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RESEARCH ARTICLE

Petrogenesis of Metamorphic Rock in the Mukito Formation at Sorawolio Region, Bau-Bau City, Buton Island, Southeast Sulawesi Province, Indonesia

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Abstract

The petrogenesis study of the metamorphic rocks of the Mukito Formation was carried out in the Sorawolio area, Bau-Bau City, Buton Island, Southeast Sulawesi Province, Indonesia. This research area is included in the southern part of the Buton sheet with coordinates S 5⁰23'40.8'' and E 122⁰43'44.9''. The aim of this research is to determine the petrogenesis of metamorphic rocks which includes determining the rock type, facies, type of metamorphism and protolith. The research methods used include megascopic and microscopic analysis of rocks in the form of petrographic analysis which includes identification of mineral content and rock texture and geochemical analysis in the form of XRF tests to determine the main oxide elements in metamorphic rock samples. Data obtained from the results of petrographic analysis show that the research area consists of several types of metamorphic rock, namely serpentinite, phyllite, chlorite schist, hornblende schist and amphibolite. The metamorphic rocks in the research area are included in the greenschist facies and amphibolite facies with regional metamorphism types as well as protoliths from igneous rocks in the form of basalt rock which were formed in the tholeiitic oceanic-island tectonic environment which is a convergent complex characterized by continental origin in the magma series in the form of the tholeiitic series and calc -alkaline series.

Keywords: Petrogenesis, Metamorphic Rocks, Sorawolio Area, Mukito Formation, Bau-Bau City, Southeast Sulawesi Province.

1. Introduction

The island of Sulawesi and the surrounding area is located at the confluence of three plates, two of which are actively moving. Based on Hamilton, 1979; Silver et al., 1983; Smith and Silver, 1991 and Smith, 1991, the western part is the southeastern edge of the Eurasian Continental Plate, the south-eastern part is formed by the Australian Continental Plate moving north and the north-eastern part occupied by the Pacific Ocean Plate or the Philippine Ocean Plate moving west (Figure 1). The tectonic complexity experienced by the island of Sulawesi makes the island has a distinctive "K" shape, resulting in the island of Sulawesi having a complex geological and stratigraphic structure, as well as diverse rock compositions (Surono, 2013). The oldest rock as bedrock in the Southeast Arm of Sulawesi Island is a complex of metamorphic rocks intruded by granite several places. Metamorphic rocks in the Southeast Arm of Sulawesi Island are exposed along the north of Bone Bay, the Mekongga Mountains to the Kolaka area, along the Mendoke Mountains, continuing to the Rumbia Mountains and Kabaena Island. A few outcrops are found on the islands of Buton and Kolono (Permana, 2013).

The research area is located on the island of Buton which is composed of metamorphic rocks in the Sorawolio area, Bau-Bau City, Southeast Sulawesi Province, Indonesia (Figure 2). Based on the geographical location of the existence of the Metamorphic Complex, namely the Mukito Formation which is mapped on the geological map of the Buton sheet, Sulawesi. that came into contact with the Winto Formation and the Kanpatoreh Ultrabase Complex (Sikumbang et al., 1995).

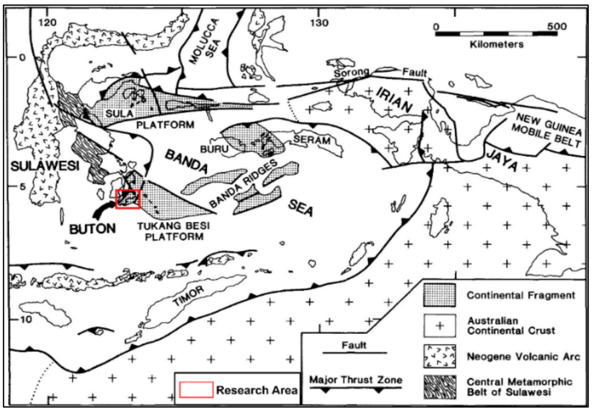

Fig 1. Generalized tectonic map of the Banda Sea region, showing the location of Buton and the inferred continental fragments derived from the northern margin of New Guinea. Modified from Hamilton, 1979, incorporating data from Silver et al., 1983 and Smith and Silver, 1991 and Smith, 1991.

The appearance of the Mukito Formation metamorphic rocks on the surface of Buton Island indicates that a complex geological process has occurred in the area. The distribution of the rock which is also in contact with the Winto formation and the Kanpatoreh Ultrabasic Complex is an interesting thing for research in the form of petrogenesis of metamorphic rocks in the area. This study aims to determine the type of metamorphic rock of the Mukito Formation in the study area, and to determine the petrogenesis of metamorphic rock which includes the determination of facies, type of metamorphism, type of protolith and tectonic environment of the metamorphic rocks of the Mukito Formation.

Research on the petrogenesis of metamorphic rocks was carried out by Hasria et al., 2023 but only covered the Kaisabu area which is part of Sorawolio District and only used petrographic analysis. This research has a wider scope, namely covering the entire Sorawolio District, Bau-Bau City, Southeast Sulawesi Province, using petrographic and geochemical analysis.

2. Geological Setting

The regional geology of Buton Island (Figure 2) is quite interesting, because there are several small islands that are geologically inseparable. In the eastern part of Buton Island there is the Buton Basin. This basin is bordered by the Banda Sea to the north and east. In the south it is bordered by the Flores Sea and in the west by the central ridge of Buton Island (Sikumbang et al., 1995).

Based on the regional geological map of the Buton sheet, the stratigraphic sequence (Figure 3) (Sikumbang et al., 1995) is as follows:

a) Alluvium (Qal), consisting of gravel, gravel, sand and peat, sediment from rivers, swamps and beaches.
b) Wapulaka Formation (Qpw), composed of algae and oral reef limestone, showing ancient beach steps and karst topography, crushed reef deposits, limestone, sandy limestone, calcareous sandstone, mudstone and marl rich in planktonic foraminifera. Asphalt seepage was found in this formation in southern Buton.
c) Sampolakosa Formation (Tmps), composed of marl, thickly layered to massive, calcarenite inserts at the top and middle. Oil and asphalt seeps were found in this formation.
d) Tondo Formation (Tmtc), it consists of conglomerate, gravelly sandstone, sandstone with intercalations of siltstone and interbeds of sandstone, siltstone and mudstone and oil and asphalt seepage is found.
e) Limestone Member of the Tondo Formation (Tmtl), composed of reef limestone and calcarenite.
f) Kanpatoreh Ultrabasic Complex (Tukc), consisting of peridotite, serpentinite and gabbro. Locally eroded and brecciated. Ophiolite rocks are exposed along the western border of Buton Island. The rocks consist of serpentinite, gabbro and dolerite and their presence is interpreted as a result of tectonics (Davidson, 1991).
g) Diorite (Di), it is a diorite hack with a hypidiomorphic equigranular structure
h) Basalt (Ba), it is a strong altered basaltic hackle.
i) Tobelo Formation (KTt), composed by calcilutite, well layered.
j) Rumu Formation (Jr), consists of interbedded fossil-rich red limestone, mudstone, marl and calcarenite.
k) Ogena (Jo) Formation, consisting of pelagos limestone, interbedded with fine clastics and sandy limestone partly bituminous or impregnated with asphalt.
l) Winto Formation (TRw), composed of interbedded shale, sandstone, conglomerate and limestone. Characterized by terrestrial clastic sediments and carbonates.
m) Doole Formation (TRd), it is a sequence of weak grade metamorphic rock, consisting of micaanite quartzite interbedded with phyllite and slate.
n) Mukito Formation (PTRm), consisting of plagioclase-hornblende schist, chlorite-epidote schist, abraded phyllite and calcareous silica schist. It is thought to be pre-Triassic based on its contact with the Winto formation. According to Smith, 1991, the Mukito Formation consists of meta basite and meta chert which range from green schist to lower amphibolite facies. He also said that the relationship between the Mukito formation and the Winto formation and ophiolite is a fault contact.

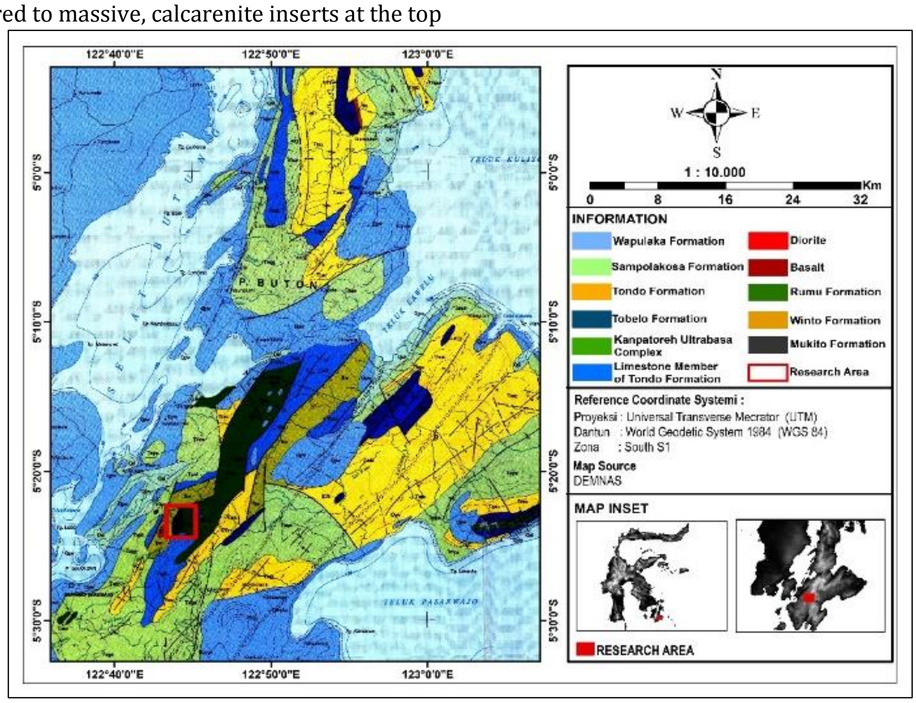

Fig 2. Regional geological map of Buton sheet (modified from Sikumbang et al., 1995).

3. Materials and Methods

In the development of this research, several stages of research were carried out, namely literature studies, field observations, research sampling and laboratory analysis.

1. Preparation phase
   The preparation stage is a series of activities before starting data collection and processing. The preparation stage includes literature study, obtaining research permits and preparing equipment.
2. Field work
   Field work is intended to collect primary data. This stage consists of taking coordinates at each observation station and photographing outcrops, taking rock position data, collecting foliation data, taking rock samples in the field using random sampling methods and data from megascopic and microscopic sample observations.
3. Laboratory Analysis
   Laboratory analysis used in this research is petrographic analysis and geochemical analysis. Petrographic analysis data is used for the type and percentage of minerals contained in the rock based on the Travis (1955) and classification. Geochemical tests were carried out using the X-Ray Fluorescence (XRF) method on metamorphic rock samples. The number of metamorphic rocks analyzed were 9 samples, namely ST-2, ST-5, ST-7, ST-9, ST-10, ST-18, ST-21, ST-23, ST-28 (Figure 3). petrographic analysis based on composition and characteristics of the Mineralogical Research Site Observation Station Map, and then 5 samples were re-selected for preparation and rock geochemical analysis was carried out using the XRF method.

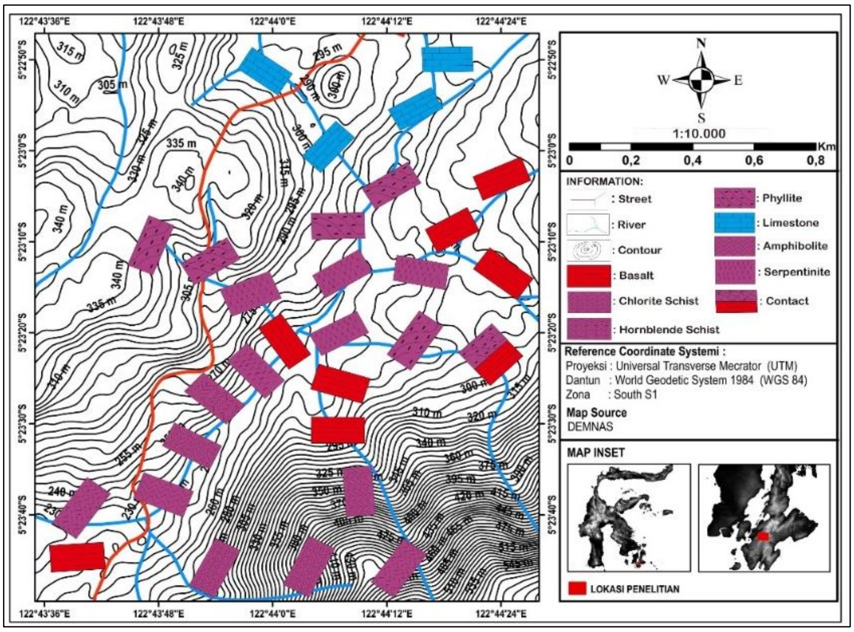

Fig 3. Research Site Observation Station Map

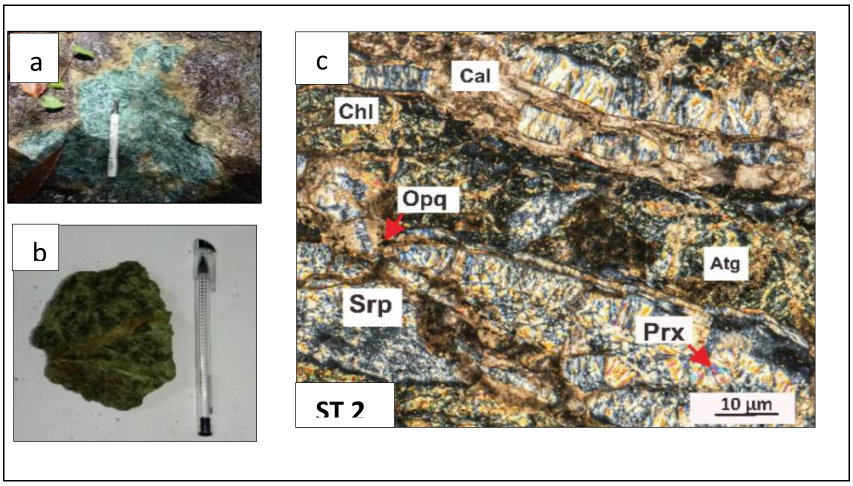

Fig 4. a) The appearance of one of the serpentinite rock outcrops at 2-way station photo N118^{0}E. b) Photograph of Serpentinite handspeciment sample. c) Microscopic appearance of serpentinite rock with mineral composition Prx: Pyroxene, Srp: Serpentine, Cal: Calcite, Khl: Chlorite, Atg: Antigorite and Opq: Opaq.

4. Results and Discussion

4.1. Metamorphic Rock Type

4.1.1. Field Observation and Petrography

Based on field observations, 31 primary data stations have been collected consisting of 9 metamorphic rock stations. Based on the results of megascopic and microscopic rock descriptions, the rock samples found at the research site consisted of 5 types of metamorphic rock units, namely serpentinite, phyllite, chlorite schist rock units, hornblende schist and amphibolite rock units (Travis, 1955).

4.1.1. Serpentinite Rock Unit

The results of megascopic analysis and petrographic analysis show that stations ST-2, ST-7, ST-10 and ST-23 are serpentinite rock units. The results of petrographic analysis of serpentinite rock units at the four stations generally have the same results and ST-2 station is considered representative of the other stations.

At the ST-2 station, an outcrop of metamorphic rock with dimensions ± 5 m long and 10 m high was found in the Sorawolio area around the Mukito river at coordinates $122^0$44'02.0'' E, $5^0$23'19.9'' S which is in situ (Figure 4a, b). The rock outcrop shows that the rock type is metamorphic rock with a xenoblastic texture with a non-foliated structure and the mineral composition is serpentine, chlorite, calcite, pyroxene and quartz. Based on the lithological data above, based on the classification of Travis (1995) the name of the rock is serpentinite.

The results of petrographic analysis on the ST-2 sample (Figure 4c) show that the mineral composition contained in ST-2 consists of 32% serpentinite, 20% chlorite mineral with a dark green color, 18% calcite mineral present as veins.

4.1.2. Phillite Rock Unit

Phyllite was found in ST-5 in the study area. At station 5 (Figure 5a, b), an outcrop of metamorphic rock with dimensions ± 6 m long and 2 m high was found in the Sorawolio area around the Mukito River at coordinates $122^0$44'10.5'' E, $5^0$23'22.2'' S which is in situ. Megascopically, this type of rock is metamorphic rock, the weathered color is black, the fresh color is gray with a lepidoblastic texture and a foliation (phylitic) structure. The mineral composition is mica, chlorite, quartz, graphite so the name of the rock is called phyllite rock (Travis, 1955). The results of petrographic analysis in ST-5 (Figure 5c) , the mineral composition contained in this rock are muscovite (30%), quartz (17%), chlorite (10%), pyroxene (10%) and clay minerals (12%).

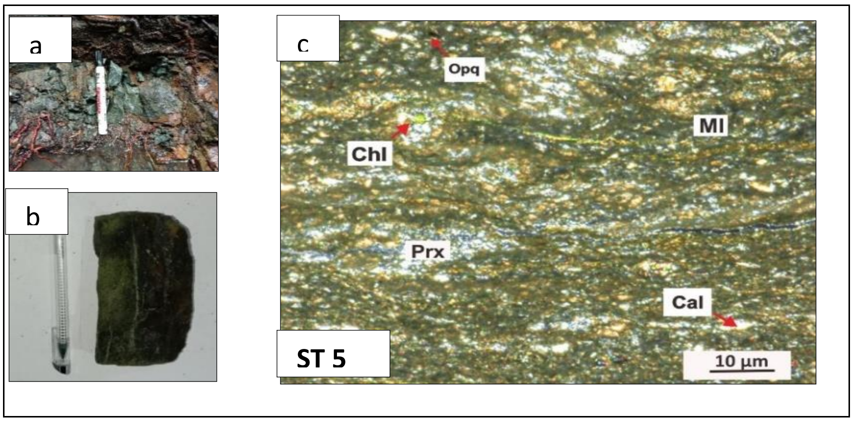

Fig 5. a) The appearance of one of the lithological outcrops of phyllite station 5, photo direction N150□E. b) Photograph of the phyllite handsspeciment sample. c) Microscopic appearance of phyllite rock with mineral composition of Mus: muscovite, Cal: calcite, Chl: chlorite, Prx: pyroxene, Gr: graphite, Ml: cay mineral, and Opq: opaque.

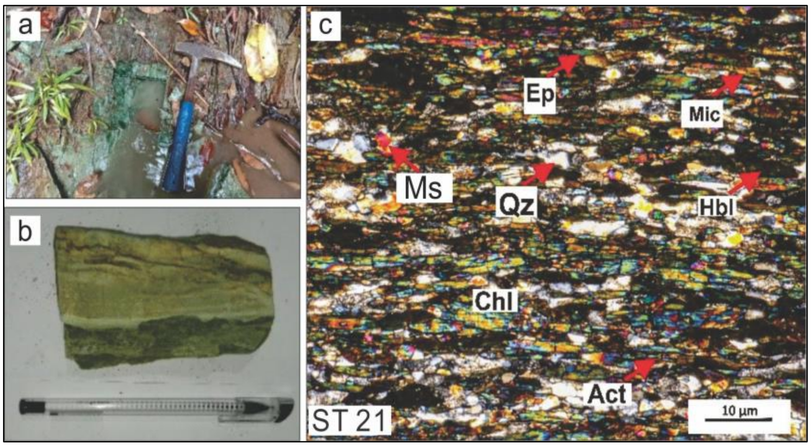

Fig 6. a, b) The appearance of the chlorite schist lithological outcrop at station 21, photo direction N168°E. c) Photograph of chlorite schist handspeciment sample. c) Microscopic appearance of chlorite schist with mineral composition Mus: muscovite, Hbl: hornblende, Ep: epidote, Chl: chlorite, Mic: mica, Qz: quartz, Act: actinolite.

4.1.3. Chlorite Schist Rock Unit

This rock unit is found in number ST-21 (Figure 6a, b) in the form of a metamorphic rock outcrop with dimensions ± 20 m long and 8 m high in the Sorawolio area around the Mukito River at coordinates $122^0$43'53.7'' E, $5^0$23'30.7'' S which in situ. Megascopically, this lithology has a fresh color appearance in the form of blackish green and a weathered color in the form of brown, the rock structure texture is in the form of foliation (schistose) (Figure 5 a, b). Megascopically, the mineral composition of this rock appears to be chlorite, actinolite, mica, quartz and plagioclase. Referring to the megascopic data, based on the name of the rock according to Travis (1955), the metamorphic rock is classified as a type of chlorite schist rock.

In thin section (Figure 6c) the constituent minerals are flat, have a foliation structure (schistose). Foliation structures can be seen in chlorite and actinolite minerals which show mineral alignment. This rock has a mineral composition, namely muscovite (13%), and quartz (10%) as the main minerals in the rock, while the minerals actinolite (8%), epidote (17%), chlorite (30%), mica (5%), minerals opaq (2%) and hornblende (15%) are present as secondary minerals in the rock. The muscovite mineral has a yellow to purple appearance, present in sections forming parallels with a lepidoblastic orientation. Quartz mineral has a white appearance, actinolite mineral has a brown-black color on section, epidote mineral has a blue appearance, subhedral shape and chlorite mineral has a dark green color.

4.1.4. Hornblende Schist Rock Unit

This metamorphic rock was found at ST-28. Megascopic observations found metamorphic rocks with dimensions of ± 10 m long and 4 m high (&a, b). These rocks are found in the Mukito Formation with a Triassic age. On microscopic observation it has physical characteristics of the texture consists of lepidoblastic minerals with a foliated structure (schistose), the appearance of foliation

where the form of flat mineral alignments is relatively much more abundant than granular minerals. The foliation structure can be seen in the Hornblende mineral which shows mineral alignment. The results of petrographic analysis, this rock has a mineral composition of pyroxene (8%), muscovite (20%), hornblende (30%) epidote (10%), chlorite (12%), quartz (15%), opaque (5%).

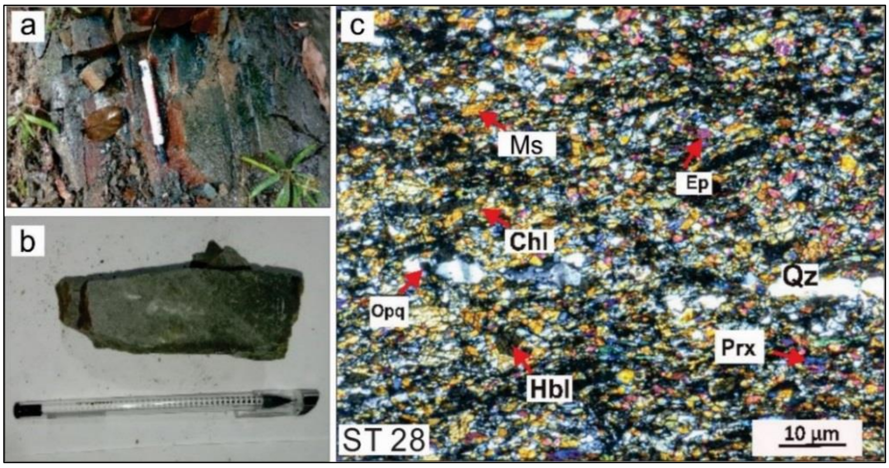

Fig 7. a) A view of one of the Hornblende schist lithological outcrops station 28, photo direction N120E. b) Handspeciment photo of hornblende schist. c) Microscopic appearance of hornblende schist with mineral composition Prx: pyroxene, Mus: muskovite, Hbl: hornblende, Ep: epidote, Chl: chlorite, Qz: quartz, Opq: opaque

4.1.5. Amphibolite Rock Unit

This rock is a type of metamorphic rock found in ST-18. This metamorphic rock outcrop has dimensions of ± 10 m long and 16 m high. the physical color of this rock has a fresh color of gray to greenish, with a brown weathered color (8a, b). Based on petrographic observations (Figure 8c), the texture consists of nematoblastic with a foliated structure (schistose) while the primary minerals are 60% hornblende minerals and 7% actinolite minerals. While plagioclase, quartz, pyroxine and opaque minerals are present as secondary minerals in rocks. With a percentage of 15% plagioclase minerals, 10% quartz minerals, 5% pyroxene minerals and 3% opaque minerals.

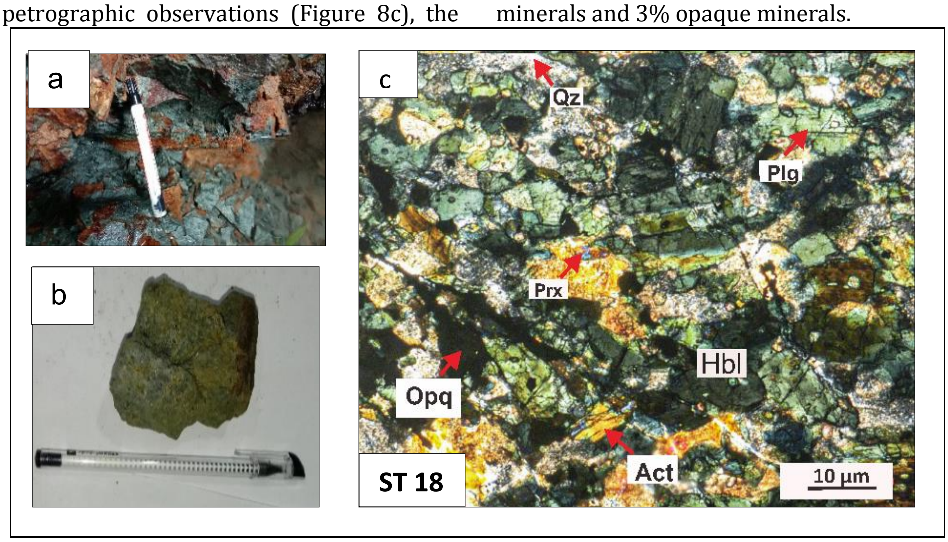

Fig 8. a) The appearance of the amphibolitic lithological outcrop of station 18, photo direction N165E, b) Photograph of the amphibolite hand specimen sample. c) Microscopic appearance of amphibolite rock with mineral composition Hbl: Hornblende, Act: Actinolite, Plg: Plagioclase, Prx: Pyroxene Qz: Quartz, Opq: Opaque.

4.1.2. Geochemical Analysis

Rock geochemical analysis has been carried out using XRF analysis on 5 rock samples that have been identified through petrographic observations, namely serpentinite rock, phyllite rock, hornblende schist rock, amphibolite rock and chlorite schist rock.

The main oxide units of metamorphic rocks in the study area show the content of silicon dioxide (SiO_2) less than 50% (45%-49%), calcium oxide (CaO) (57%-72%), aluminum oxide (Al_2O_3) (4%-23%), less magnesium (MgO) (0.19%-0.27%), iron oxide (Fe_2O_3) (1%-5%), and low in potassium (K_2O), titanium dioxide (TiO_2), manganese dioxide (MnO) and sodium dioxide (Na_2O).

Table 1. Main oxide analysis results using XRF

Sample Code	Station 2	Station 9	Station 18	Station 21	Station 28
Rock Type	Metamorphic Rock				
Rock Name	Serpentinite	Phyllite	amphibolites	schist Chlorite	Hornblende schist
Weight in percent (%)					
Ni	0.0004	0.0011	0	0.0001	0.0003
Co	0	0	0.0021	0	-0.0042
Al_2O_3	4.7122	12.9867	7.3392	22,418	11.8716
CaO	71.9204	66.3203	57.6378	64.4991	61.8292
Cr_2O_3	0.0101	0.0172	0.0062	0.0043	0.0114
Fe_2O_3	0.9887	0.7632	4.9026	1.7681	3.6652
K_2O	2.7611	2.8472	2.1614	1.8774	1.8773
MgO	0.2416	0.2188	0.2781	0.2467	0.1983
MnO	0.0016	0.0022	0.0021	0.0014	0.0032
Na_2O	0.0011	0.0072	0.146	0.0088	0.0981
P_2O_5	0.007	0.0042	0.0819	0.0061	0.0077
SiO_2	45.9677	48.4157	45.0014	47.0173	47.7107
TiO_2	0.6711	0.3482	0.8379	0.6001	0.56416
S	0.0017	0.0003	0.0006	0.0081	0.0004

FACIES	MAFIC ROCKS (ALL ASSEMBLAGES ± Fe-Ti OXIDES)	PELITIC ROCKS (ALL ASSEMBLAGES ± QUARTZ ± Fe-Ti OXIDES)	QUARTZO-FELDSPATHIC ROCKS (ALL ASSEMBLAGES + QUARTZ ± Fe-Ti OXIDES)	CALCAREOUS AND CALC-SILICATE ROCKS
Zeolite	Laumontite; heulandite	Mixed-layer clays	Heulandite + analcite and laumontite + albite (wairalcitemayy occur in lieu heulandite; some rocks contain chlorite)	Calcite, dolomite, quartz, talc, clays
Prehnite-pumpellyite	Prehnite + pumpellyite ± chlorite ± albite ± epidote; actinolite takes place of prehnite at higher T; lawsonite + albite + chlorite occurs at higher P	White mica/illite + chlorite + albite ± stilpnomelane	Albite + chlorite ± pumpellyite ± prehnite ± stilpnomelane ± white mica ± titanite ± epidote carbonate; actinolite takes the place of prehnite at higher T; lawsonite is stable at higher P	Calcite, prehnnite, albite, quartz, chlorite
Greenschist	albite + chlorite + actinolite + epidote + titanite ± quartz ± white mica ± calcite; stilpnomelane is widespread at lower T and biotite at higher T where hornblende also occurs	Muscovite + chlorite ± albite± paragonite ± graphite ± rutile ± magnetite ± hematite ± carbonate ± epidote ± K-feldspar ± Fe-Ti oxides ± stilpnomelane (low Al) ± pyrophyllite ± chloritoid (the latter two in high- Al rocks); biotite in the biotite zone; + almandine-rich + garnet in the garnet zone	Albite + epidote + muscovite + chlorite ± titanite ± stilpnomelane ± actinolite; biotite is stable at higher T	Calcite, dolomite, quartz, talc, muscovite, albite, K-feldspar, chlorite, zoisite
Amphibolite	Hornblende + oligoclase + epidote ± almandine-rich garnet ± titanite ± biotite ± chlorite ± quartz	Biotite + muscovite + plagioclase + aluminosilicate + rich garnet ± cordierite ± aluminosilicate ± chlorite + alkali feldspar + magnetite + graphite; ± staurolite in the staurolite zone; + kyanite in the kyanite zone; + silimanite in the silimanite zone	Plagioclase + alkali feldspar + biotite ± muscovite ± hornblende	Calcite, dolomite, quartz, diopside, tremolite, forsterite, grossular, anorthite, hornblende, clinozoisite
Granulite	Plagioclase + clinopyroxene + orthopyroxene ± hornblende ± olivine (low P); Plagioclase + clinopyroxene + orthopyroxene + garnet ± hornblende (medium P); Plagioclase + clinopyroxene + garnet + quartz ± hornblende (high P)	Alkali feldspar ± plagioclase ± scapolite ± cordierite ± garnet ± rutile ± ilminite ± magnetite ± graphite ± olivine ± corundum ± spinel ± kyanite (high P) ± sillimanite (moderate P); Orthopyroxene + (sapphirine high T)	Alkali feldspar + plagioclase + garnet ± kyanite ± orthopyroxene ± clinopyroxene ± hornblende ± magnetite ± ilmenite	Calcite, dolomite, quartz, diopside, scapolite, anorthite, forsterite, wollastonite, graphite
Blueschist	Glaucophane + lawsonite ± aragonite ± jadeiticclinopyroxene ± chlorite ± albite ± titanite ± pumpellyite ± actinolite or hornblende ± stilpnomelane ± epidote ± garnet	Glaucophane + lawsonite ± albite ± phengite ± paragonite ± garnet ± chlorite ± epidote ± loyanite ± chloritoid ± titanite	Jadeit cclinopyroxene + lawsonite + muscovite + chlorite + titanite ± glaucophane	Aragonite, calcite
Eclogite	Omphacite + pyrope-rich garnet ± kyanite ± rutile ± quartz or coesite	Omphacite + pyrope-rich garnet ± kyanite ± rutile ± quartz or coesite		
Pyroxene-hornfels	Essentially as granulite facies	Essentially as granulite facies but andalusite is typical aluminosilicate; cordierite + biotite tends to be more stable than almandine garnet, except where Fe2+ / Mg is high; silica deffident rocks contain spinel, corundum, and alkali feldspar in place of an aluminosilicate	Essentially as granulite facies	Essentially as granulite facies ± vesuvianite ± wollastonite
Sanidinite	Near subsolidus basalts assemblage	Sanidine, tridymite, cordierite, mullite ($3Al_2O_3$ $2H_2O$), glass, clinopyroxene, spinel corundum (in silica-poor rocks)	Sanidine, tridymite, cordierite, glass, clinopyroxene	Anorthite + wollastonite ± diopside in silica-rich rocks; calcite, wollastonite, melilite (Ca2MgSiO2), larnite (Ca2SiO4), merwinite (Ca3Mgi2O8), monticellite in silica-poor rocks

Fig 9. Mineral assemblages in conventionally recognized metamorphic facies listed according to the major chemical groups of metamorphic rocks (Best, 2003).

4.2. Petrogenesis of Metamorphic Rocks Research Area

4.2.1. Facies

Based on the results of petrographic analysis of 9 tested rock samples, it can be determined that the metamorphic facies of the research area are divided into two types of metamorphic facies (Bucher and Grapes, 2011; Winter, 2014), namely the greenschist facies and the amphibolite facies (Figure 9). Each facies in metamorphic rocks is generally named according to the type of rock (mineral assemblage) that is considered critical and diagenetic for the facies concerned (Barker, 1990).

a. Greenschist facies

The greenschist facies is formed at a temperature range of 300˚C-500˚C at a pressure of 2.5 Kbar - 4 Kbar with a depth ranging from 8 km - 18 km (Winter 2014; Barker, 1990). This facies is characterized by the appearance of chlorite, epidote, actinolite, and quartz and mica minerals (Best, 2003).

Metamorphic rock samples in the research area that show greenschist facies are found in ST-2, ST-5, ST-7, ST-9, ST-10, ST-21 and ST-23. The formation of metamorphic rocks (Barker, 1990) in the research area is in the greenschist facies, phyllite rocks are formed at temperatures ranging between 300˚C - 320˚C with pressures of 2.5 kbar - 4 kbar, including low grade metamorphism. Chlorite schist rock is formed at a temperature of 300˚C - 500˚C at a pressure of 3 Kbar - 4.5 Kbar which is included in medium/medium grade metamorphism. Serpentinite rocks are formed at a temperature of 350⁰C - 450⁰C at a pressure of 2 kbar – 3.5 kbar.

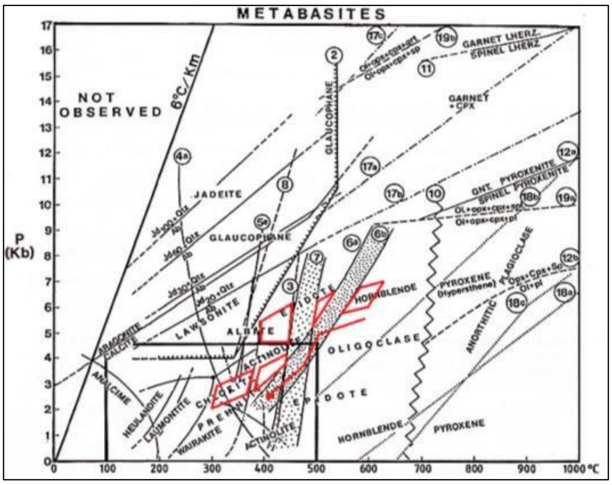

Fig 10. Petrogenetic grid of metamorphic rocks of the study area (Barker, 1990).

b. Amphibolite Facies

The amphibolite facies are found at station 18 and station 28. This amphibolite facies are characterized by the discovery of minerals hornblende, plagioclase, epidote, chlorite, and quartz. The amphibolite facies which consist of hornblende schist rock is included in the moderate grade rocks of the amphibolite facies with a relatively high temperature which is formed at a temperature of 500˚C - 580˚C at a pressure of 4.5 kbar - 6 kbar. Meanwhile, amphibolite rock is formed at a temperature of 580˚C at a pressure of 6 Kbar, which is included in moderate metamorphism rocks but at a relatively high temperature. (high T).

The amphibolite facies are formed at slightly higher pressures and temperatures than the greenschits facies. The amphibolite facies are formed at a temperature range of 500˚c - 580˚c with a pressure of 3 kbar – 6 kbar at a depth of 10 km – 20 km. Based on Winter (2014) this facies is formed at pressures ranging from 3-14 kilobars, with temperatures around 500-700˚c. Based on this theory, it can be concluded that the amphibolite facies in the study area is still classified as low amphibolite. This is in line with what was said by Smith, 1991 and Hasria et al., 2023 in his research.

The formation of metamorphic rocks (Barker, 1990) in the research area is in the greenschist facies, phyllite rocks are formed at temperatures ranging from 300˚C - 320˚C with pressures of 2.5 kbar - 4 kbar, including low grade metamorphism (Figure 10.)

Chlorite schist rock is formed at a temperature of 300˚C - 500˚C at a pressure of 3 kbar - 4.5 kbar which is included in medium/medium grade metamorphism. Serpentinite rocks are formed at a temperature of 350⁰C - 450⁰C at a pressure of 2 kbar – 3.5 kbar. The amphibolite facies which consist of of hornblende schist rock is included in the middle grade rocks of the amphibolite facies with a relatively high temperature which is formed at a temperature of 500˚C - 580˚C at a pressure of 4.5 kbar - 6 kbar. Meanwhile, amphibolite rock is formed at a temperature of 580˚C at a pressure of 6 kbar, which is included in moderate metamorphism rocks but at a relatively high temperature.

Based on the results of the plot in the diagram (Barker, 1990) that the greenschist facies is formed at a temperature range of 300˚C-500˚C at a pressure of 2.5 kbar - 4 kbar with a depth ranging from 8 km - 18 km, while the amphibolite facies is formed at pressure and slightly greater temperature than the greenschits facies. The amphibolite facies is formed in the temperature range of 500˚C - 580˚C with a pressure of 3 kbar – 6 kbar at a depth of 10 km – 20 km. Based on Winter, 2014, this facies is formed at pressures ranging from 3-14 kbar, with temperatures around 500-700˚C (Figure 11). Based on this theory, it can be concluded that the amphibolite facies in the research area is still classified as low grade amphibolite. This is in accordance with research by Smith, 1991 and Hasria et al., 2023 regarding metamorphic rock facies on Buton Island.

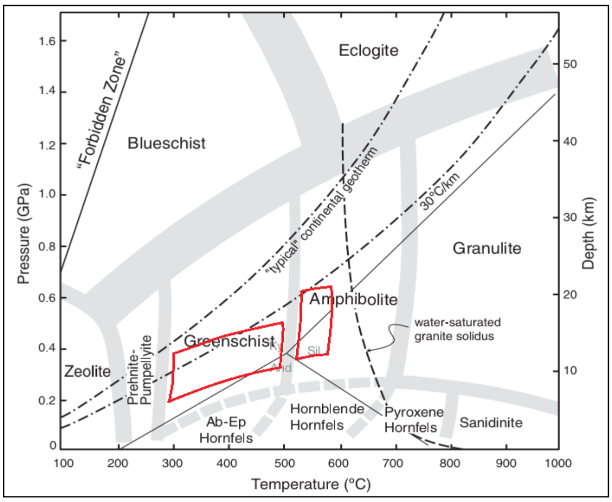

Fig 11. Metamorphism facies zone of the study area (Winter, 2014).

4.2.2. Metamorphism Type

The type of metamorphism can be determined based on the results of petrographic analysis as seen from the constituent minerals, structure, and texture of the metamorphic rocks of the research site. Based on the 9 rock samples analyzed, it shows that the metamorphic rocks in the study area have crystalloblastic textures in the form of lepidoblastic, nematoblastic, and xenoblastic, with rock structures in the form of non-foliation in serpentinite rocks and structures in the form of phyliitic and schistose in phyllite rocks, chlorite schists, hornblende schists, and amphibolites. Where the foliated structure is formed due to rocks that have undergone a metamorphic process through the addition of pressure and temperature, while the non-foliated structure is formed due to rocks that have undergone a metamorphic process through reducing pressure and temperature (Bucher and Grapes, 2011; Winter, 2014) occurs over a wide area.

4.2.3. Protolith Type

The type of rock that becomes the protolith of metamorphic rock in the study area can be determined by testing rock samples using petrographic and geochemical analysis. Rock geochemical analysis was carried out on rock samples that had been analyzed using petrographic analysis, namely serpentinite rock, phyllite rock, hornblende schist rock, amphibolite rock and chlorite schist rock.

Based on geochemical data of the main oxide elements from 5 rock samples analyzed for determining the type of protolith metamorphic rock in the study area using the ACF diagram according to (Cornell et al., 1996) this diagram is based on the weight percent content of A(Al□O□), C(CaO), and (Fe□O□+ MgO) (Robertson, 1999). However, each component must be slightly considered to account for the presence of other major elemental oxide components in the rock, the modification causes A(Al□O□+ Fe□O□- Na□O + K□O), C(CaO[(10/3)P□O□]CO□), and (Fe□O□+ MgO + MnO). The plotting results of 5 metamorphic rock samples in the research area show that the type of protolith is metamorphic rock which originates from igneous rock (metamafic-rock) (Fugire 12) in the form of basalt (Smith, 1991).

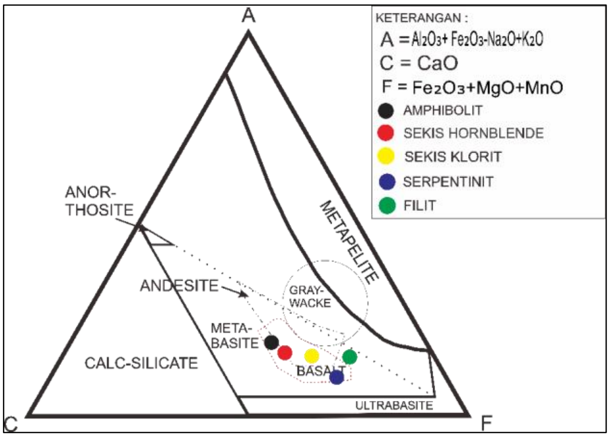

Fig 12. The results of plotting on 5 rock samples based on the ACF diagram (Cornell et al., 1996).

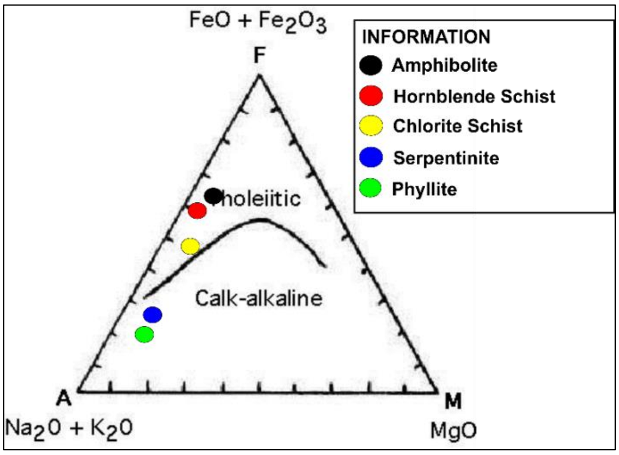

Fig 13.The results of plotting on 5 rock samples to etermine the magma series (Irvine and Baragar, 1971).

4.2.5. Magma Series

To determine the magma series from which rocks form metamorphic rocks along the Mukito river, a comparison is used in the triangular diagram according to (Irvine and Baragar, 1971), dividing the rock series into tholeiitic series and calc-alkaline series using the AFM triangle diagram. A is the alkali content (Na□O+K□O), F is iron oxide (FeO+Fe□O□), and M is magnesium (MgO). It was found that the magma affinity of metamorphic originating rocks along the Mukito river at Station 18 with amphibolite rock, Station 28 with Hornblende schist rock, and Station 21 with chlorite schist rock has a Tholeiitic magma series type which indicates that the rock originates from.

Primitive magma (early volcanism formation) that is low in K content. Tholeiitic series magmas can form in a variety of tectonic settings (Wilson, 1989) at station 2 with serpentinite rocks and Station 9 with phyllite rocks, the type of calc-alkaline magma series is formed only in subduction tectonic settings. The rock magma affinity characterizes the tectonic setting of the rock formation site (Figure 13).

5. Conclusion

The conclusions of this research are:

1) The types of metamorphic rocks in the research area are serpentinite, phyllite, hornblende schist, amphibolite, and chlorite schist.
2) The metamorphic rocks in the research area are included in the greenschist facies and amphibolite facies with regional metamorphism types as well as protoliths from igneous rocks in the form of basalt rock which were formed in the tholeiitic oceanic-island tectonic environment which is a convergent complex characterized by continental origin in the magma series in the form of the tholeiitic series and calc -alkaline series.

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