillites). Siltstones mainly consist of quartz with rare chlorites and sericites. In contrast, argillites consist mainly of chlorites and sericites, as well as a feldspathic fraction.

• *Plutonic Complex Rocks*

The plutonic rocks in Bougouni exhibit a variety of petrographic compositions. These include gabbros, diorites, granodiorites, tonalites, biotite monzogranites, and two-mica monzogranites (Figure 2).

✓ *Diorites and Quartz Diorites*

In addition to the intermediate to felsic, intrusive rocks (granitoids) found in the Bougouni region, the mafic rocks including diorites and a quartz diorites are also present. Diorites outcrop in Banko, and quartz diorites outcrop in Sinsinkourou and Banko (Figure 2). These rocks appear as lenticular bands on maps and tend to cluster in zones of weakness, such as contact zones between plutons and metasedimentary rocks or along fault zones (Figure 2). At outcrops, they appear as scattered "balls". They are melanocrate with 75 to 80% ferromagnesian minerals (black micas and amphiboles) (Figures 4a and 4b; Table 1). They have an equigranular texture and coarse crystal size (Figures 4a and 4b). They are composed of euhedral amphibole crystals and subhedral or anhedral plagioclases.

✓ *Granodiorites*

Granodiorites outcrop in various locations, including Diamana, Sinsinkourou, Boundio, Massala and Sogola (Figure 2). These plutonic bodies are mainly intrusive in the metasedimentary rocks of the Bougouni-Kékoro basin. They appear as subcircular bodies ranging in size from a few dozen to several hundred square meters. At outcrops, granodiorites generally appear as sills and, locally, as small, multi-sided "whalebacks" with a slight positive relief.

They are mesocrate to leucocrate with 10 to 40% of ferromagnesian minerals (black micas and amphiboles) (Figures 4c, and 4d). The grain size is coarse (5 to 10 mm) and equigranular (Figure 4c). However, at Bougoula, the rock is porphyritic, with the presence of 10 to 50 millimeters feldspar phenocrysts (Figure 4d). The rock's constituent minerals are plagioclase, amphibole and/or biotite, quartz and rare alkali feldspars. Granodiorites are characterized by a significant abundance of mafic enclaves (quartz microdiorites), that represent a few percent to over 50% of the

rock's total volume.

• *Tonalites*

The tonalites outcrop in the west-central part of the region (Figure 2) and fall into two different varieties types (Table 1). The coarse-grained variety have grain sizes ranging from one to five millimeters (Figure 4f), and the medium-grained variety has grain sizes of less than five millimeters (Figure 4e). The coarse-grained variety take the form of a sills about 500 meters long. The medium-grained variety outcrop forms a hill about 50 meters high, to the east of Tentou. There are numerous sills of the same variety are found at its foot (Figure 4f). A network of small, quartz veins, each 1 to 2 centimeters thick, is present. The tonalites are very leucocratic (light gray with a pink patina) (Figure 4e) with only 1 to 2 % ferromagnesian minerals (amphiboles). It is remarkably rich in quartz (Figure 4f). The other rock-forming minerals are amphibole, alkali feldspar, and plagioclase (Table 1).

• *Biotite Monzogranites*

The biotite monzogranites consist of four varieties: porphyritic variety, medium-grained variety, bright pink medium-grained variety and a pink, fine-grained variety (Table 1). The porphyritic variety have grained ranging from 5 to 20 mm, and is gray to milky white in color (Figure 5a). It outcrops as small hills and sills in the southern part of the region, Banimonotié commune. The medium-grained variety have equigranular grained ranging from two to five millimeters with a gray appearance (Figure 5b). It outcrops at Sibirila, Tinguéléni, Sido and Faragouran. The bright pink, medium-grained variety has equigranular grained ranging from two to five millimeters and corresponds to the "Massigui-type" variety (Figure 5c). It outcrops at Tinkéléni in the form of small hills and sills, measuring around 500 m long by 100 m wide. The pink, fine-grained variety has equigranular grained measuring less than one millimeter. It outcrops at Diran as small hills and sills, measuring approximately 500 m long by 100 m wide. These varieties occur as batholiths and small, circular plutons in various locations, particularly in the south (Figure 2). At outcrops, they appear as almost sills and "whale backs." These varieties are leucocratic containing 2 to 15% ferromagnesian minerals (black micas) by volume, which are represented by biotite. The other main minerals are potassium feldspar, quartz and plagioclase.

• *Two-Mica Monzogranites*

Two-mica monzogranites are the most abundant rock type in the region, accounting for over 50% of the plutonic complex rocks in the study area. These rocks outcrop in several locations, notably in the northwest and southeast of the region. They form large sectors in areas such as Dogo, Biko, Sémana, Sido, Makono, Kondo, Biladié, Diaka, Kébila, Koualé, Mamissa, Niaralé, Zantogola, Kéléya, Ouroun, Syantoula, Diéba, Tiérou, Kologo, Békobougouda, and Djiné. They take the form of batholiths and small plutons. These rocks outcrop as sills, ranging from a few dozens to a few hundred meters wide. Sometimes, they are in relief, forming small hills a few dozen meters high. The Dogo-Tyinra outcrop to the north is exceptionally exposed in the

form of a large hill. Granulometry varies from fine to coarse (from less than 1 mm to 10 mm), enabling division into three varieties (Table 1). These rocks are composed of clusters of micas, alkali feldspars, quartz and plagioclase. The abundance of alkali feldspar in two-mica monzogranites often gives them a pinkish hue (Figure 5c).

➤ Detailed Petrographic Analysis

Table 2 shows the average mineral proportions of the various lithology. The average modal composition of the plutonic complex rocks was being projected onto the Streckeisen diagram in order to determine the specific names (Figure 6). The modals values were estimated using the comparison charts for visual estimation of percent composition of Terry and Chilingar, (1955).

• Coarse-Grained Metasediments.

The metagreywackes contain angular to subangular clasts of quartz and feldspar, measuring between 500 and 1,000 μm in size. Texturally, they consist of 25–60% matrix by volume (Figure 7a). This matrix comprises chlorite, quartz and fine-grained feldspar (50–200 μm) (see Figure 7b). Quartz is the main detrital component and is primarily monocrystalline with undulating extinction. Among the feldspars, plagioclases are more abundant than potassium feldspars. Micas are present as both large and small lamellae (Figure 7b). These are more or less oriented along the S1 foliation, which is subparallel to the So stratification (Figure 7a). They are primarily biotite in nature and are more or less chloritised. Accessory minerals include zircon, magnetite and pyrite.

The schists have a grain size ranging from fine to very fine and consist mainly of biotite, muscovite and quartz (Figure 7c). They contain 50% or more quartz by volume. The figure-shaped elements (200–500 μm) and matrix grains (less than 100 μm) are much smaller than those found in greywackes. The alignment of the mica crystals illustrates the foliation (Figure 7). The S1 foliation, which is subparallel to the So stratification, is also much more pronounced than that of the metagreywacks.

Quartz and plagioclase occur as blastic or xenoblastic grains, forming a granoblastic phase in which mica and amphibole flakes are dispersed. Biotite ranges in colour from brown to green (Figure 7d). Muscovite resembles biotite in appearance to that of biotite, but it is less abundant. Metamorphosed muscovite sometimes cuts across the foliation (Figure 4d). Magnetite is identified as an accessory mineral.

• Diorite and Quartz Diorite

✓ Diorite

This is a mesocratic, equigranular rock, consists of amphibole, biotite, plagioclase and accessory minerals (Figure 8a). Amphiboles account for 50% of the volume. They occur as euhedral or subhedral crystals. These amphiboles are mainly magnesiohornblende, however, some data fall within the pargasite and actinote fields, with $(\text{Ca} + \text{Na})^{\text{B}} = 1.88 \pm 0.05$ apfu (atoms per formula unit), and $\text{Ca}^{\text{B}} =$

1.84 ± 0.04 apfu (Table 3). Plagioclases account for 40% of the volume and occur as subrectangular or anhedral crystals. Their composition varies from labrador to andesine, with an average anorthite content of 50.30 ± 3.51 (Table 6). Biotites account for 10% of the volume. They occur as subrectangular or anhedral crystals with the following compositions in table 4. Primary accessory minerals include zircon, titanite, apatite, and magnetite (Table 2).

✓ Quartz Diorite

This is a coarse, equigranular melanocratic rock, consists of amphibole, plagioclase, quartz and accessory minerals (Figure 8b). Amphiboles account for 75% of the volume. Some crystals look zoned so external parts are actinotes rich ones. They range between the magnesiohornblende and actinote fields, with $(\text{Ca} + \text{Na})^{\text{B}} = 1.92 \pm 0.05$ apfu and $\text{Ca}^{\text{B}} = 1.89 \pm 0.06$ apfu (Table 3). Plagioclases account for 22% of the volume. They consist of subrectangular to anhedral crystals whose composition ranges from labrador to andesine, with an average anorthite content of 43.97 ± 4.44 (Table 6). Quartz, representing 3% of the volume, occurs as small, interstitial, anhedral crystals between the aforementioned minerals. Accessory minerals include zircon, titanite, pyrite, chalcopyrite and magnetite (Table 2).

• Granodiorites

These lithology types comprise of three lithology varieties: (i) quartz granodiorite; (ii) standard granodiorite, and (iii) porphyritic granodiorite.

✓ Standard Granodiorite and Quartz Granodiorite

This is a mesocratic, equigranular rock, consists of amphibole, biotite, plagioclase, alkali feldspar, quartz and accessory minerals (Figures 8c and d). Quartz occurs as globular or anhedral crystals (40–45 % by volume). Plagioclases (30 % by volume) are quite altered. They occur as euhedral crystals. Their composition ranges from labrador to oligoclase, with anorthite proportions ranging from 33.75 ± 6.24 to 49.38 ± 5.56 (Table 6). The amphiboles (12–15 vol %), are in euhedral crystals. They are ferrohornblende, magnesiohornblende and actinote with $(\text{Ca} + \text{Na})^{\text{B}} = 1.82 \pm 0.15$ to 1.93 ± 0.02 apfu and $\text{Ca}^{\text{B}} = 1.7 \pm 0.2$ to 1.9 ± 0.02 apfu (Table 3). The biotites (10 % by volume) are subhedral to anhedral crystals that usually form clusters with amphibole crystals. They have the following contents in table 4. The alkali feldspars (3–5 % by volume) are microcline crystals with an orthose proportion of 95.52 ± 0.80 (Table 7). They occur as more or less altered euhedral crystals. Accessory minerals include zircon, epidote, apatite, titanite, sphalerite, pyrite, chalcopyrite and magnetite (Table 2).

✓ Porphyritic Granodiorite

This is a leucocratic; coarse-grained rock composed of amphibole, biotite, plagioclase, quartz, and accessory minerals (Figures 8e). Quartz (35 % by volume) is present as small anhedral crystals. The plagioclases consist of subhedral to anhedral medium-grained and coarse-grained crystals (20 % by volume) and euhedral phenocrysts (25 % by volume). Regardless of their size, the plagioclases are composed of andesine with an average anorthite proportion of 28.77 ± 3.12

(Table 6). They exhibit an evolutionary trend from an andesitic core to oligoclasic peripheries. The amphiboles (10 % by volume) are in the form of strongly altered subhedral to anhedral crystals. They are magnesiohornblende with $(Ca + Na)^B$ and Ca^B content values of 1.93 ± 0.02 and 1.92 ± 0.01 apfu respectively (Table 3). The biotites (10 % by volume) are in the form of subhedral to anhedral crystals that are $\pm$ chloritized (Table 4). Accessory minerals include zircon, epidote, apatite, titanite, sphalerite, pyrite, chalcopyrite, barite, and magnetite (Table 2).

- *Quartz Microdiorite*

In general, the granodiorite enclaves contain fine-grained mesocratic lithology, which usually includes 0.3–1 cm alkali feldspar phenocryst (Figure 8f). This lithology consists of amphibole, biotite, plagioclase, alkali feldspar, quartz, and accessory minerals. Amphiboles (25% by volume) are present as subhedral crystals. They are magnesiohornblende with compositions of $(Ca + Na)^B = 1.91 \pm 0.01$ apfu and $Ca^B = 1.89 \pm 0.01$ apfu (Table 3). Phenocrysts (20% by volume) of alkali feldspar ($Or = 94.89 \pm 1.29$), are present as euhedral crystals of orthose and microcline crystals (Table 7) that are fairly weathered. Biotites (15% by volume) are present as subhedral to anhedral crystals showing the beginnings of chlorite alteration. They have the following compositions in table 4. Plagioclases (37% by volume) are present as euhedral to subhedral crystals, which are significantly altered from the core to the periphery. They have an oligoclasic composition ($An = 24.96 \pm 1.98$) (Table 6). Quartz (3% by volume) is present in the form of as a few anhedral crystals. Accessory minerals include zircon, apatite, titanite, and magnetite (Table 2).

- *Tonalite*

This is coarse-grained very leucocratic rock. It is composed of plagioclase, alkali feldspar, quartz, amphibole, and accessory minerals (Figures 9a and b). Quartz (45% by volume) occurs as medium-to-small, subhedral to anhedral crystals. Plagioclases (45% by volume) occur as euhedral phenocrysts, and subhedral medium crystals (0.5–1 mm) and as well as anhedral small crystals (50 – 300 μ m). Regardless of their size, they are albite in nature, with an average composition of $An = 4.91 \pm 2.65$ (Table 6). Alkali feldspars (5% by volume) occur as medium-to-small subhedral crystals of microcline and orthose ($Or = 96.29 \pm 0.64$) (Table 7). The amphiboles, which account for 5% of the volume, and occur as highly altered subhedral to anhedral crystals within the rock's matrix. These amphiboles are monoclinic calcic amphiboles (ferroedenite and edenite), with a composition of $(Ca + Na)^B = 1.78 - 1.88$ apfu and $Ca^B = 1.78 - 1.88$ apfu (Table 3). Accessory minerals include zircon, titanite, apatite, pyrite, barite and magnetite (Table 2).

- *Biotite Monzogranites*

This is coarse-grained leucocratic rock type, composed of alkali feldspar, quartz, biotite and accessory minerals (Figure 9c). Plagioclases (40% by volume) are present as euhedral crystals that are strongly altered from the core to the periphery. Their composition is oligoclase, with $An = 16.10 \pm 0.54$ (Table 6). Quartz (35% by volume) occurs as small anhedral crystals in the matrix. The biotites, which account

for 15% of the volume, and are subhedral, altered crystals that are present in clusters. Their composition is as follows in table 4. Alkali feldspars (10% by volume) occur as more or less altered subhedral microcline crystals (Table 7). Accessory minerals include zircon, titanite, apatite, monazite, pyrite, galena and magnetite (Table 2).

- *Nimissila Biotite Porphyritic Monzogranite*

This is coarse-grained leucocratic rock type. It is composed of plagioclase, alkali feldspar, quartz, biotite, and accessory minerals. Quartz (45% by volume) is present as anhedral crystals. The plagioclases (25% by volume) are present as subhedral albite. The alkali feldspars are represented by euhedral to subhedral microcline phenocrysts (15% by volume) as well as by small, subhedral crystals ranging from 200 to 500 μ m (10% by volume). Phenocrysts contain other mineral inclusions. The biotites (5% by volume) are present as subhedral to anhedral crystals. Accessory minerals include zircon, titanite, apatite, monazite, chalcopyrite, galena and magnetite (Table 2). No analyses of solid solution minerals were available. The minerals of this lithology are too altered.

- *Massigui-Type Pink Biotite Monzogranite*

This is coarse-grained hololeucocratic rock, composed of plagioclase, alkali feldspar, quartz biotite and accessory minerals (Figures 9d and e). Quartz (45% by volume) occurs as anhedral crystals. The alkali feldspars (35% by volume); are microclines in subhedral crystals, that are more or less altered. Plagioclases (17% by volume) are albite in composition. They occur as euhedral crystals that are altered from the core to the periphery. The biotites (3% by volume) are present as highly altered, subhedral to anhedral crystals. Accessory minerals include apatite and zircon in plagioclase and microcline. No analyses of solid solution minerals could be carried out, as they are too altered.

- *Two-Mica Monzogranite*

It is subdivided into three lithology varieties: coarse, medium, and fine grained types. Its composition includes biotite, muscovite, plagioclase, alkali feldspar, quartz, and accessory minerals (Figure 9f). Quartz (40% by volume) occurs as euhedral to anhedral crystals. The alkali feldspars (30% by volume) are orthose, and occur as small- to medium-sized, partially altered, subhedral crystals, with an average $Or = 97.23 \pm 0.42$ (Table 7). Plagioclase (20% by volume) occurs as euhedral to subhedral crystals that are altered from the core to the periphery. Their composition ranges from oligoclase to albite, with an average $An = 10.80 \pm 2.17$ (Table 6). The muscovite (7% by volume) occurs as euhedral to anhedral crystals, often in clusters with biotite within the matrix. The Mn/Fe ratio is 0.02 ± 0.01 (Table 5). The biotites (3% by volume) are strongly chloritized, and range from subhedral to anhedral in form. Accessory minerals include zircon, apatite, titanite, monazite, pyrite, chalcopyrite, and magnetite (Table 2). Sample STNR51 from Dogo-Tyinra stands out for its high muscovite content (10% by volume), which dominates the biotite, and plagioclase (50% by volume), as well as its low microcline content (5% by volume). It also contains garnet.

IV. MINERAL CHEMISTRY

➤ *Classification of Solid Solution Minerals*

• *Amphiboles*

According to the classification of Leake et al. (1997), projecting the data onto the $Mg/(Mg + Fe)$ versus Si diagram shows two distinct amphibole groups that forming two parallel, sloping series (Figure 10). The first group comprises mafic lithology variety analyses (diorite; quartz diorite, and quartz microdiorite). These range from pargasite to actinote and magnesiohornblende. The second group comprises granitoid lithology, such as granodiorites and tonalites. This group includes ferropargasite, pargasite, ferrohornblende, and magnesiohornblende.

With zonation of some amphiboles (Figure 8b) and according to Leake et al. (1997) and green schist-type metamorphism (Figure 7), only amphiboles with Si values below 7.50 apfu are magmatic. Samples containing amphiboles exhibited cationic replacement between magnesio-hornblende and pargasite (Figure 10). It was not always possible to identify the phase or the non-magmatic (metamorphic) component using a microscope. Figure 11, shows that the linear arrays indicate that the amphibole composition of these rocks depends on the amount of Al^T and the substitution of $(Na + K)^C + Al^C$ for Si cations in the octahedral sets. Figure 11 shows edenitic ($Al^T + Al^C = Si + Mg$), tschermakitic ($Al^T + Al^C = Si + Mg$) and titanotschermakitic ($Ti + 2Al^T = Mg - 2Si$) substitutions in all lithology types. At best, the two-amphibole groups defined in Figure 10 always remain distinct in tschermakitic and titanotschermakitic substitutions. Furthermore, richeritic, glaucophane and titanoglaucophane substitutions were not identified in our samples. Noted that edenitic and tschermakitic substitutions are magmatic, while richeritic and glaucophane substitutions are metamorphic. These cationic substitutions are therefore related to magmatic processes.

These substitution relationships do not establish continuity between the different lithologies. However, they do suggest continuous chemical evolution within each lithology.

• *Black Micas*

As with amphiboles, analyses of black micas are fall into two distinct groups. The first group consists of black micas found in mafic plutonic rocks, such as diorite and quartz microdiorite while the second group consists of black micas found in granitoids, such as granodiorite and biotite monzogranite. According to the Mg-Al-Fe ternary classification diagram (Figure 12a), all of the analyzed black micas analyzed correspond to biotites. According to the $Fe / (Fe + Mg)$ versus Si diagram (Figure 12b), all biotites are magnesian biotites. These observations are valid for all biotites in both black mica groups. According to the $MgO-FeO-10^*TiO_2$ diagram (Figure 12c), most of the studied biotites are in the re-equilibrated biotite domain. However, the biotite monzogranite data are the only ones predominantly in the primary biotite domain. Analyses show that the total aluminum content of the biotites is too low (less than 2.15;

Table 4 and in the Appendix). These results are consistent with microscopic observations (Figures 8 and 9). Similar to amphiboles, biotites have $Fe\# = Fe/(Fe + Mg)$ values below 0.6.

• *Feldspars*

The feldspar calculation results were projected onto the ternary albite-orthose-anorthite feldspar classification diagram (Figure 13).

The chemical analysis results indicate significant differences in the plagioclase composition, which generally overlap from one lithology to the next.

The chemical composition of alkali feldspars is less contrasting. Most of the data is concentrated at the potassic pole (Figure 13).

➤ *Estimation of Intensive Parameters*

• *Al-in-Hornblende Method*

Calculations are based on the chemical composition of amphiboles whose magmatic nature is certain. To ensure this, only amphiboles with Si values below 7.40 apfu were considered to obtain intrusion-related pressure and temperature data.

The results are presented in the table 8; in the figures 14, 15 and 16 and in the supplementary materials. Overall, the lithology of the Bougouni plutonic complex rocks meet these conditions for using amphiboles as a barometer. Figures 14, 15, and 16 show a series of graphs labeled a from f and A. Each set consists of a histogram and a box-and-whisker plot, also known as a "boxplot." These graphs are used to analyze the distribution, central tendency, and dispersion of various temperature, pressure, and oxygen fugacity datasets.

Histograms show the frequency distribution of different value classes on the horizontal axes and on the vertical axes. The height of the bars indicates the proportion of data in each interval.

Box-and-whisker plots summarize the distribution. The median (the central line in the box) corresponds to the middle of the data (half is above and half is below). The red/black "+" sign corresponds to the arithmetic mean of the series. The edges of the box correspond to the first quartile (Q_1 , the bottom) and the third quartile (Q_3 , the top). The whiskers (the horizontal bars at the ends) represent the minimum and maximum values that are not considered outliers. The isolated points (♦) are outliers that are far from the rest of the data.

The calculated temperature results are summarized in Table 8 (column g) and in the figure 14. The temperature values differ from one lithology to another. Quartz diorite (Figure 14a) exhibits a main peak around 760–770°C. Its distribution ranges primarily from 719°C to 839°C. The median is approximately 760°C, which is very close to the mean. The distribution appears fairly symmetrical with no visible outliers. The diorite (Figure 14b) shows a distribution ranging from 736°C to 876°C, with a distinct major peak

around 810°C. The box is located very high (between ~790°C and ~820°C). The mean (symbol +) and the median are close to 810°C. The whiskers extend downward to approximately 730 °C, indicating a bias toward lower values. The data for the standard and porphyry granodiorites (Figure 14c) are concentrated between 670°C and 720°C. The median and mean temperatures are virtually identical, both around 690-695°C. There are several outliers, represented by isolated points at 675°C and 720°C. The quartz granodiorite (Figure 14d) data range from 671°C to 751°C. The highest peak occurs at the end of the distribution around 735°C. The box is narrower between 720°C and 735°C, at the top. Note the single outlier at 675°C at the bottom. The microdiorite quartz (Figure 14e) distribution ranges from 728°C to 768°C. The peak occurs around 745°C. The mean is slightly lower than the median, indicating slight asymmetry. An outlier is visible above 770°C at the very top. Finally, for the tonalite (Figure 14f), the data are distributed fairly uniformly over wide interval between 704°C and 729°C, with two main peaks around 705°C and 718°C. The box is elongated, indicating high dispersion between Q_1 and Q_3 . The mean and median are approximately 715°C. No outliers were detected. Overall, Figure 14A shows the widest range of data (from 670°C to over 900°C). There is a high concentration of data (peak) between 740°C and 770°C, followed by a long tail extending to the right. The box plot reflects this high dispersion with very elongated whiskers, ranging from less than 700°C to nearly 900°C. The mean (+) and median are around 750°C. The lowest values are observed in the tonalite, standard granodiorite and porphyry granodiorite. These lithologies do not overlap with any others within the margin of error (Table 8g).

The pressure values differ from one lithology to another (Table 8 column AP). The pressure values from the calibrations by Hollister et al. (1987), Mutch et al. (2016), Schmidt (1992), Hammarstrom and Zen (1986), Johnson and Rutherford (1989b), and Ridolfi et al. (2010) are very similar (Table 8, columns a, b, c, e, and f). Previously, we used to use the average pressure for each lithology (Table 8, column AP). The quartz diorite distribution (Figure 15a) is right-skewed, with two main multimodal peaks: a strong peak between 1.03 kbar and 1.53 kbar and a weaker peak around 4.53 kbar. The median is approximately 2.7 kbar. The diorite distribution (Figure 15b) is left-skewed, with a very pronounced peak at 4.4 kbar. The box-and-whisker plot shows one single outlier at a lower value near 2.0 kbar. The data distribution for the standard and porphyry granodiorites (Figure 15c) is highly asymmetric and decreasing. Most of the data are concentrated between 0.75 and 2.0 kbar. An outlier is visible beyond 3.0 kbar on the box-and-whisker plot. The granodiorite quartz data (Figure 15d) exhibits a bimodal distribution ranging from 2.85 to 5.85 kbar, with two distinct peaks around 4.35 and 4.85 kbar. An outlier is visible below the 3.0 kbar. The data distribution for microdiorite quartz (Figure 15e) is broad, with a major peak around 1.73 kbar. There is a right-hand tail with a high outlier near 2.9 kbar. The tonalite data distribution (Figure 15f) shows two main peaks at 1.80 and 2.30 kbar. The mean and median are very close (around 1.9–2.0 kbar). The broader overall summary distribution (Figure 15A) ranges from 0.75 kbar to 6.75 kbar. There is an initial strong

concentration, with a peak at 1.75 kbar, followed by a long, asymmetric, right-skewed tail. This is confirmed by a highly elongated, upward-pointing box-and-whisker plot, with the mean exceeding the median. The highest values are found in diorite and quartz granodiorite lithologies (mean upper 5 kbar), two lithologies that do not overlap with any others within the margin of error (Table 8, column AP).

The oxygen fugacity values differ from one lithology to another (Table 8 column h). Quartz diorite (Figure 16a) exhibits an asymmetric, bimodal distribution with a pronounced main peak at around 1.69 and a weaker secondary peak at around 1.09. The median is about 1.5, and the mean is slightly higher, at approximately 1.6. These results confirm slight positive asymmetry. Diorite (Figure 16b) exhibits an irregular, broad distribution. There are two main peaks at 0.15 and 0.65 (bimodal). The median is close to 0.6, and the mean is around 0.7. The upper whisker extends beyond 1.6. Both the standard granodiorite and the porphyry granodiorite (Figure 16c) show a very high concentration of data (major peak) between 0.6 and 0.7, forming a major peak. The rest of the data is more widely dispersed to the right, up to 1.37. The median and mean are nearly aligned at around 0.9, indicating that despite the initial peak, the center of gravity of the data shifts toward the higher values. The quartz granodiorite data (Figure 16d) range primarily from negative values of -0.46 to 0.24, with a major peak around -0.21. The median is approximately -0.25. An isolated data point (black diamond) appears near at the very top 0.22, indicating an outlier. Figure 16e shows the narrow distribution of quartz microdiorite, ranging from 1.28 to 1.78. It is characterized by a very distinct dominant peak at 1.43. The median and mean are close together, both falling around 1.55. Finally, the tonalite rock's histogram (Figure 16f) shows a left-skewed distribution (with values clustering toward the upper end) and a peak between 0.75 and 0.80. Figure 16A shows the broader overall distribution summary. The range is extends, extending from negative values of -0.46 to over 2.0. The largest peak is around 1.6. The median is around 1.2, which is close to the mean. This illustrates a high degree of data dispersion.

• *Ti-in-Biotite Method*

The calculated temperature of Ti-in-biotite method results are summarized in Table 9. It can be seen that these temperatures (197 °C - 573 °C) are lower than those previously calculated using the Al-in-hornblende method.

The calculated pressure results with the Al^{IV} content of biotite are summarized in Table 9. The Ti-in-biotite method estimates negative pressure values. Geological crystallization pressure cannot be negative. Values indicating otherwise suggest that the analyzed biotite's composition falls outside the scope of this method due to its low aluminum content, alteration, or exhibits chemical imbalance. Therefore, the formula is not applicable to our samples.

V. DISCUSSION

➤ *Bougouni Plutonic complex Rocks Crystallization Conditions (P-T-fO₂)*

• *Temperature (T)*

Edenite substitution reactions ($\text{Si} + \text{vac}^{\text{A}} = \text{Al}^{\text{T}} + (\text{K} + \text{Na})^{\text{A}}$), and reactions involving titanium ($\text{Ti} + \text{R}^{2+} = 2\text{Al}^{\text{C}}$ and $\text{Ti} + \text{Al}^{\text{T}} = \text{Al}^{\text{VI}} + \text{Si}$) are temperature-controlled (Anderson and Smith, 1995). The higher the temperature, the more efficient the edenite substitution. The result is an increase in the Al content of hornblende.

The abundance of hydrated minerals, such as biotite, muscovite, and amphiboles, in the Bougouni plutonic complex (Figures 4, 5, 8 and 9) suggests that the initial magma contained a high concentration of water. This enrichment allowed these hydrated phases to crystallize during the Eburnean orogeny. This aspect is a fundamental petrological principle that has been discussed by many authors of textbooks on geochemistry and magmatism, both classical and modern. Leading figures such as Yoder (1955), Burnham et al., (1969), Piwinskii, (1973), Wyllie, (1978) and Sisson and Grove (1993) have also conducted experiments to study the role of water. The presence of water significantly decreases the temperature at which magma crystallizes (Goranson, 1931 and Tuttle and Bowen, 1958).

The temperatures estimated by the Al-in-hornblende method (ranging from 700°C to nearly 900°C) are considered representative of the complete crystallization and cooling of the Bougouni plutonic complex rocks (Table 8 and Figure 14). Indeed, it is generally accepted that amphiboles, such as hornblende and pargasite usually crystallize between 750 °C and 1,050 °C in hydrated magmas (Bowen, 1928; Holland and Blundy, 1994; Ridolfi et al., 2010 and Ridolfi and Renzulli, 2012). In addition, many studies are supported by other similarities observed in neighboring regions and around the world: i) many granitic plutons produce temperatures in excess of 700°C (Anderson and Smith, 1995); ii) Archean granitoids in Brazil are 831–926°C (De Oliveira et al., 2018); iii), alc-alkaline granitoids in Massigui near Bougouni are 590–808°C (Wane, 2010); iv) El-Awady et al., (2024) recorded temperatures of 807°C for granodiorites and 792°C for syenogranites in the Mount Abu Kibash and Tulayah regions of Egypt and Thomas et al., (2023) observed the late crystallization of amphibole rims and titanite at relatively low temperatures (between 800 and 680 °C) in the upper crust. These last authors urge caution when interpreting the chemical composition of minerals that crystallize at low temperatures (below 800 °C), due to the potential effects of accessory mineral crystallization on the residual melt compositions.

Furthermore, the low temperatures (197 °C–573 °C) estimated using the titanium-in-biotite (Ti-in-biotite) method (Table 9) are considered representative of complete recrystallization under conditions typical of green schist and early amphibolite (Figure 7) in the Bougouni area. The chloritization of biotite in rocks from the Bougouni plutonic complex also supports this suggestion (Figures 8 and 9).

Indeed, green schist facies undergo metamorphism at moderate temperatures, ranging from 300 °C to 500 °C (Eskola, 1915; Winkler, 1979 and Turner, 1983). These temperatures align with those Wyllie and Huang (1976) and Lasheen et al., (2025) obtained temperatures ranging from 550 to 650 °C for younger granites using the Ti-in-biotite method.

• *Pressure (P)*

The Tschermak substitution ($\text{Si} + \text{R}^{2+} = \text{Al}^{\text{T}} + \text{Al}^{\text{C}}$) is considered pressure sensitive (Hollister et al., 1987). As pressure increases, the aluminum content of the hornblende lattice increases.

Pressure values obtained by the Ti-in-biotite method are negative and do not reflect to the pressure conditions of geological crystallization. Therefore, they are rejected immediately. However, since the pressure values from the various calibrations are highly similar (Figure 15 and Table 8, columns a through f), we can use the calculated average values ranging from 0.75 kbar to 6.75 kbar (Figure 15 and Table 8, column AP), obtained using the Al-in-hornblende method, as the crystallization pressures of the rocks in the Bougouni plutonic complex.

Using, the calculated pressures (0.75 kbar to 6.75 kbar, Figure 15 and Table 8, column AP), and the equation $P = \rho gh$ (P: lithostatic pressure; ρ : average crustal density = 2700 kg/m³; g: acceleration of gravity = 9.81 m/s²; h: depth of emplacement), all the plutonic complex rocks from Bougouni indicate an emplacement depth of between 2847 m and 23603 m. The highest values are found in diorite and quartz granodiorite lithologies (mean about 1700 m, Table 8, column Deph). These deduced pressures and depths of emplacement are comparable to those of typical of evolved magmatic reservoirs in arcs (oceanic or continental) mid-oceanic ridge or rift ($P \leq 1\text{--}2.5$ kbar) (Chappell and White, 1992; Holtz et al., 2001 and Nzolang, C., 2005), and of magmas of crustal origin emplaced in thick crusts ($P < 4\text{--}5$ kbar) (Burnham, 1979; Chappell and White, 1992; Holtz et al., 2001; Robb, L., 2005 and Pirajno, 2009). Its also are comparable to those of other granitoids in the region and worldwide. Pressure conditions between 2 and 7.5 kbar were recorded at Massigui (Wane, 2010), and a pressure of 2.2 kbar (at a temperature of 677°C) was measured for the calc-alkaline granitoids of Winneba in Ghana (Nyarko et al., 2012).

• *Oxygen Fugacity (fO₂)*

In general, the color of biotite analyzed under polarized light can be used to estimate the oxidation state of the magma in which it crystallized. Greenish-brown biotite indicates a more oxidizing environment that is low in titanium (Ti) and aluminum (Al), but high in magnesium (Mg) and iron (Fe³⁺). Conversely, reddish-brown biotite indicates a less oxidizing environment that is high in titanium and aluminum, but low in magnesium and iron (Lalonde and Bernard, 1993).

Spear, (1981) found that decreasing the oxygen fugacity increases the probability that Fe²⁺ being incorporated into the hornblende crystal lattice. A high Fe²⁺/Fe³⁺ ratio favors aluminum (Al) substitution for magnesium (Mg) during

Tschermak substitution. This occurs because oxygen fugacity controls the $Fe^{\#} = Fe/(Mg + Fe)$ ratio. Thus, low oxygen fugacity leads to a high aluminum content in hornblende. Anderson and Smith, (1995) propose classifying amphiboles according to their $Fe/(Fe + Mg)$ ratio. They defined high fugacity as a ratio between 0 and 0.6, medium as a ratio between 0.6 and 0.8, and low as a ratio greater than 0.8.

Low $Fe^{\#}$ values (between 0.24 and 0.66 for amphiboles and between 0.39 and 0.58 for biotites) and high Fe^{2+}/Fe^{3+} values (between 1.36 and 2,395.28 for biotites) indicate that the magma crystallized in an oxidizing condition (Anderson et al., 2008); (Figures 17a and 17b).

The $Fe / (Fe + Mg)$ ratio in biotites enables the classification of Fe-Ti oxides into two groups: magnetite (Fe_3O_4) and ilmenite ($FeTiO_3$). With their low $Fe^{\#}$ ranging from 0.39 to 0.58, the Bougouni samples fall within the magnetite and two-mica granite domains (Figure 17b). This is consistent with magnetite being the dominant Fe oxide in our samples. However, not all magnetite-bearing granites are not necessarily oxidized, and the presence of magnetite may indicate a reduced conditions (Anderson and Smith, 1995).

➤ *Petrogenesis and Source of Bougouni Plutonic Complex Rocks*

The aim is to assess the character of the magma(s) that formed the Bougouni plutonic rocks by relying on variations in the chemical composition of amphiboles and biotites.

• *Geodynamic Setting of Bougouni Plutonic Complex Rocks*

Amphiboles from magmas related to subduction contexts (S-amphiboles) have lower Na_2O and TiO_2 contents than amphiboles from magmas originating from intraplate tectonic contexts (I-amphiboles) (Coltorti et al., 2007). The amphiboles in the Bougouni plutonic complex have the following compositions of $48.27 \pm 2.53\%$ SiO_2 , $0.88 \pm 0.29\%$ Na_2O , and $0.68 \pm 0.42\%$ TiO_2 . These contents correspond to the S-amphibole type. This suggests that the magmas originate from at least one subduction-related tectonic setting.

In the K versus Al^T variation and discrimination diagram of Ridolfi and Renzulli (2012), amphiboles fall within the calc-alkaline series field (Figure 18a). The Al^T of amphiboles can be used as a discriminant to determine the tectonomagmatic environment in which they formed. Amphiboles with Al^T values above 1.5 formed at 10 kbar in island arcs, and those with values below 1.5 formed on active continental margins (Ghent et al., 1991). All of the amphiboles in the Bougouni plutonic complex rocks have Al^T values below 1.5 (Table 3). Therefore, they were likely formed in an active continental margin tectonic context, i.e., in associated with a subduction zone.

According to Abdel-Rahman, (1994)'s statistical analysis of biotites in various igneous rock types identified three distinct compositional categories. These categories are alkaline anorogenic suite biotites, peraluminous orogenic suite biotites, and calc-alkaline orogenic suite biotites. Plotting the biotites on Abdel-Rahman, (1994)'s $MgO-FeO-Al_2O_3$ ternary diagram indicates that the Bougouni plutonic

complex rocks formed in an orogenic setting. The data are distributed between the calc-alkaline and the peraluminous (including the S-type) orogenic series fields. There is a clear dominance of the data in the calc-alkaline series field (Figure 18b). Note that the peraluminous series data are close to the dividing line between the calc-alkaline and peraluminous series. This is consistent with the magnesium-rich composition of the biotites and the calcium-rich composition of the amphiboles found in Bougouni's plutonic complex rocks. Indeed, (Sami et al., 2023) discovered iron-rich of the biotites and sodium-rich to the amphiboles with an alkaline magmatic signature.

Granites that are strongly oxidized during crystallization form under compressive tectonic conditions. Conversely, granites formed by fractionation from mantle-derived magmas in rift zones are reduced (Chappell and White, 1992). So the plutonic complex rocks of Bougouni formed in a calc-alkaline orogenic context, which indicating an active margin (subduction zone or even a continental arc tectonic environment). This is not an isolated case worldwide. For example, (El-Awady et al., 2024) identified collision (volcanic arc) settings for calc-alkaline, and metaluminous granodiorites, as well as an extension context for the alkaline, and peraluminous syenogranites in Mount Abu Kibash, and Tulayah, in Egypt.

• *Magmatic Sources*

Jiang, C. and An, S., (1984) and (Zhou, 1986) have defined three magma source domains using amphiboles and biotites. These are crustal origin, mantle origin and mixed (crustal-mantle) origin.

In the TiO_2 versus Al_2O_3 amphibole discrimination diagram (Figure 19a), the primary amphiboles in the Bougouni plutonic complex rocks extend from magmas of crustal origin to magmas of mantle origin. This broad distribution is observed at the scale of each amphibole-bearing lithology. Clearly, the TiO_2 versus Al_2O_3 diagram does not allow us to determine the origin of the magma(s) in the Bougouni plutonic complex rocks.

The $FeO/(FeO + MgO)$ versus MgO discrimination diagram of (Zhou, 1986), seems to provide more information on the origin of magmas in the Bougouni plutonic complex rocks. The biotite analyses are indeed divided between magmas of crustal origin and magmas of mixed origin (Figure 19b). Diorite and quartz microdiorite are thought to originate from magmas of mixed origin. Granodiorites and biotite monzogranites, on the other hand, are derived from magmas of crustal origin.

This is not an isolated case worldwide. In fact, El-Awady et al., (2024) identified two sources of the Mount Abu Kibash and Tulayah granites in Egypt: a mixed crust-mantle source and a crustal source. A contribution of crustal material (metasediments) has been suggested to have occurred during the petrogenesis of the Winneba, Ghana granitoids through assimilation or anatexis (Nyarko, 2010).

VI. CONCLUSION

The Bougouni province plutonic complex rock are intruded in the metasedimentary rock of the Bougouni-Kékoro basin. Numerous aplite and pegmatite dikes cut through the metasedimentary and plutonic complex rocks.

The plutonic complex rocks studied exhibit a wide range of compositions, from diorites to two-mica monzogranites, with the latter predominating. Their petrography and mineral chemistry are characterized by a variable proportion of monoclinic calcic amphiboles with calcium contents ranging from 1.25 to 1.95, magnesium-rich black micas, plagioclases with compositions ranging from labrador to albite, alkali feldspars, and quartz. Accessory phases include titanite, magnetite, epidote, apatite, and zircon.

The samples exhibit subalkaline (calc-alkaline) signatures and range from metaluminous to slightly peraluminous. They are classified as type I with a slight S tendency, and are believed to have formed in a near-collisional subduction setting. However, the substitution relationships observed in the amphiboles and feldspars do not demonstrate cogenetic continuity among the different lithologies. Rather, they suggest continuous chemical evolution within each lithology. Data suggest that the Bougouni plutonic complex may have formed from two

sources: magmas of crustal origin and magmas of mixed origin (partial melting of the crust and mantle).

During subduction, the downward movement of the oceanic lithosphere causes it to partially melt. This process produced the Bougouni diorite and quartz microdiorite, which are magmas of mixed origin. As these magmas ascended, they may have heated the continental crust, causing it to partially melt. Mixing these magmas with magmas from the continental crust produces granodiorites, biotite monzogranite, and two-mica monzogranite in Bougouni to varying degrees.

They evolved under conditions of high oxygen fugacity. The presence of calcic amphiboles and biotite, as well as the very low percentage of clinopyroxene, is consistent with the plutonic rocks relatively high-water content. The Bougouni plutonic complex rocks were emplaced at depths ranging from 2.85 km to 23.60 km. They crystallized at temperatures ranging from 671 - 869 ± 44°C, which corresponding to the solidus temperatures for complete crystallization and cooling in the presence of water. The low temperatures from 197 °C to 573 °C are represented of complete recrystallization under conditions typical of green schist. Pressures ranging from 0.75 kbar to 6.25± 1.47 kbar are their emplacement.

➤ Figures

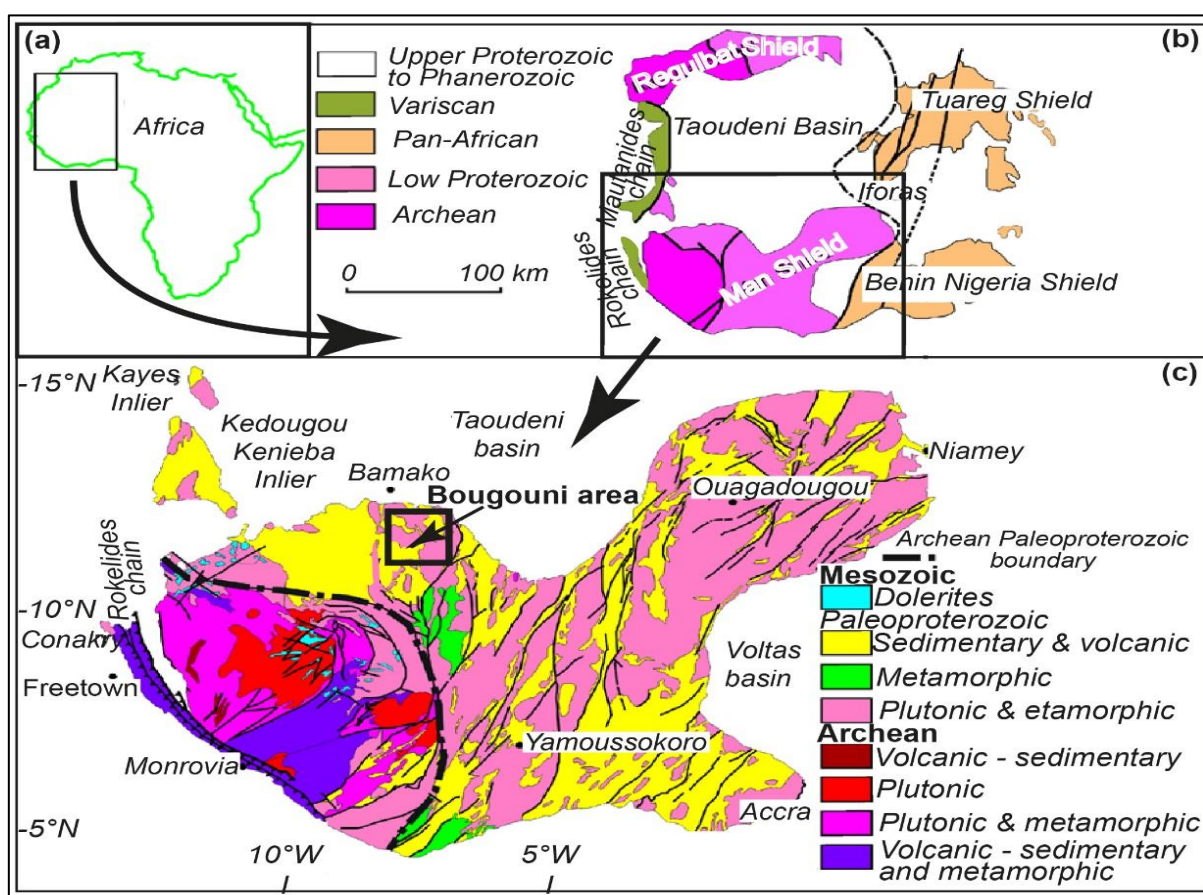


Fig 1 (a) Simplified map of Africa. (b) Simplified geological map of the West African Craton after Milési et al., (1992a). (c) Simplified geological map of the Leo-Man Shield, after Thiéblemont, D., et al., (2016) in Wane et al., (2021) with the localization of study area (black square).

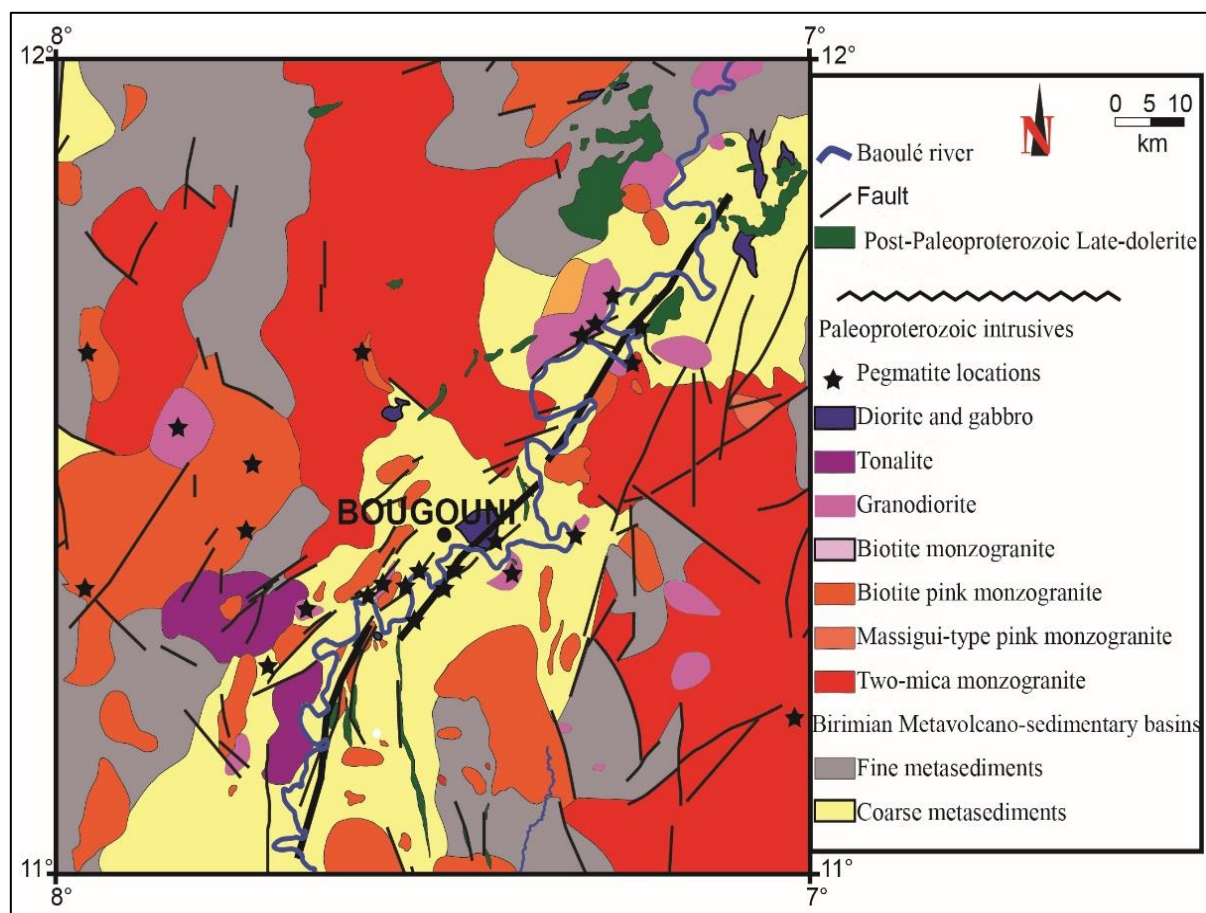


Fig 2 Bougouni Geological Map after Sanogo et al., (2025)

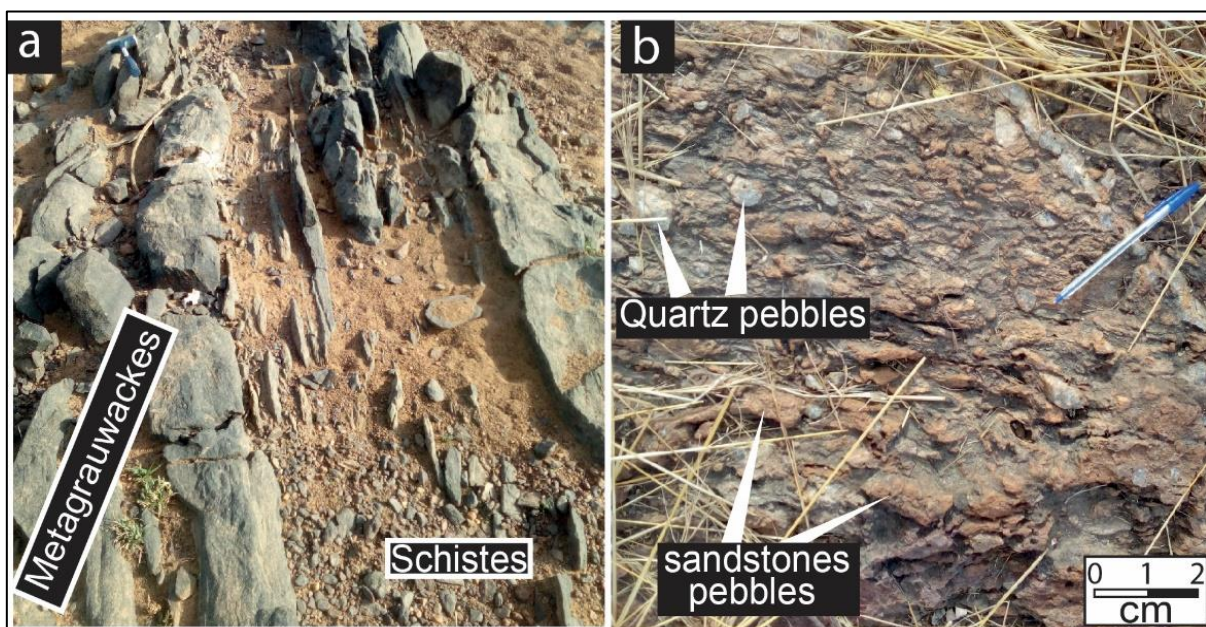


Fig 3 Field Photographs of the Coarse-Grained Metasedimentary Facies. a: Metagreywackes and Schist Facies; c: Sogola Conglomerate

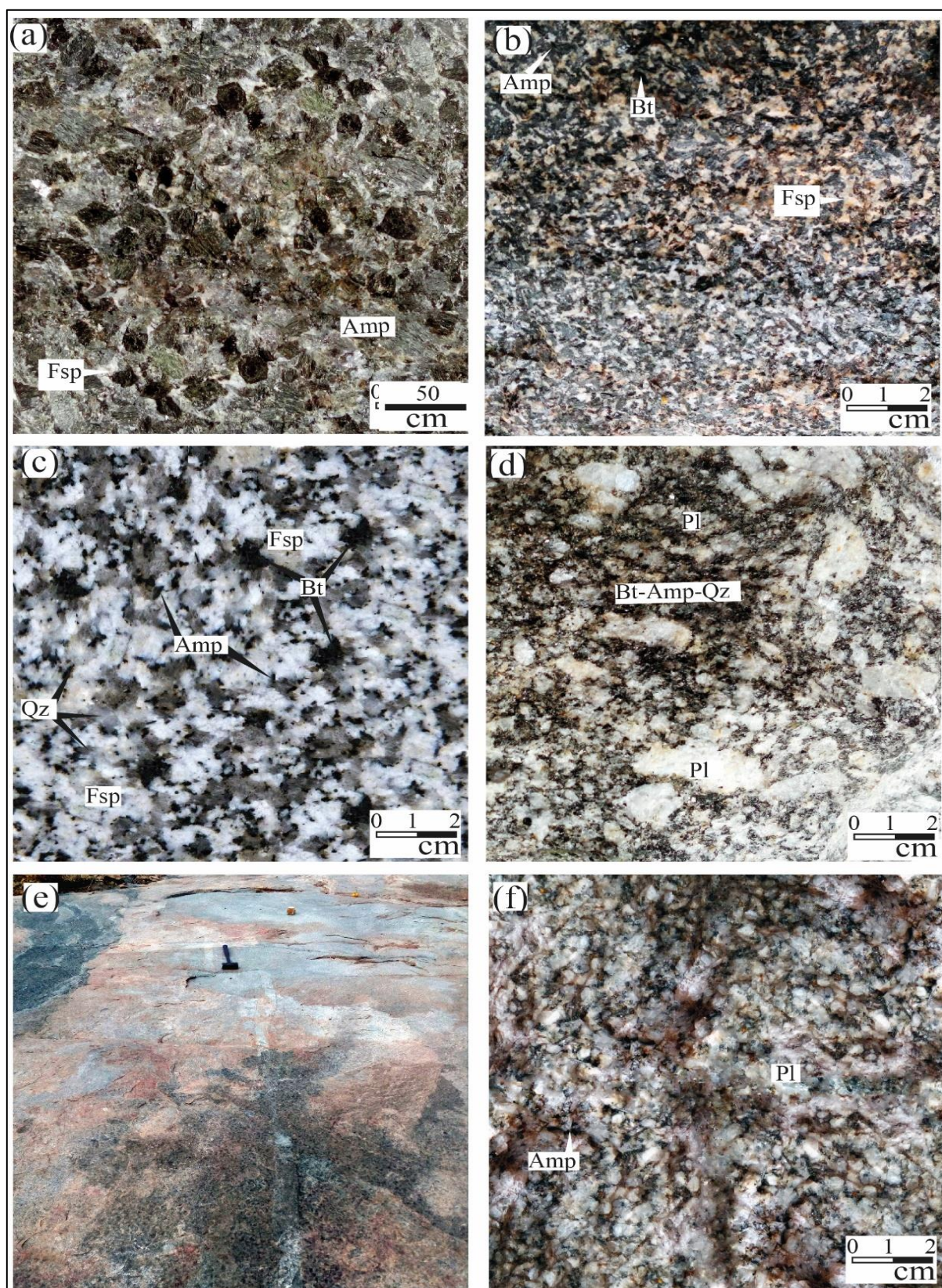


Fig 4 Macroscopy photographs of the mafic rocks; a : macroscopic view of the quartz diorite ; b : macroscopic view of the diorite; c : macroscopic view of the standard granodiorite lithology; d : macroscopic view of the porphyritic granodiorite lithology; e : flat outcrop fine-grained tonalite with pink pate; f : macroscopic view of the coarse-grained tonalite Amp = amphibole ; Bt = biotite ; Fsp = feldspar ; Pl = plagioclase; Qz = quartz.

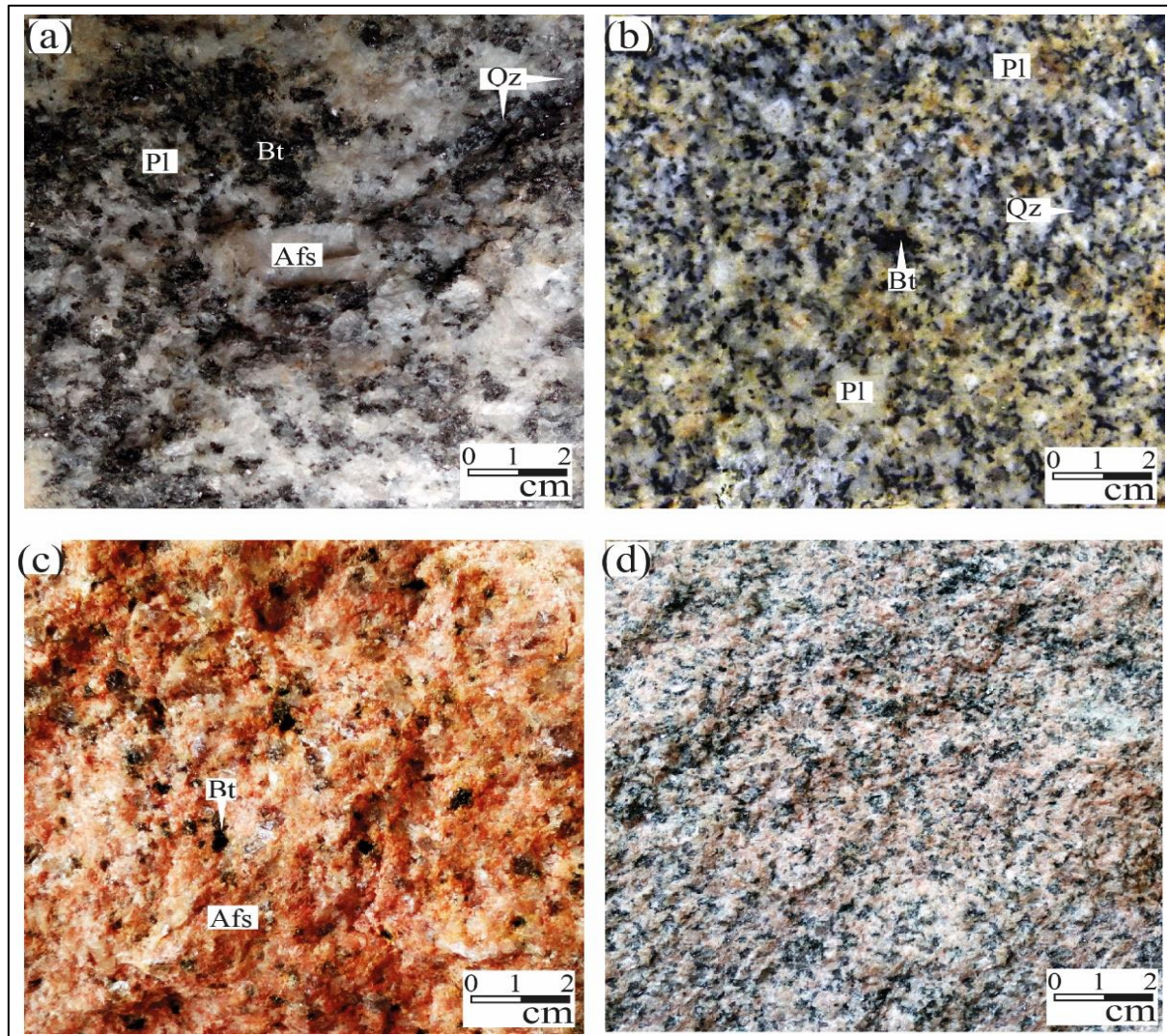


Fig 5 Field photographs for main monzogranite lithologies from the Bougouni area. a: macroscopic view of the porphyry biotite monzogranite; b: macroscopic view of the grey biotite monzogranite; c: macroscopic view of the pink «Massigui-type» biotite monzogranite; d: macroscopic view of the coarse-grained two micas monzogranites with a pinkish appearance (SBKO52); (STKL60); Afs = K-feldspar; Bt = biotite; Qz=quartz.

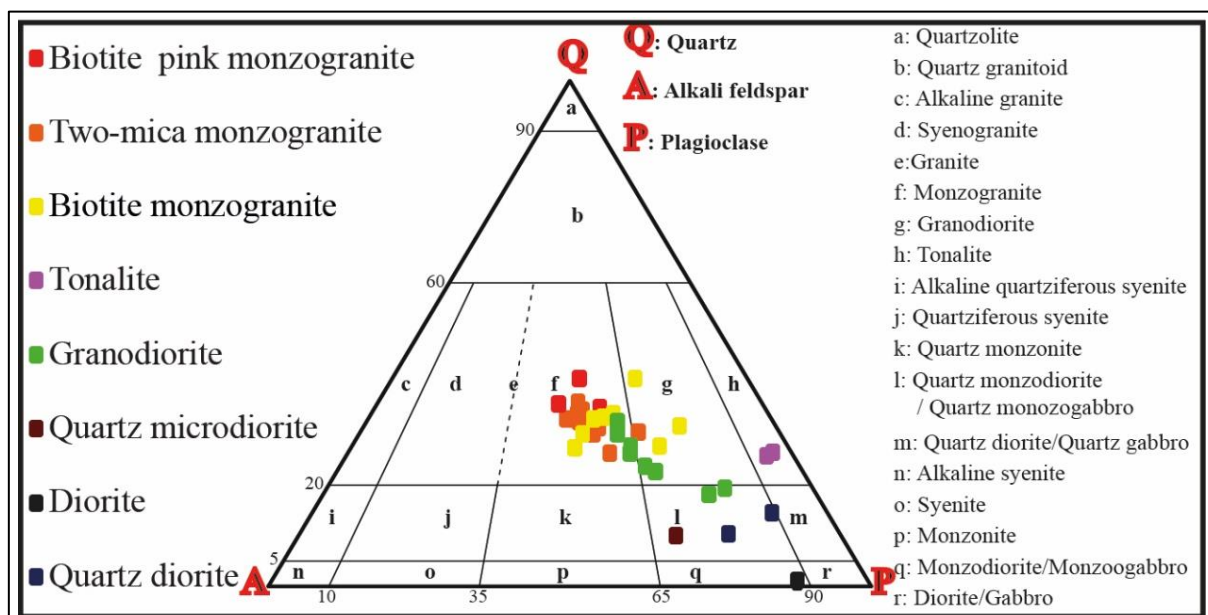


Fig 6 Classification of the Bougouni Plutonic Complex Rocks in the QAP Diagram of Streckeisen (1976)

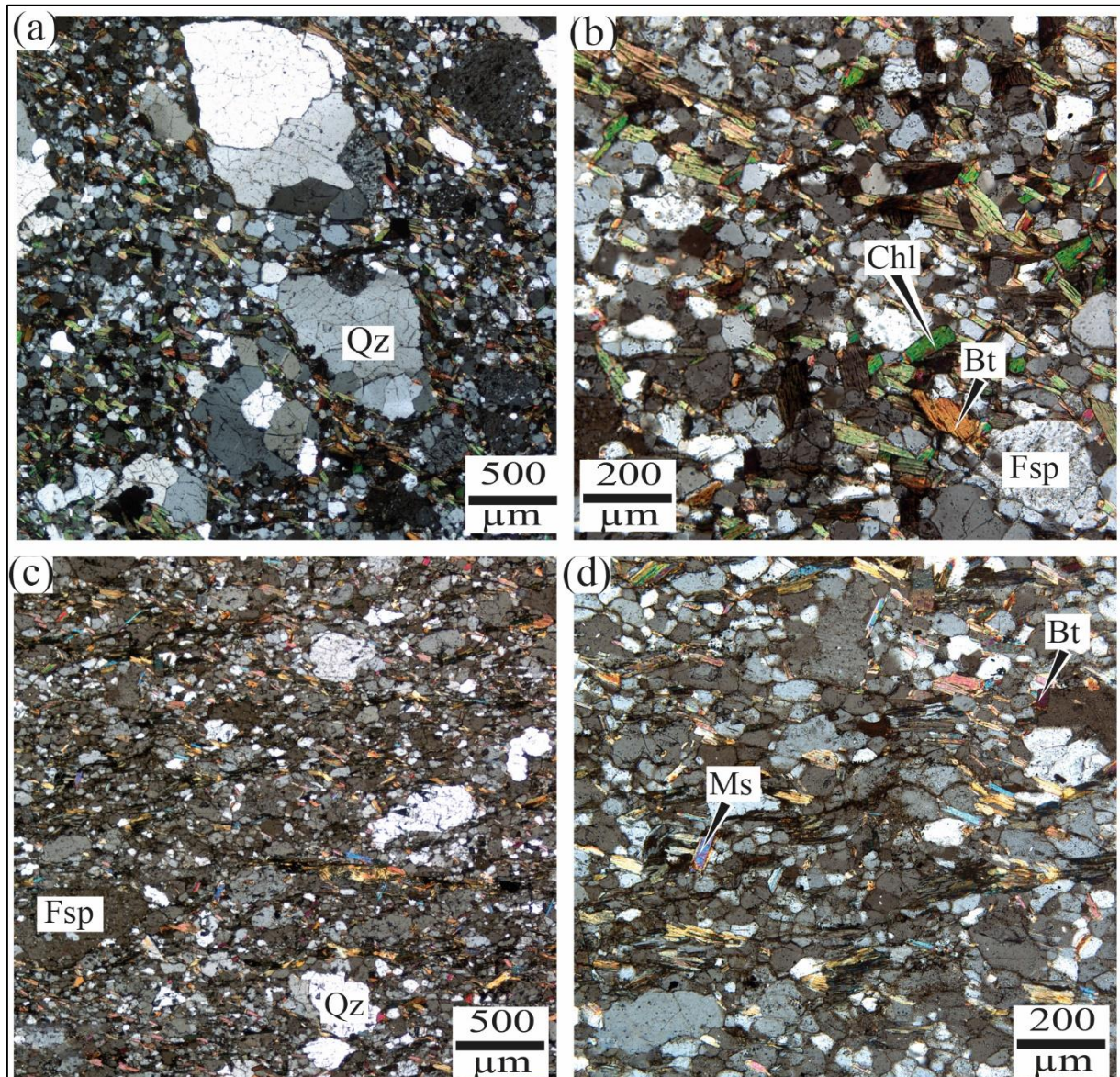


Fig 7 Microphotographs of Metagreywackes and Schist; a: Metagreywacke; b: Zoom on the Metagreywackes Matrix ; c: Schist and d: Zoom on the Schist Matrix.

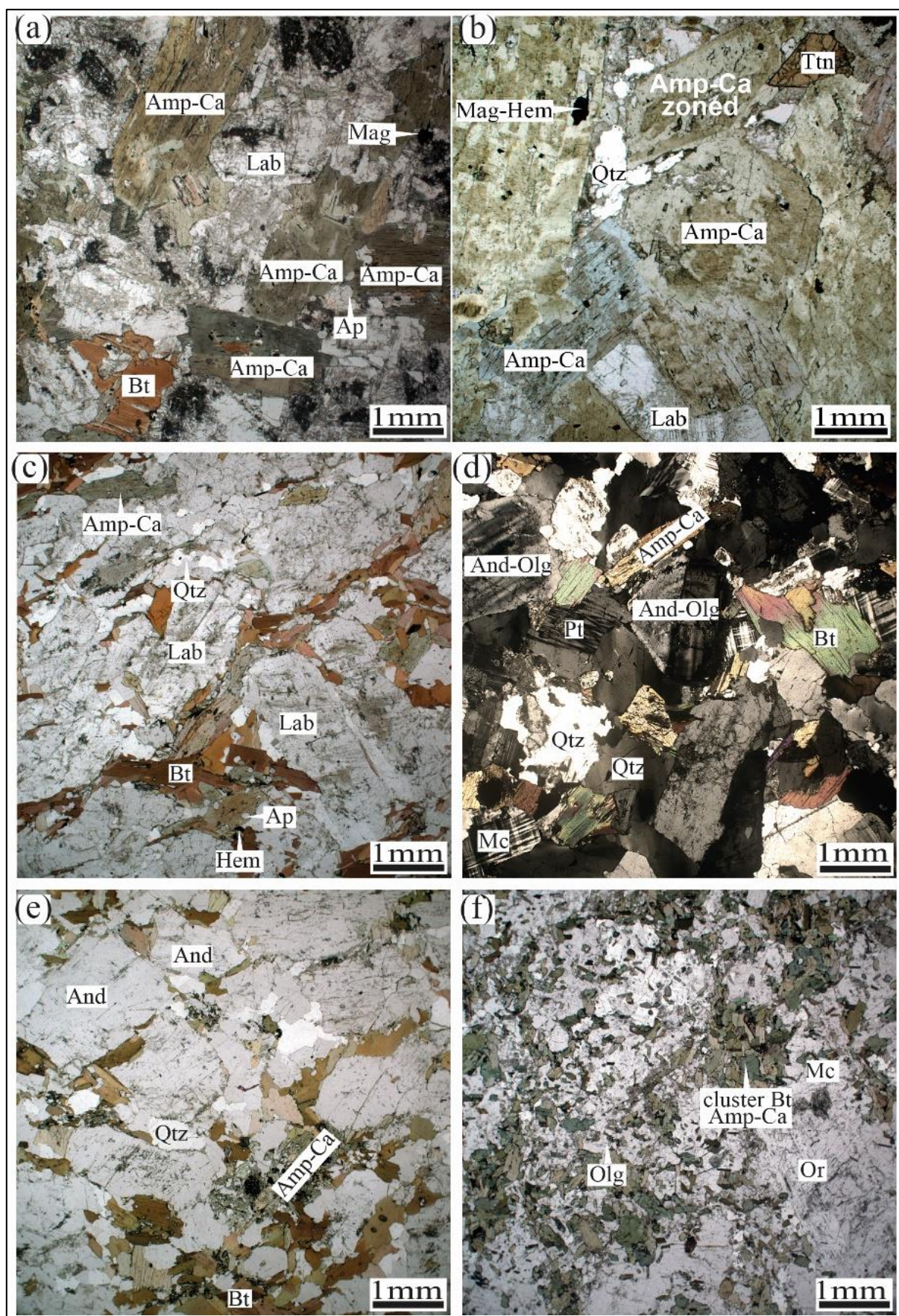


Fig 8 Microphotographs of the Mafic Rocks; a: Diorite; b: Quartz Diorite; c: Quartz Granodiorite; d: Standard Granodiorite; e: Porphyry Granodiorite and f: Quartz Microdiorite

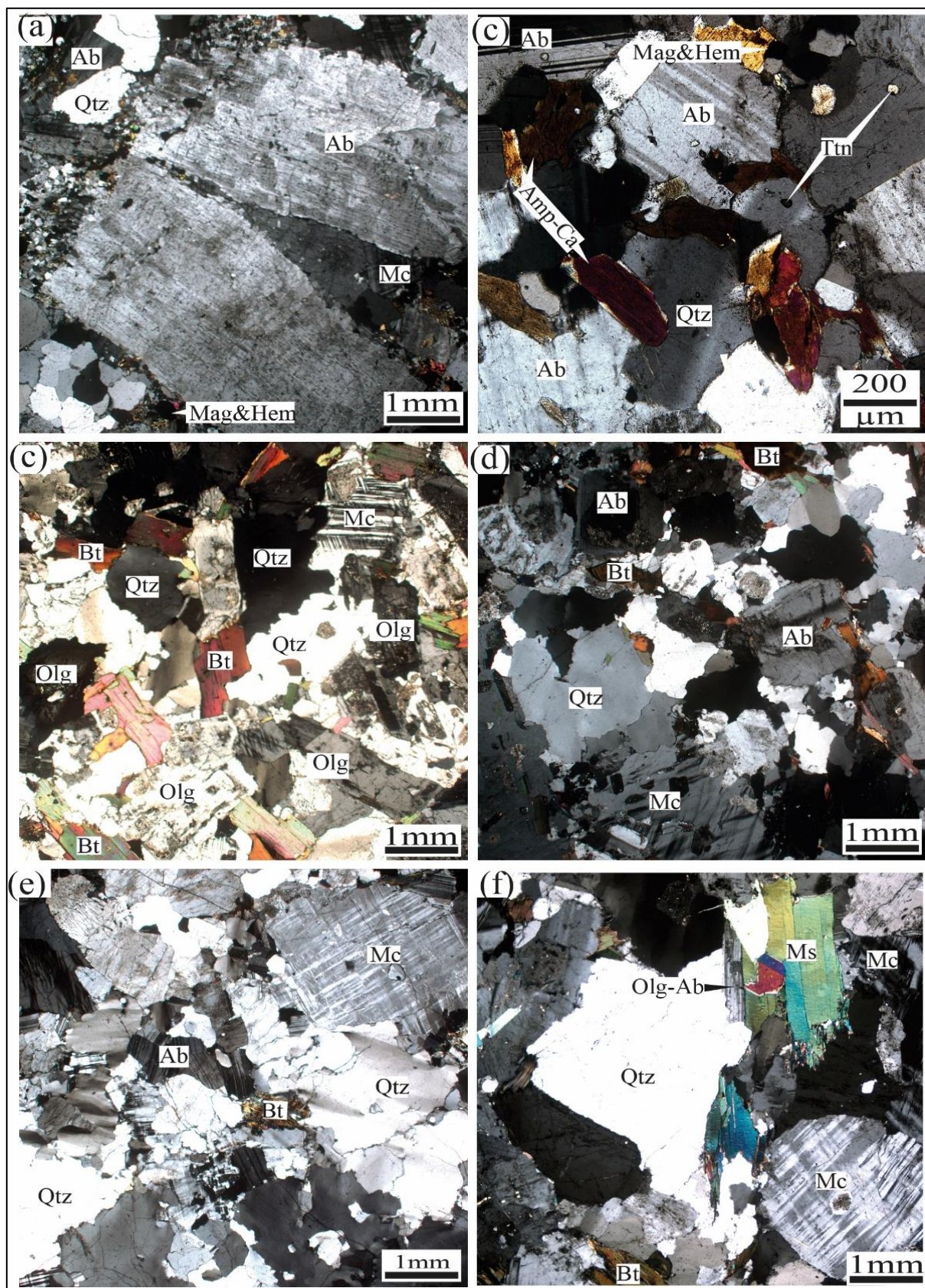


Fig 9 Microphotographs of the Tonalities and Monzogranites: a: Porphyry Coarse-Grained Tonalite; b: Zoom on the Matrix of Porphyry Coarse-Grained Tonalite; c: Biotite Monzogranite; d: Massigui Type» Pink Biotite Monzogranite; e: Biotite Pink Monzogranite and f: Two-Mica Monzogranite.

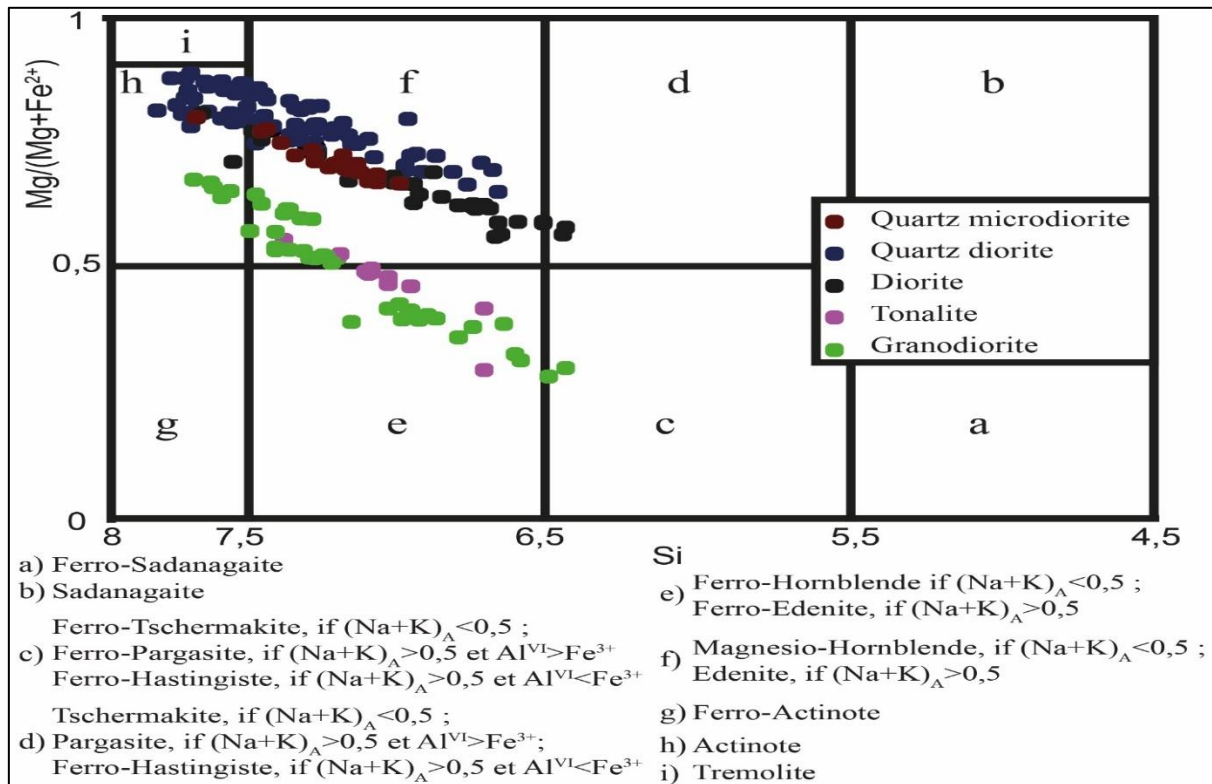


Fig 10 Classification of amphiboles of Bougouni plutonic complex rocks in the diagram of Leake et al. (1997)

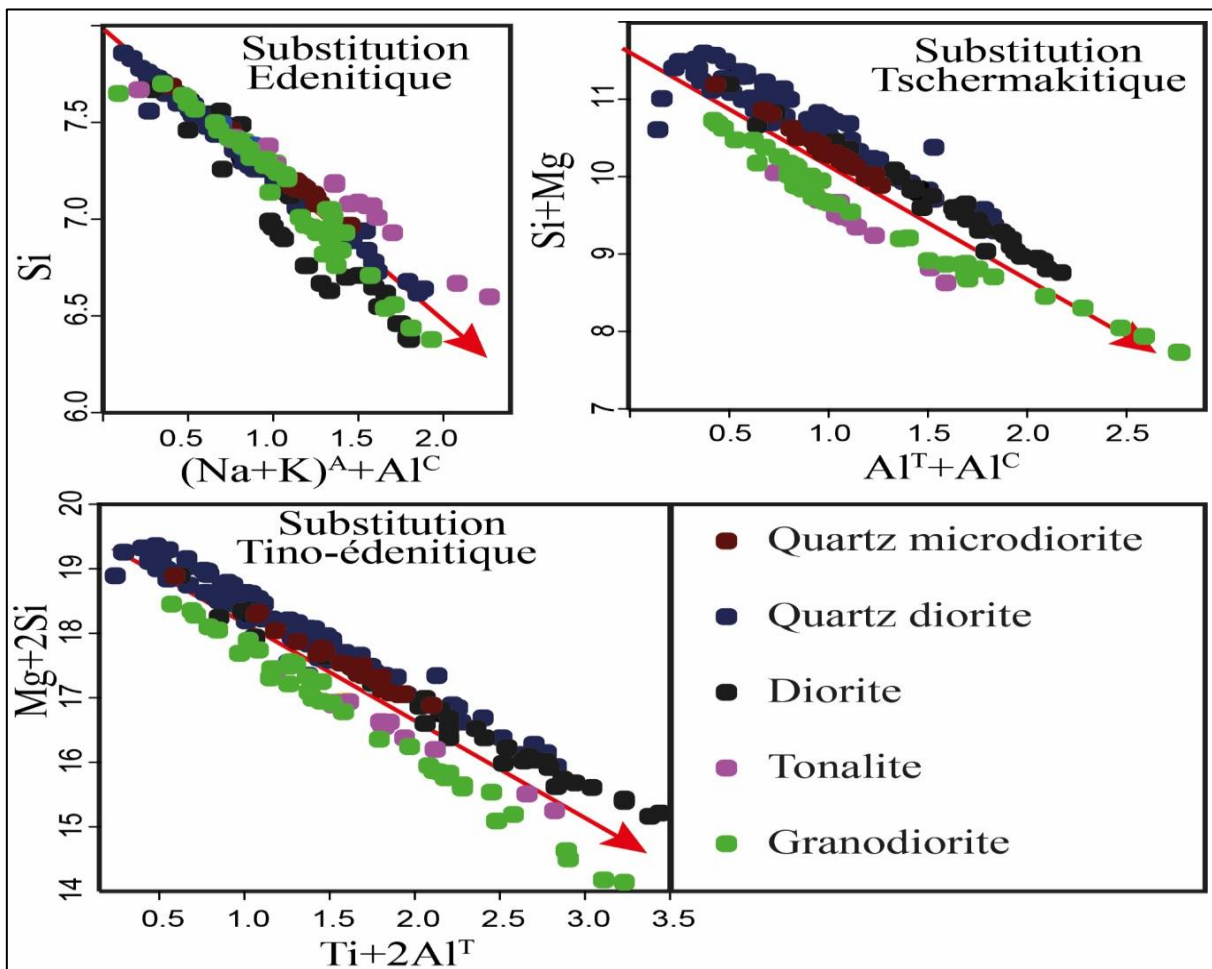


Fig 11 Substitutions in Amphiboles of Bougouni Plutonic Complex Rocks

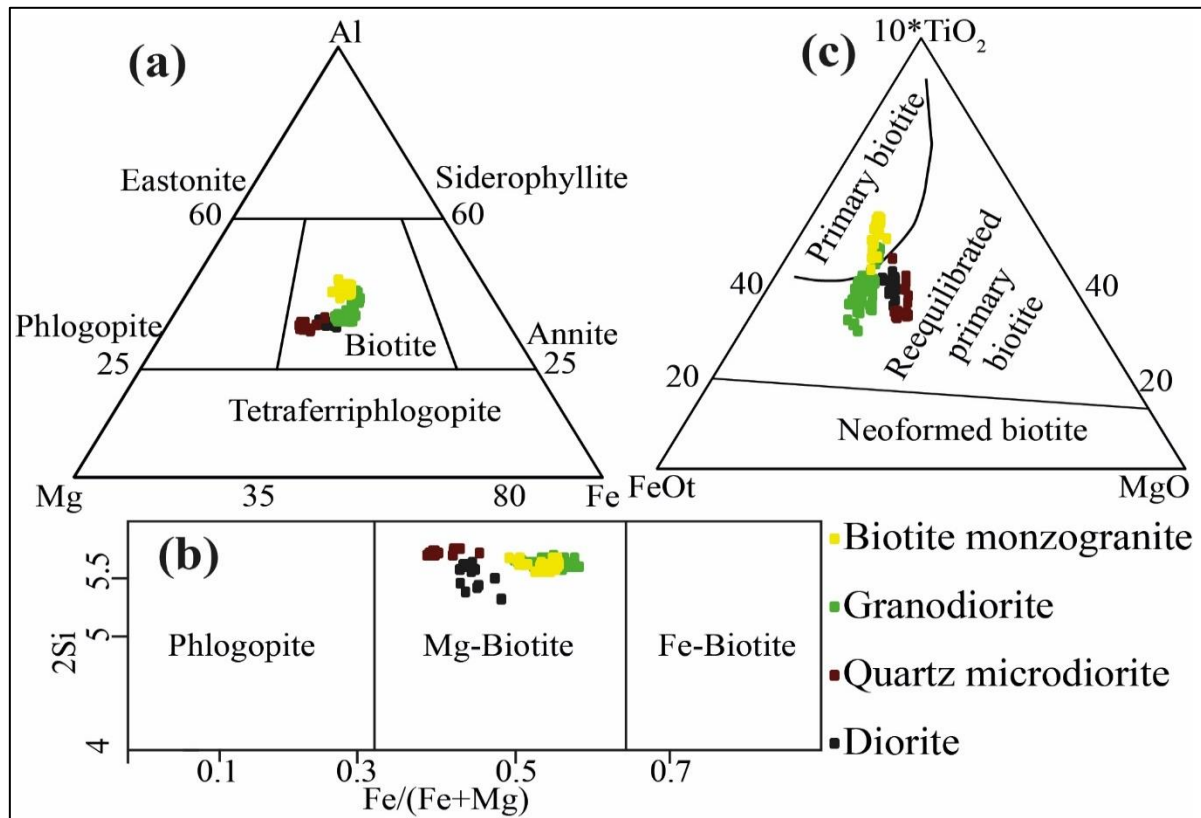


Fig 12 Classification of ferromagnesian micas of Bougouni plutonic complex rocks; A: Mg-Fe-Al diagram modified (after Nachit et al., 2005) showing that ferromagnesian micas are biotites; B: Fe / (Fe + Mg) versus Si, showing that biotites are Mg-Biotite (Dymek, 1983) ; 10^*TiO_2 -(FeOt +MnO) - MgO ternary diagram (Rieder et al., 1999) used to discriminate between primary biotite and reequilibrated primary biotite.

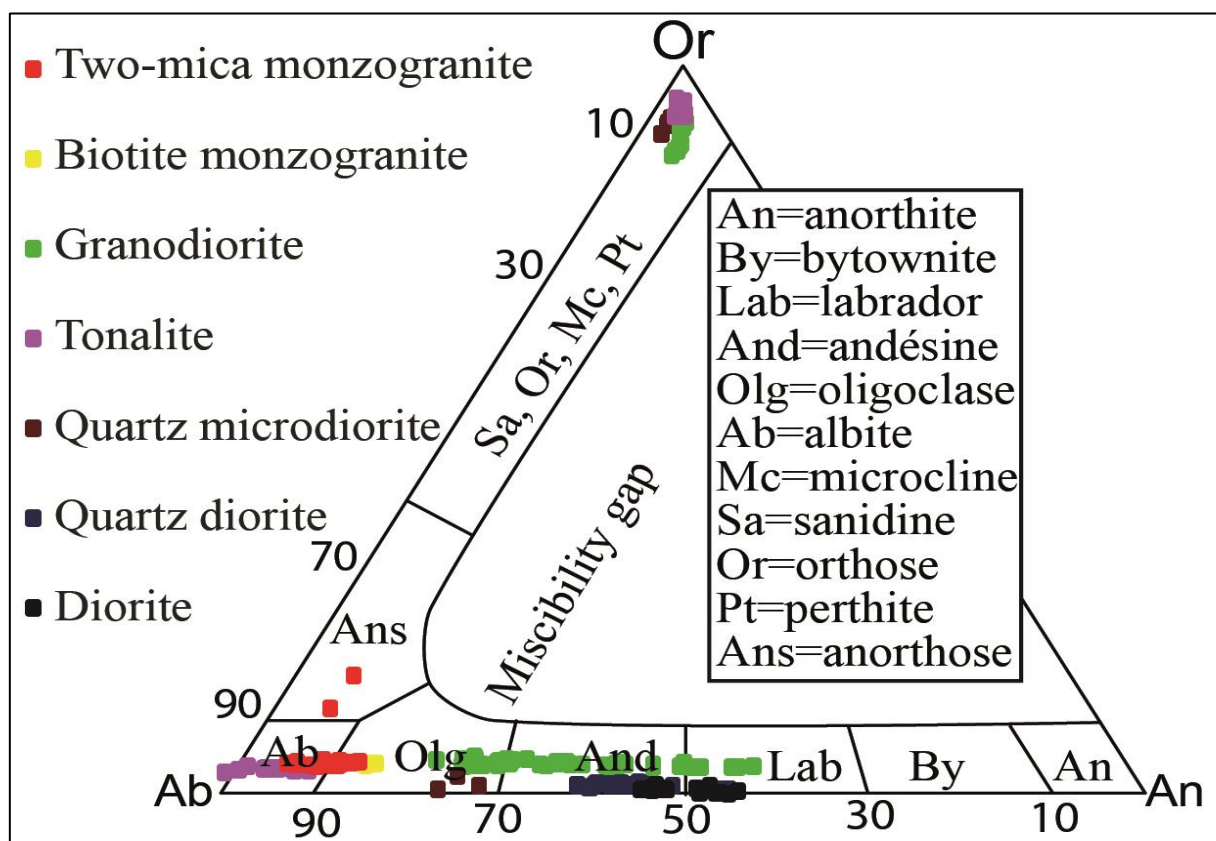


Fig 13 Classification of Feldspars of Bougouni Plutonic Complex Rocks in the An-Ab-Or Ternary Diagram (after Deer et al., 1992)

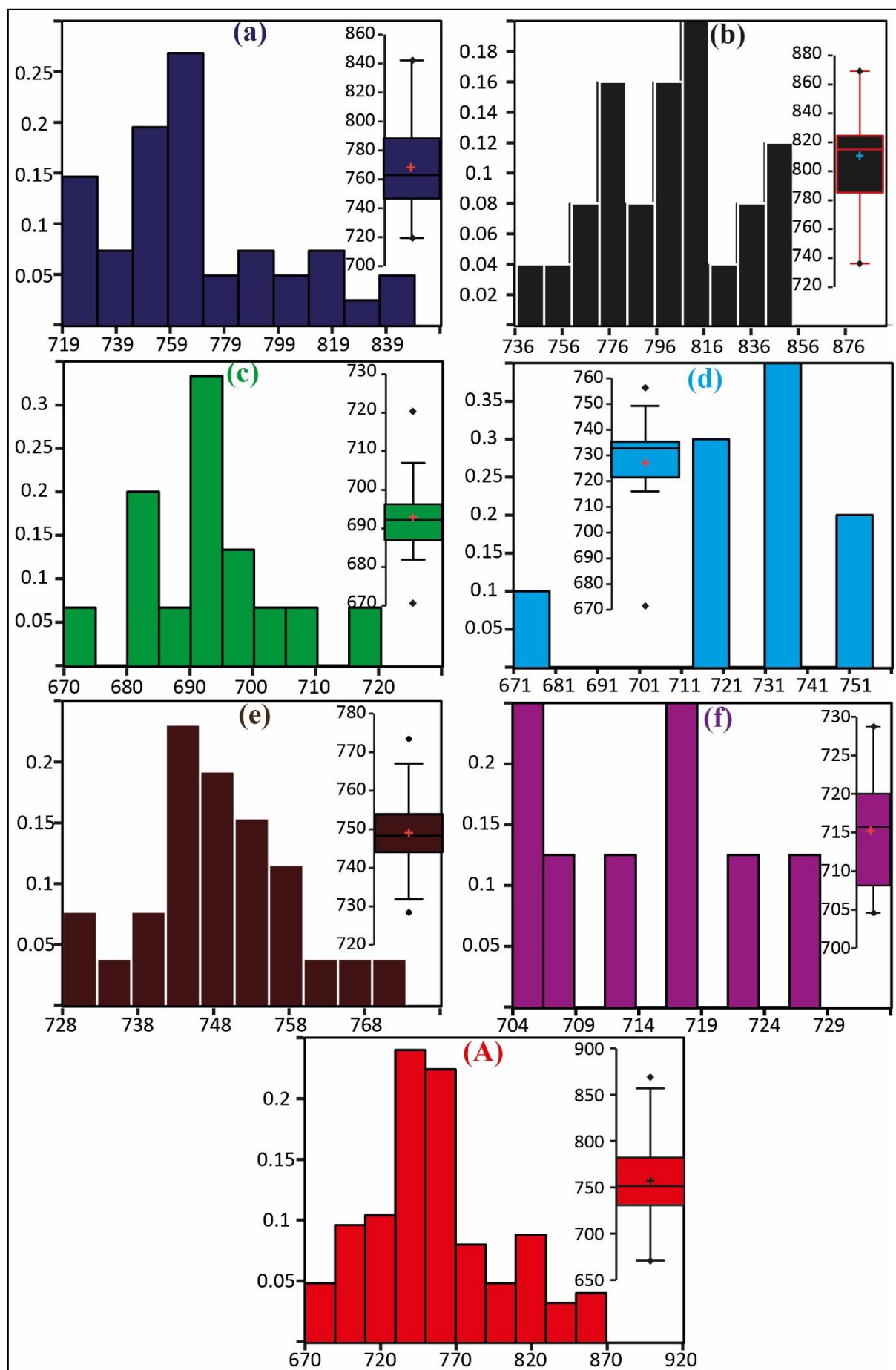


Fig 14 Plot Box and Histograms of Temperature Value Distributions

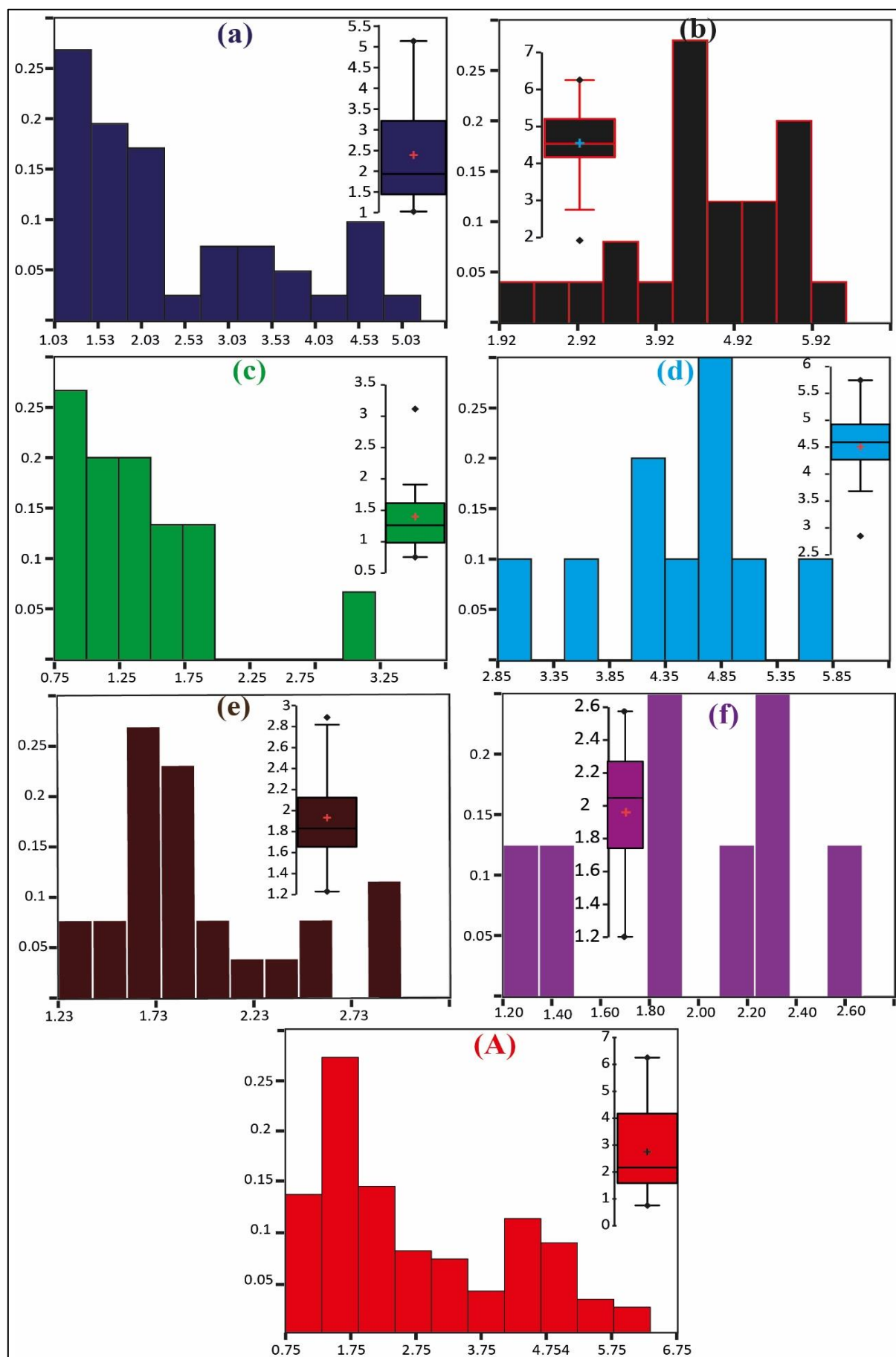


Fig 15 Plot Box and Histograms of Pressure Value Distributions

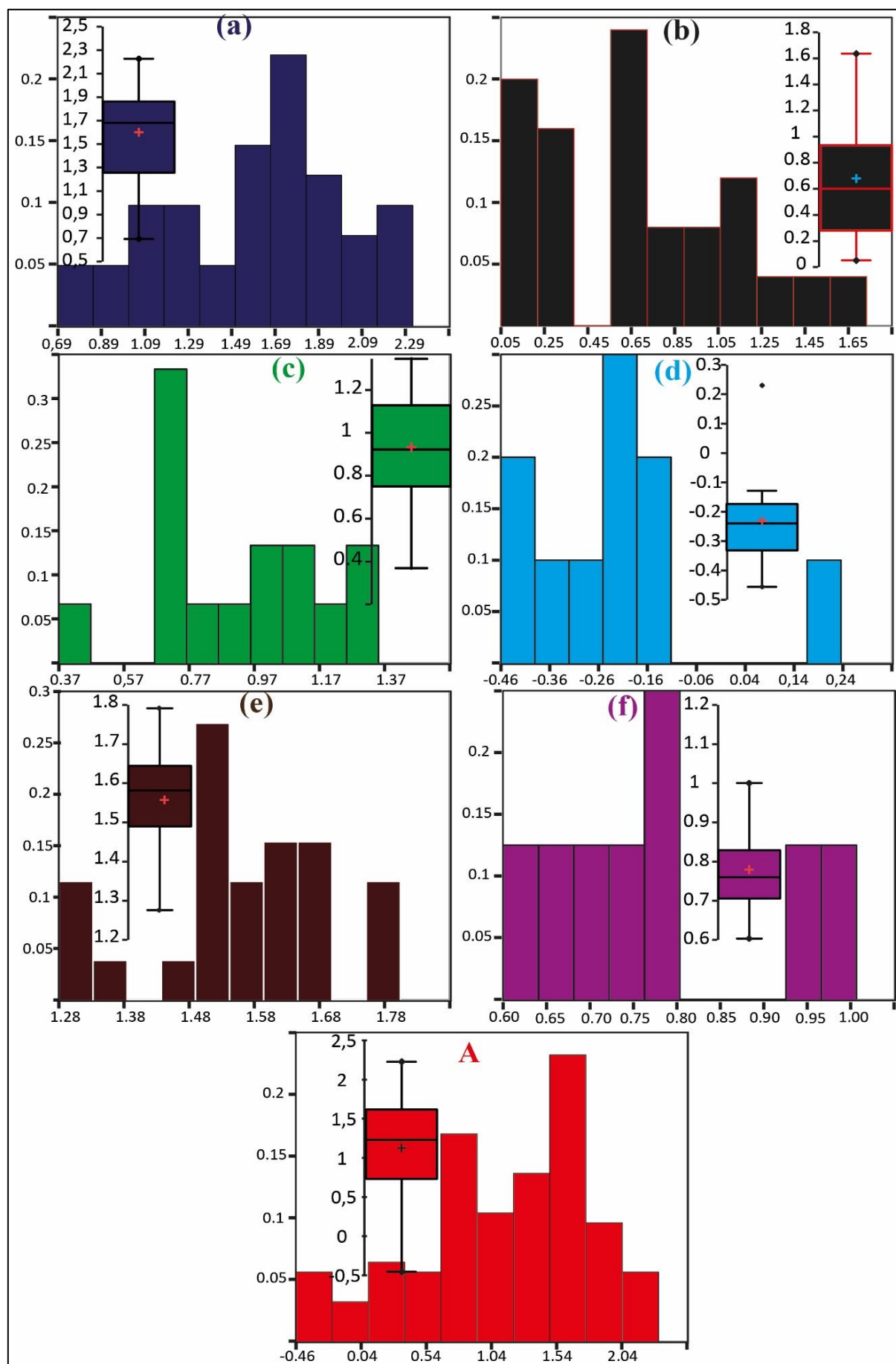


Fig 16 Plot Box and Histograms of Pressure Value Distributions

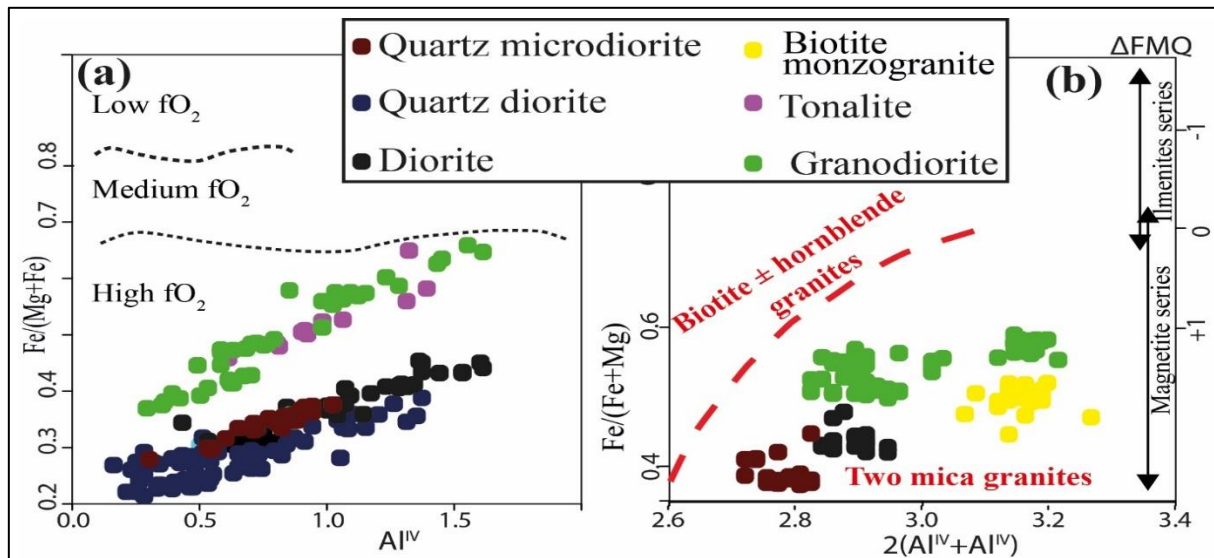


Fig 17 a: $\text{Fe} / (\text{Fe} + \text{Mg})$ versus Al^{IV} diagram showing the compositional of amphibole of Bougouni plutonic complex rocks in high $f\text{O}_2$ field ((Anderson and Smith, 1995)); b: $\text{Fe} / (\text{Fe} + \text{Mg})$ versus Al variation diagram showing biotite composition in ilmenite and magnetite series and ΔFMQ (Fayalite-Magnetite-Quartz) values (Anderson et al., 2008).

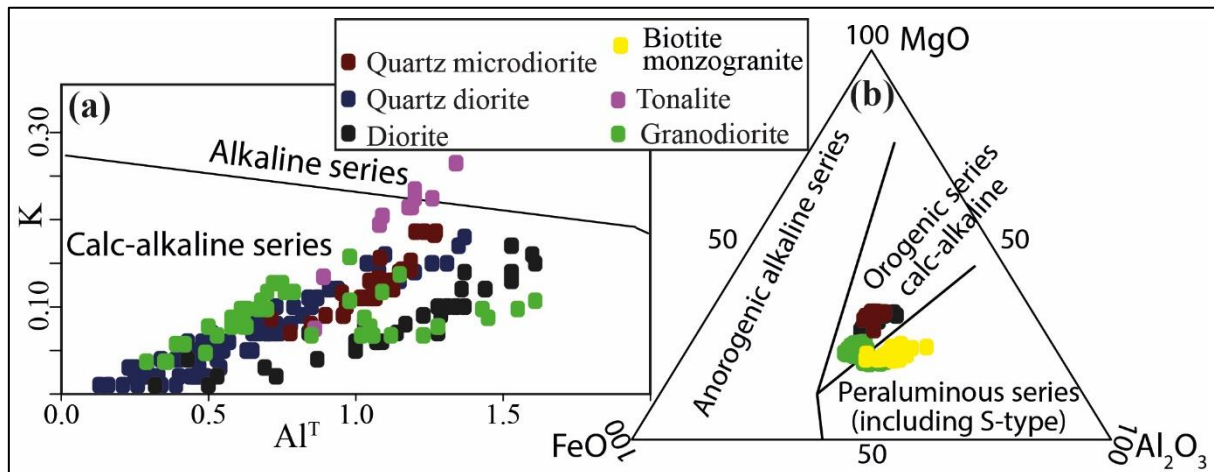


Fig 18 Discrimination of the magmatic series and the geotectonic environment; a: K versus Al^{T} discrimination diagram of amphiboles (Ridolfi and Renzulli, 2012) of Bougouni plutonic complex rocks and b: $\text{FeOt}-\text{MgO}-\text{Al}_2\text{O}_3$ discrimination diagram of Biotites (Abdel-Rahman, 1994).

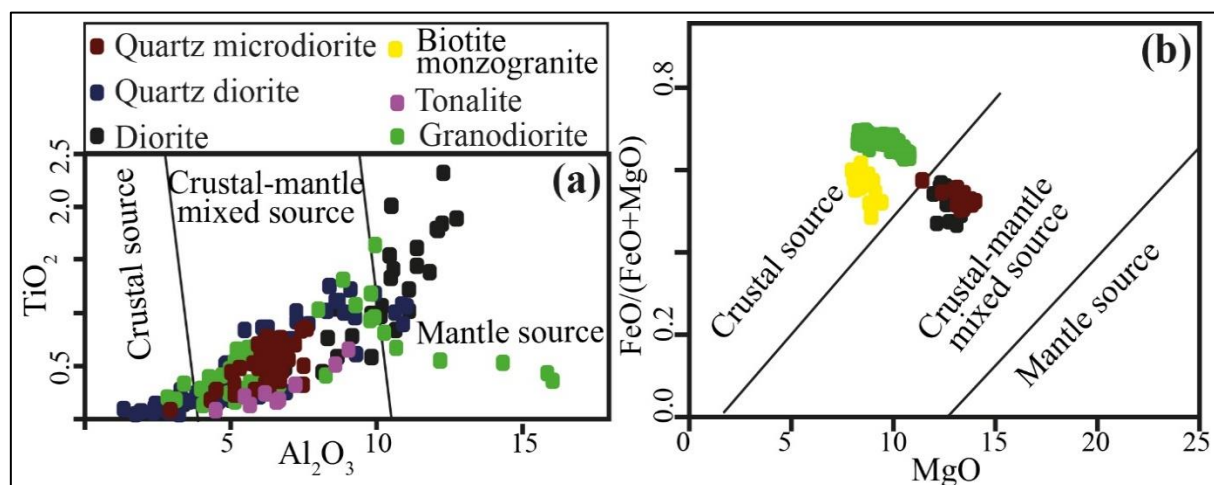


Fig 19 Discrimination of the magmatic series and the geotectonic environment; a: TiO_2 versus Al_2O_3 discrimination diagram of amphiboles (Jiang, C. and An, S., 1984) of Bougouni plutonic complex rocks and b: $\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3$ discrimination diagram of Biotites (Abdel-Rahman, 1994).

➤ Tables

Table 1 Summary of the macroscopic characteristics of the lithologies (Sanogo et al., 2025).

Lithologies	Sub-lithologies	Color index	Color	Texture	Grain	Grain size
Metagreywackes	Metagreywackes	Dark	Dark grey	Equigranular	Elements barely discernable	< 1 mm
Conglomerate	Conglomerate	Dark	Grey, white with reddish patina	Heterogranular	Figured elements + binder	mm - cm
Diorite	Diorite	Mesocrate	Dark	Equigranular	Coarse-grained	0,5 -1cm
Quartz diorite	Quartz diorite	Melanocrate	Dark	Equigranular	Coarse-grained	0,5 -1cm
Granodiorite	Quartz granodiorite	Leucocrate	More or less dark	Equigranular	Coarse-grained	0,5 -1cm
	Standard granodiorite	Leucocrate	More or less dark	Equigranular	Coarse-grained	0,5 -1cm
	Porphyry granodiorite	Leucocrate	More or less dark	Heterogranular	Coarse-grained and medium-grained	2 – 5 cm
Quartz microdiorite	Quartz microdiorite	Mesocrate	More or less dark	Heterogranular	Coarse-grained and medium-grained	3 mm - 5 cm
Tonalite	Porphyritic tonalite	Leucocrate	Greyish	Heterogranular	Coarse-grained	0.5 – 2 cm
	Equigranular tonalite	Hololeucocrate	Grey with a pinkish patina	Equigranular	Medium grained	2 - 5 mm
Biotite monzogranite	Biotite monzogranite	Leucocrate	Greyish	Equigranular	Medium grained	2 - 5 mm
	Biotite porphyry monzogranite	Leucocrate	Grey, milky white	Heterogranular	Coarse-grained and medium-grained	3 mm - 5 cm
	Pink biotite monzogranite	Hololeucocrate	Pink-beige	Equigranular	Fine grained	< 1 mm
	Bright pink biotite monzogranite "Massigui type"	Hololeucocrate	Bright pink	Equigranular	Medium grained	2 - 5 mm
Two-mica monzogranite	Two-mica monzogranite coarse-grained	Hololeucocrate	Pinkish grey	Equigranular	Coarse-grained	0.5 – 2 cm
	Two-mica monzogranite medium grained	Leucocrate	Pinkish grey	Equigranular	Medium grained	2 - 10 mm

Table 2 Average mineralogical content of Bougouni plutonic complex plutonic rocks. Amp = amphibole; Bt = biotite; Ms = muscovite; Afs = Alkali Feldspar; Qz = quartz; Ap = apatite; Mag = magnetite; Zrn = zircon; Ttn = titanite; Py = pyrite; Mnz = monazite; Ccp = chalcopyrite, Sp = sphalerite; Brt = barite; Gn = gale-na; X = % < 1.

Lithologies	Amp	Bt	Ms	Pl	Afs	Qz	Accessory minerals
Diorite	50%	10%		40%			Mag, Ttn, Ap, Zrn
Quartz diorite	75%			22%	X	3%	Mag, Ttn, Zrn, Py, Ccp,
Quartz granodiorite	12%	10%		30%	3%	45%	Mag, Ttn, Ap, Zrn, Ep, Py, Ccp, Sp
Standard granodiorite	15%	10%		30%	5%	40%	Mag, Ttn, Ap, Zrn, Ep, Py, Ccp, Sp
Porphyry granodiorite	10%	10%		45%		35%	Mag, Ttn, Ap, Zrn, Ep, Py, Ccp, Sp, Brt
Quartz microdiorite	25%	15%		37%	20%	3%	Mag, Ttn, Ap, Zrn,

Tonalite	5%		X	45%	5%	45%	Mag, Ttn, Ap, Zrn, Py, Brt
Biotite monzogranite		15%		40%	10%	35%	Mag, Ttn, Ap, Zrn, Py, Mnz, Gn
Biotite porphyry monzogranite		5%		25%	25%	45%	Mag, Ttn, Ap, Zrn, Ccp, Mnz, Gn
Bright pink biotite monzogranite "Massigui type"		3%		17%	35%	45%	Mag, Ap, Zrn
Two-mica monzogranite		3%	7%	20%	30%	40%	Mag, Ttn, Ap, Zrn, Py, Ccp, Mnz

Table 3 Geochemical of Compositions of Amphiboles ($A_{0-1}B_2C_5T_8O_{22}W_2$) from Bougouni Plutonic Complex Rocks

Lithologies	Si ₂ O	Ti ₂ O	Al ₃ O	Mn ₂ O	Fe ₂ O ₃	Mg ₂ O	CaO	Na ₂ O	K ₂ O	Total	Si _T	Al _I ^T	Ti _I ^C	Al _I ^C	Fe _C	Mg _C	Fe _B	Ca _B	Na _A	K _A	(Ca+Na) _B	Fe/(Mg+Fe)
Quartz diorite (n=84), SSSK28 et SBNK72																						
Average	51.22	0.47	5.62	0.22	11.10	15.47	12.25	0.61	0.38	97.34	7.36	0.63	0.05	0.03	1.28	3.32	0.06	1.89	0.14	0.07	1.92	0.51
Standard deviation	2.52	0.35	2.26	0.03	1.15	1.46	0.53	0.29	0.35	0.48	0.29	0.22	0.04	0.01	0.18	0.08	0.06	0.06	0.08	0.07	0.05	0.01
Diorite (n=29), SBNK49																						
Average	46.65	1.09	9.71	0.24	14.21	12.33	11.70	1.06	0.44	97.43	6.85	1.15	0.02	0.05	1.63	2.70	0.01	1.84	0.28	0.08	1.88	0.40
Standard deviation	3.10	0.60	2.48	0.04	1.24	1.51	0.29	0.26	0.23	0.56	0.33	0.67	0.03	0.02	0.15	0.29	0.04	0.04	0.05	0.04	0.05	0.05
Granodiorite (n=39), SGL32, SDIA4 et SBGS54																						
Average	48.30	0.53	7.19	0.39	17.61	10.49	11.57	0.70	0.47	97.33	7.28	0.80	0.06	0.04	2.14	2.33	0.06	1.85	0.05	0.09	1.88	0.49
Standard deviation	2.60	0.33	3.40	0.06	1.87	2.26	0.85	0.19	0.14	0.29	0.33	0.33	0.04	0.02	0.21	0.18	0.03	0.11	0.04	0.03	0.11	0.08
Sublithology1 : Quartz granodiorite (n=13), SGL32																						
Average	45.29	0.87	11.22	0.39	19.71	7.74	10.70	0.89	0.44	97.28	6.81	1.11	0.08	0.01	2.35	1.74	0.01	1.77	0.17	0.09	1.82	0.59
Standard deviation	1.51	0.37	2.64	0.11	0.90	1.05	0.99	0.12	0.12	0.35	0.22	0.33	0.04	0.04	0.05	0.24	0.04	0.11	0.05	0.02	0.15	0.03
Sublithology2 : Standard granodiorite (n=14), SDIA4																						
Average	50.65	0.43	4.57	0.38	15.53	12.75	12.02	0.57	0.39	97.27	7.46	0.54	0.05	0.02	1.89	2.80	0.03	1.90	0.13	0.07	1.93	0.41
Standard deviation	1.18	0.11	1.07	0.03	0.51	0.66	0.18	0.15	0.12	0.32	0.14	0.11	0.02	0.00	0.06	0.33	0.02	0.02	0.04	0.02	0.02	0.02
Sublithology3 : Porphyry granodiorite (n=13), SBGS54																						
Average	48.83	0.29	5.88	0.40	17.76	10.83	12.00	0.65	0.55	97.19	7.30	0.77	0.03	0.04	2.20	2.42	0.02	1.92	0.18	0.11	1.93	0.46
Standard deviation	0.069	0.00	1.05	0.03	0.35	0.60	0.09	0.12	0.15	0.22	0.13	0.13	0.01	0.07	0.05	0.22	0.01	0.01	0.03	0.02	0.01	0.01
Tonalite (n=11), SNKM56																						
Average	45.95	0.28	6.66	0.23	19.49	10.33	11.36	1.45	1.20	96.94	7.03	0.97	0.03	0.03	2.38	2.35	0.01	1.84	0.42	0.03	1.96	0.51
Standard deviation	1.89	0.11	1.31	0.03	1.08	0.88	0.23	0.29	0.25	0.28	0.22	0.22	0.02	0.03	0.14	0.18	0.03	0.03	0.08	0.05	0.02	0.04

Quartz microdiorite (n=31), SSSK50																						
Average	49 .1 9	0. 5 0	6. 37	0. 34	13 .2 8	14 .0 4	12 .1 0	0. 83	0. 6	97 .2 8	7. 2 0	0. 8	0. 0	0. 3	1. 5 6	3. 0 6	0. 0 7	1. 8 9	0. 2 3	0. 1 2	1.91	0.35
Standard deviation	1. 28 9	0. 1 9	1. 00	0. 03	0. 66	0. 71	0. 12	0. 13	0. 1	0. 39 5	0. 1 4	0. 1 4	0. 0 2	0. 0 4	0. 0 8	0. 0 4	0. 0 1	0. 0 1	0. 0 4	0. 0 3	0.01	0.02

Table 4 Geochemical Compositions of Black Micras from Bougouni Plutonic Complex Rocks ($XY_{2-3}Z_4O_{10}(OH, F, Cl)_2$)

Lithologies	Si O 2	Ti O 2	Al 2 O 3	Fe O t	Mn O	Mg O	Na2 O	K 2 O	Total	Fe O 3	Fe 2 O 3	H 2 O	S i	Al ^I V	Al ^{IV} I	T i	Fe ³ +	Fe ² +	Mn	Mg	Na	K	O H	Fe ³ +/Σ Fe
Diorite (n=15), SBNK49																								
Average	36.58	2.27	16.19	17.92	0.12	12.58	0.12	9.33	95.10	15.61	2.57	3.98	2.75	1.25	0.19	0.13	0.115	0.098	0.01	1.41	0.02	0.090	2.00	0.12
Standard deviation	0.74	0.19	0.20	0.81	0.01	0.35	0.05	0.91	1.03	2.17	3.12	0.02	0.05	0.05	0.05	0.01	0.18	0.14	0.00	0.04	0.01	0.09	0.00	0.15
Granodiorite (n=65), SSGL32, SDIA4, SBGS54																								
Average	36.85	2.13	16.72	17.98	0.19	9.47	0.05	9.74	95.03	18.26	1.78	3.93	2.81	1.19	0.31	0.12	0.11	1.16	0.01	1.08	0.01	0.095	2.00	0.08
Standard deviation	0.32	0.42	1.00	0.53	0.06	0.82	0.03	0.38	0.75	1.10	1.00	0.03	0.01	0.01	0.08	0.02	0.00	0.08	0.00	0.09	0.00	0.04	0.00	0.05
Quartz microdiorite (n=19), SSSK50																								
Average	38.12	1.83	15.58	17.97	0.22	13.31	0.05	10.23	95.31	14.68	1.44	4.01	2.85	1.15	0.23	0.01	0.08	0.09	0.02	1.48	0.01	0.098	2.00	0.08
Standard deviation	0.29	0.31	0.29	0.51	0.03	0.61	0.02	0.18	0.50	0.78	0.57	0.03	0.01	0.01	0.02	0.02	0.03	0.05	0.00	0.06	0.00	0.02	0.00	0.03
Biotite monzogranite (n=29), STGL38																								
Average	37.16	3.13	18.11	17.41	0.23	8.47	0.07	9.86	94.44	14.09	3.69	3.99	2.80	1.20	0.40	0.08	0.21	0.09	0.01	0.95	0.01	2.95	0.00	0.19
Standard deviation	0.49	0.45	0.50	0.53	0.03	0.33	0.04	0.24	0.66	1.25	0.95	0.04	0.02	0.02	0.03	0.03	0.05	0.08	0.00	0.04	0.01	0.02	0.00	0.05

Table 5 Geochemical Compositions of Muscovites from Bougouni Two Micras Monzogranite Rocks ($IM_{2-3}□_{1-0}T_4O_{10}W_2$)

Lithologies	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	Na ₂ O	K ₂ O	Total	Si	Al _T	Al _M	Fe	Mg	Na	K	Mn/Fe
Average	46. 38	0.7 3	33.1 0	2.2 6	0.05	1.2 7	0.30	11. 81	95.9 6	3.1 1	0.8 9	1.7 3	0.1 3	0.1 3	0.0 4	1.0 1	0.02
Standard deviation	0.6 1	0.2 8	2.06	0.5 8	0.03	0.5 2	0.12	0.1 7	0.66	0.0 6	0.0 6	0.0 9	0.0 3	0.0 5	0.0 2	0.0 2	0.01

Table 6 Geochemical Compositions of Plagioclases from Bougouni Plutonic Complex Rocks

Lithologies	SiO ₂	Al ₂ O ₃	CaO	Na ₂ O	K ₂ O	Total	Si	Al	Ca	Na	K	An	Ab	Or
Quartz diorite (n=26), SBNK72														
Average	57.40	27.31	8.99	6.24	0.14	100.08	2.57	1.44	0.43	0.54	0.01	43.97	55.21	0.82
Standard deviation	1.11	0.76	0.85	0.52	0.06	0.50	0.04	0.04	0.04	0.04	0.00	4.40	4.20	0.36
Diorite (n=16), SBNK49														
Average	55.92	28.49	10.25	5.56	0.06	100.28	2.50	1.50	0.49	0.48	0.00	50.30	49.37	0.33
Standard deviation	0.92	0.52	0.66	0.44	0.02	0.41	0.03	0.03	0.03	0.04	0.00	3.51	3.52	0.11
Granodiorite (n=54), SDIA4, SMSL75, BGS54														
Average	59.41	25.97	7.38	7.31	0.14	100.20	2.64	1.36	0.35	0.63	0.01	35.63	63.59	0.77
Standard deviation	2.23	1.65	1.86	1.15	0.06	0.41	0.09	0.09	0.09	0.10	0.00	9.48	9.28	0.34
Sublithology1 : Quartz granodiorite (n=13), SMSL75														
Average	56.42	28.33	9.99	5.61	0.07	100.42	2.52	1.49	0.48	0.49	0.00	49.38	50.20	0.42
Standard deviation	1.40	0.92	1.11	0.63	0.03	0.37	0.05	0.05	0.05	0.05	0.00	5.56	5.49	0.20
Sublithology2 : Standard granodiorite (n=21), SDIA4														
Average	59.66	25.77	7.13	7.66	0.13	100.35	2.65	1.35	0.34	0.66	0.01	33.75	65.51	0.75
Standard deviation	1.69	1.07	1.27	0.80	0.04	0.32	0.06	0.06	0.06	0.07	0.00	6.24	6.29	0.23
Sublithology3 : Porphyry granodiorite (n=20), SBGS54														
Average	61.07	24.66	5.95	8.02	0.18	99.88	2.71	1.29	0.28	0.69	0.01	28.77	70.20	1.03
Standard deviation	0.83	0.58	0.64	0.36	0.05	0.35	0.03	0.03	0.03	0.03	0.00	3.12	3.05	0.31
Quartz microdiorite (n=3), SSSK50														
Average	62.32	24.37	5.21	8.51	0.22	100.61	2.74	1.26	0.25	0.73	0.01	24.96	73.79	1.25
Standard deviation	0.48	0.19	0.39	0.26	0.07	0.29	0.01	0.01	0.02	0.02	0.00	1.98	2.06	0.42
Tonalite (n=13), SNKM56														
Average	67.34	20.38	1.02	10.93	0.09	99.89	2.95	1.05	0.05	0.93	0.01	4.91	94.57	0.52
Standard deviation	1.00	0.65	0.54	0.50	0.04	0.89	0.03	0.03	0.03	0.04	0.00	2.65	2.63	0.21
Biotite monzogranite (n=3), STGL38														
Average	64.58	22.58	3.37	9.63	0.12	100.27	2.84	1.17	0.16	0.82	0.01	16.10	83.23	0.67
Standard deviation	0.12	0.07	0.06	0.21	0.02	0.22	0.00	0.00	0.00	0.02	0.00	0.54	0.61	0.10
Two-mica monzogranite (n=19), SBLD53														
Average	65.73	21.45	2.24	10.03	0.31	99.76	2.89	1.11	0.11	0.86	0.02	10.80	87.40	1.80
Standard deviation	0.78	0.47	0.46	0.47	0.55	0.78	0.02	0.02	0.02	0.04	0.03	2.17	3.02	3.22

Table 7 Geochemical Compositions of Alkali Feldspars from Bougouni Plutonic Complex Rocks

Lithologies	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	Total	Si	Al	Na	K	An	Ab	Or
Quartz microdiorite (n=8), SSSK50												
Average	64.17	18.70	0.58	16.45	99.91	2.98	1.02	0.05	0.97	0.03	5.08	94.89
Standard deviation	0.19	0.10	0.15	0.21	0.26	0.01	0.01	0.01	0.01	0.09	1.31	1.29

Standard granodiorite (n=9), SIDA4												
Average	64.07	18.58	0.49	16.58	99.75	2.98	1.02	0.04	0.98	0.17	4.32	95.52
Standard deviation	0.27	0.15	0.09	0.32	0.61	0.01	0.00	0.01	0.02	0.07	0.76	0.80
Tonalite (n=10), SNKM56												
Average	63.79	18.41	0.41	17.08	99.73	2.97	1.01	0.04	1.02	0.22	3.52	96.26
Standard deviation	0.25	0.15	0.07	0.26	0.44	0.00	0.01	0.01	0.01	0.09	0.64	0.64
Two-mica monzogranite (n=8), SBLD53												
Average	64.10	18.49	0.36	16.96	99.95	2.98	1.01	0.03	1.01	0.21	2.55	97.23
Standard deviation	0.16	0.09	0.15	0.14	0.29	0.00	0.00	0.00	0.01	0.11	0.46	0.42

Table 8 Pressure (kbar) (a,b,c,d,e,f,AP), Temperature (°C) (g) and Oxygen fugacity (h) calculation results using the chemical composition of amphiboles from the Bougouni plutonic complex rocks from several studies. a : (Hollister et al., 1987); b : (Mutch et al., 2016); c : (Schmidt, 1992); d : (Hammarstrom and Zen, 1986); e : (Johnson and Rutherford, 1989b); f : (Ridolfi et al., 2010); AP: Average pressure; g: (Hollister et al., 1987); h: (Ridolfi et al., 2010)

Statistique	a	b	c	d	e	f	AP	g	h	Deph
Quartz diorite (n= 41 analyses)										
Minimum	0.59	1.71	1.51	0.85	0.55	0.69	1.03	719	0.69	3881.91
Maximum	6.08	4.81	6.14	5.75	4.67	11.50	5.14	842	2.23	19402.06
1 st quartile	1.21	1.97	2.03	1.40	1.02	0.94	1.44	747	1.26	5443.07
Median	1.90	2.28	2.61	2.02	1.54	1.19	1.94	763	1.68	7305.84
3 rd quartile	3.67	3.22	4.10	3.59	2.86	1.86	3.22	788	1.86	12142.61
Mean	2.45	2.64	3.08	2.51	1.95	1.71	2.39	768	1.60	9024.48
Variance (n-1)	2.73	0.85	1.94	2.17	1.54	3.02	1.43	1013	0.18	20435662.53
Standard Deviation (n-1)	1.65	0.92	1.39	1.47	1.24	1.74	1.20	32	0.42	4520.58
Diorite (n=25 analyses)										
Minimum	1.90	2.28	2.61	2.02	1.54	0.68	1.92	736	0.05	7241.19
Maximum	7.94	6.29	7.70	7.40	6.06	11.34	6.25	869	1.64	23602.57
1 st quartile	4.91	3.99	5.15	4.70	3.79	0.86	4.17	785	0.28	15741.71
Median	5.64	4.50	5.77	5.36	4.34	1.11	4.54	815	0.60	17126.51
3 rd quartile	6.65	5.24	6.62	6.26	5.10	2.48	5.20	825	0.93	19629.93
Mean	5.55	4.51	5.69	5.28	4.28	1.97	4.55	811	0.68	17166.07
Variance (n-1)	2.38	1.11	1.69	1.89	1.34	4.63	1.10	1136	0.20	15723616.71
Standard Deviation (n-1)	1.54	1.05	1.30	1.37	1.16	2.15	1.05	34	0.45	3965.30
Standard and Porphyry granodiorite (n=15 analyses)										
Minimum	0.20	1.56	1.17	0.50	0.26	0.81	0.75	671	0.37	2847.82
Maximum	3.60	3.18	4.04	3.53	2.81	1.56	3.12	720	1.35	11761.64
1 st quartile	0.52	1.68	1.45	0.79	0.50	0.91	0.98	687	0.75	3718.11
Median	0.93	1.85	1.79	1.15	0.80	1.03	1.26	692	0.92	4763.58
3 rd quartile	1.44	2.07	2.22	1.61	1.19	1.09	1.61	696	1.13	6095.33
Mean	1.13	1.95	1.96	1.33	0.96	1.08	1.40	693	0.93	5289.63
Variance (n-1)	0.72	0.16	0.51	0.57	0.40	0.06	0.34	135	0.07	4832026.60
Standard Deviation (n-1)	0.85	0.40	0.72	0.76	0.64	0.25	0.58	12	0.27	2198.19
Quartz granodiorite (n=10 analyses)										
Minimum	3.37	3.05	3.85	3.33	2.64	0.88	2.85	671	-0.46	10760.52
Maximum	7.50	5.93	7.34	7.02	5.74	7.48	5.75	756	0.23	21690.73
1 st quartile	4.75	3.89	5.01	4.56	3.67	1.87	4.27	721	-0.33	16112.03
Median	5.22	4.21	5.42	4.98	4.03	3.07	4.59	733	-0.24	17335.33
3 rd quartile	5.47	4.38	5.62	5.20	4.21	4.32	4.93	735	-0.17	18597.23
Mean	5.20	4.22	5.40	4.96	4.01	3.25	4.51	727	-0.23	17015.43
Variance (n-1)	1.21	0.59	0.86	0.96	0.68	3.96	0.66	535	0.04	9439376.94
Standard Deviation (n-1)	1.10	0.77	0.93	0.98	0.83	1.99	0.81	23	0.20	3072.36
Quartz microdiorite (n=26 analyses)										
Minimum	0.89	1.83	1.76	1.12	0.78	0.75	1.23	728	1.28	4645.17
Maximum	2.80	2.73	3.37	2.82	2.21	4.89	2.89	773	1.79	10901.87
1 st quartile	1.53	2.11	2.30	1.69	1.26	0.86	1.66	744	1.49	6249.54
Median	1.79	2.23	2.52	1.92	1.46	1.06	1.83	748	1.58	6904.00
3 rd quartile	1.95	2.30	2.65	2.06	1.57	1.89	2.12	754	1.64	8017.31
Mean	1.80	2.24	2.53	1.93	1.46	1.63	1.93	749	1.56	7295.01
Variance (n-1)	0.26	0.06	0.18	0.20	0.14	1.31	0.21	100	0.02	3013199.19

Standard Deviation (n-1)	0.51	0.24	0.43	0.45	0.38	1.15	0.46	10	0.14	1735.86
Tonalite (n=8 analyses)										
Minimum	0.86	1.82	1.73	1.09	0.75	0.97	1.20	705	0.60	4540.82
Maximum	2.65	2.65	3.24	2.69	2.10	4.31	2.57	729	1.00	9719.39
1 st quartile	1.44	2.07	2.22	1.61	1.19	1.74	1.74	708	0.71	6573.63
Median	1.68	2.18	2.43	1.82	1.37	2.18	2.05	716	0.76	7732.16
3 rd quartile	2.00	2.33	2.70	2.11	1.61	2.45	2.27	720	0.83	8570.36
Mean	1.69	2.19	2.44	1.84	1.38	2.22	1.96	715	0.78	7399.54
Variance (n-1)	0.33	0.07	0.24	0.27	0.19	1.02	0.23	77	0.02	3242606.01
Standard Deviation (n-1)	0.58	0.27	0.49	0.52	0.43	1.01	0.48	9	0.13	1800.72
All analyses (n=125 analyses)										
Minimum	0.20	1.56	1.17	0.50	0.26	0.68	0.75	671	-0.46	2847.82
Maximum	7.94	6.29	7.70	7.40	6.06	11.50	6.25	869	2.23	23602.57
1 st quartile	1.34	2.02	2.14	1.52	1.12	0.91	1.59	731	0.73	5990.44
Median	1.97	2.31	2.67	2.08	1.59	1.12	2.17	751	1.23	8178.51
3 rd quartile	4.64	3.82	4.92	4.46	3.59	2.34	4.17	782	1.62	15741.71
Mean	2.95	2.94	3.50	2.96	2.32	1.82	2.75	757	1.13	10380.17
Variance (n-1)	4.22	1.48	3.00	3.35	2.37	2.74	2.16	1946	0.43	30802480.31
Standard Deviation (n-1)	2.05	1.22	1.73	1.83	1.54	1.66	1.47	44	0.65	5550.00

Table 9 Pressure (kbar) and Temperature (°C), Calculation Results Using the Biotites from the Bougouni Plutonic Complex Rocks; (Uchida et al., 2007b), P (kbar) = $3.03 \cdot Al^{IV} - 6.53$; (Henry et al., 2005), T (°C) = $\{[\ln(Ti) - a - c(XMg)3]/b\}^{0.333}$

Statistique	T (°C) after Henry et al. (2005)	P (kbar) after Uchida et al. (2007b)
Nb analyses	133	133
Minimum	196.99	-2.65
Maximum	572.66	-1.59
1 st quartile	381.23	-2.43
Median	446.89	-2.30
3 rd quartile	510.74	-1.90
Mean	441.15	-2.19
Variance (n-1)	6251.54	0.08
Standard Deviation (n-1)	79.07	0.28

- Supplementary Materials
- Additional data can be found in the appendices' tables.
- Author Contributions

Conceptualization, writing, and preparation of the original version: Séko Sanogo, Salia Coulibaly and Ousmane Wane. Investigation: Séko Sanogo, Salia Coulibaly, Dasso Yollande Traoré, Ousmane Wane, and, Cyril Durand. Expertise: Séko Sanogo, Ousmane Wane, Cyril Durand, and Michel Dubois. Writing, revision, and editing: Séko Sanogo, Salia Coulibaly, Dasso Yollande, Ousmane Wane, and Adama Youssouf Koné. Visualization: Cyril Durand, Michel Dubois, Adama Youssouf Koné, Dasso Yollande and Salia Coulibaly.

➤ Highlights

The petrographical, mineralogical and chemical compositions of amphiboles and biotites indicate:

- A subalkaline (calc-alkaline) and range from metaluminous to slightly peraluminous types.
- A crystallization under conditions of high fugacity of oxygen with pressure 2.75 kbar and temperature 800°C.
- A mostly of type I with a low S tendency.
- Formation during the subduction setting near-collisional.

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➤ Data Availability Statement

The analyzed data of this work are presented in this manuscript.

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➤ *Conflicts of Interest:*

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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