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RESEARCH ARTICLE

Petrogenesis of Intrusive Rocks in Galela, North Halmahera Regency, North Maluku Province

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Abstract

Halmahera Island has a row of volcanoes stretching from North to South, known as the Halmahera volcanic belt. In general, intrusive rocks in the belt are associated with the potential for mineral deposits such as those in the Gosowong gold deposit (PT. NHM). This condition provides an opportunity to find considerable mineral resource potential in North Halmahera, so research related to the genesis of intrusive rocks carrying mineralization (host-rock) needs to be carried out comprehensively to understand the genesis to the characterization of magma. The study aims to understand the genesis and characterization of magma and to conduct initial investigations related to the fertilization of magma in the research location. The study was conducted using the surface mapping and sampling of intrusive rocks carrying mineralization in the research area. Furthermore, it was analyzed petrographically and geochemically—geochemical analysis using X-ray fluorescent (XRF) to determine the levels of oxide elements in rock samples. From the petrographic data, the rocks in the research area can be classified as a hornblend diorite. The whole-rock geochemical analysis (XRF) results show an average composition of SiO2 (49.87-55.18 wt.%), Al_2O_3 (17.74-20.00 wt. %), CaO (9.25-13.03 wt. %), Fe_2O_3 (5.57-10.14 wt. %), Na_2O (3.31-4.22 wt. %), MgO (1.96-2.95 wt. %), K_2O (1.20-2.60 wt. %), TiO_2 (0,79-1.06 wt. %), MnO (0.18-0.31 wt. %), P_2O_5 (0.13-0.31 wt. %). Based on the geochemical classification of intrusive rocks in the research area, they are included in the gabbroic-diorite group. In general, intrusive rocks in the research area are affiliated with a series of calc-alkaline magmas with intermediate characteristics formed in tectonic settings associated with oceanic arcs.

Keywords: Petrogenesis, Wholerock Geochemistry, Intrusion, Halmahera

1. Introduction

Halmahera Island is one of the areas in Indonesia traversed by a magmatic arc (Bemmelen, 1970), which suggests that the region has significant potential for volcanism. The presence of a magmatic arc indicates the presence of hydrothermal systems and mineral deposits, which are commonly associated with volcanic systems. Consequently, a volcanic arc makes North Halmahera an attractive target for exploration (Sillitoe, 2010).

However, the process of magmatism and volcanic genesis in the North Halmahera area is still rarely investigated, necessitating new

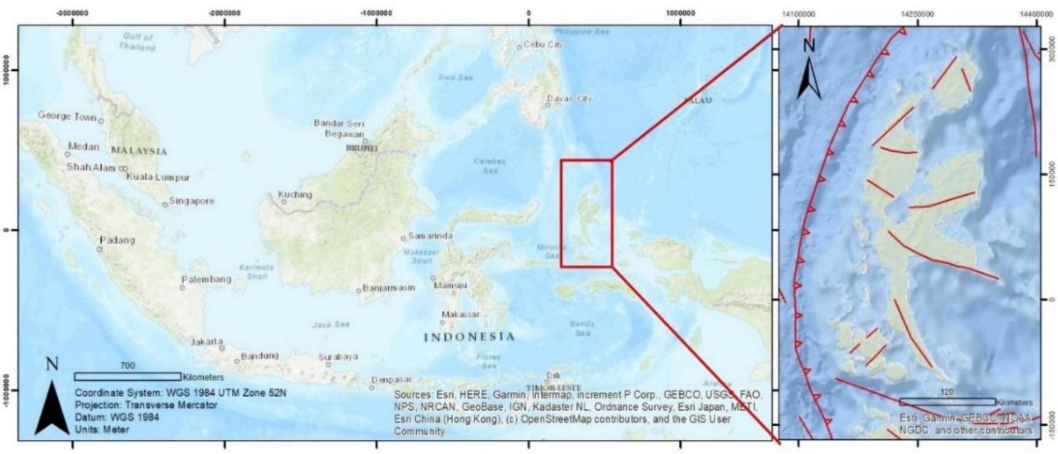

Fig. 1. Location map of research area (red box: research area)

research to provide additional information that is very useful in developing science through petrogenesis studies. Petrogenesis studies processes ranging from magma formation in the Earth's mantle, magma movement towards the surface, and crystallization that produces igneous rocks. The characteristics of the resulting igneous rock are greatly influenced by factors such as pressure, temperature, chemical composition, and cooling rate (Winter, 2014). The study of petrogenesis holds significant relevance in the exploration of minerals and natural resources. Valuable minerals such as gold, copper, and nickel are often closely linked to specific igneous processes (Rollinson, 1993). Therefore, a thorough understanding of igneous petrogenesis can greatly enhance exploration and mining efforts.

2. Geological Setting

The regional conditions of the research area are pivotal for a deep and comprehensive understanding of its unique physiography, geology, and tectonism, as presented in Fig 1. Nestled within the breathtaking North Halmahera, this area is part of the enchanting Halmahera archipelago, specifically located in the striking West Halmahera Mandala Zone, as illustrated in Fig. 2.

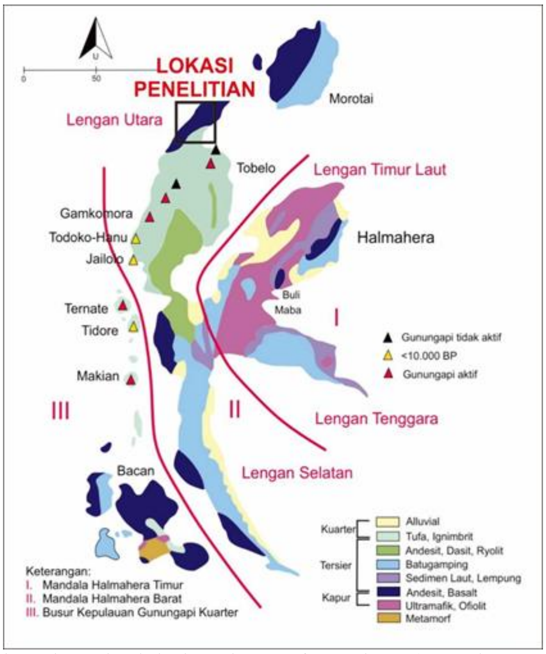

Fig 2. The Regional physiography map of research area (Bemmelen, 1970)

This zone is distinguished by its undulating hilly landscapes, predominantly formed from sedimentary rocks, with limestone dating back to the Neogene period taking center stage. In contrast, certain sections reveal a rugged and dramatic topography, a testament to the Oligocene volcanic rocks that hint at the ancient magmatic processes that have sculpted the land, marked by an intricate tapestry of intrusions and flowing lava. Gaining a thorough understanding of the regional stratigraphy is vital for uncovering the rich distribution of lithology and geological structures within the study area. According to the Regional Geological Map of the Morotai Sheet, North Maluku, created by the Geological Research and Development Centre at a detailed scale of 1:250,000 (Supriatna, 1980), the research site showcases a remarkable array of geological formations. This includes layers of alluvium deposits, sprawling reef limestone, dynamic Holocene volcanic rocks, as well as the distinguished Bacan and Weda formations, all vividly captured in Fig 3. This intricate geological framework serves as a solid foundation for further exploration and detailed analysis within this captivating region. The regional conditions of the research area are essential for comprehensively understanding its physiography, geology, and tectonism. Located in North Halmahera, this area is part of the Halmahera archipelago, specifically situated within the West Halmahera Mandala Zone, as depicted in Fig. 2. This zone is characterized by hilly landscapes primarily composed of sedimentary rocks, notably limestone, which dates back to the Neogene period. Furthermore, certain regions exhibit a rugged topography, indicative of Oligocene volcanic rocks, reflecting the historical magmatic activity that shaped the area, marked by various intrusions and lava flows. A thorough understanding of the regional stratigraphy is crucial for mapping the distribution of lithology and geological structures within the study area. According to the Regional Geological Map of the Morotai Sheet, North Maluku, produced by the Geological Research and Development Centre at a scale of 1:250,000 (Supriatna, 1980), the research site includes formations of alluvium deposition, reef limestone, Holocene volcanic rocks, as well as the Bacan and Weda formations, as illustrated in Fig. 3. This geological framework lays the groundwork for further exploration and analysis in the region. The regional conditions of the research area are essential for comprehensively understanding its physiography, geology, and tectonism. Located in North Halmahera, this area is part of the Halmahera archipelago, specifically situated within the West Halmahera Mandala Zone, as depicted in Fig. 2. This zone is characterized by hilly landscapes primarily composed of sedimentary rocks, notably limestone, which dates back to the Neogene period. Furthermore, certain regions exhibit a rugged topography, indicative of Oligocene volcanic rocks, reflecting the historical magmatic activity that shaped the area, marked by various intrusions and lava flows.

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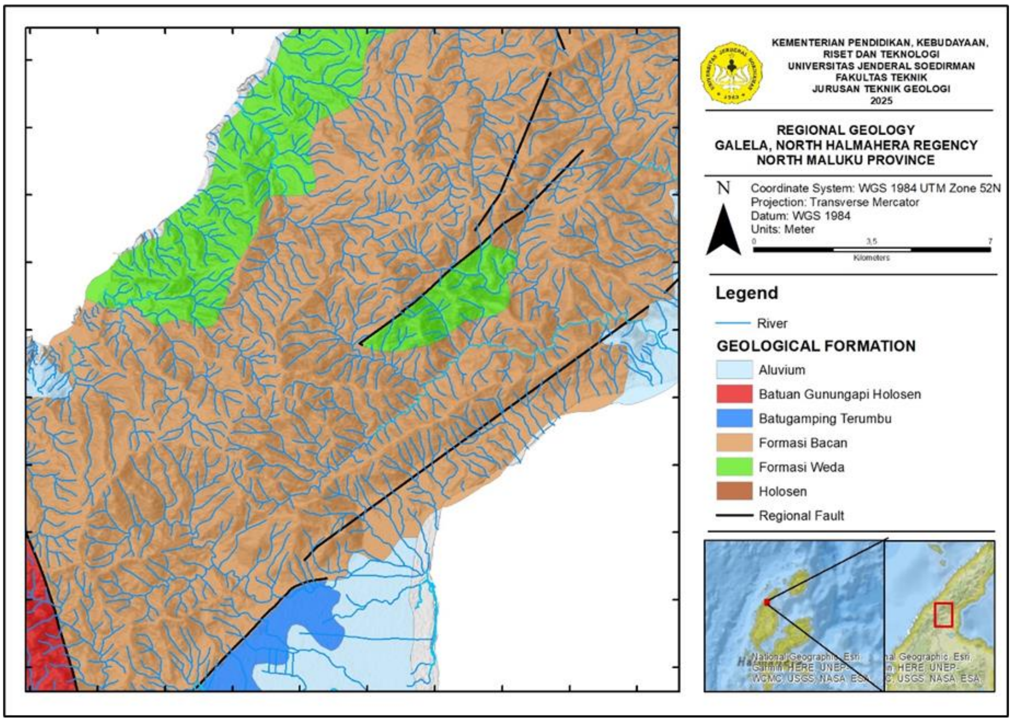

Fig 3. Regional geology of the research aea (modified from Supriatna, 1980)

Holocene volcanic rocks, as well as the Bacan and Weda formations, as illustrated in Fig. 3. This geological framework lays the groundwork for further exploration and analysis in the region.

The geological formations in the area exhibit a distinct sequence when arranged from oldest to youngest. The oldest formation identified is the Bacan Formation, first described by Supriatna (1980). This formation is characterized by its lithology, which predominantly consists of breccia, along with andesite and basalt lava.

Above the Bacan Formation lies the Weda Formation, which comprises a variety of sedimentary rocks, including sandstone, mudstone, siltstone, marl, limestone, and conglomerate. Subsequent to the Weda Formation is the Holocene Volcanic Rock Formation, primarily composed of lava lithology, andesite breccia, and basalt lava; this formation is younger than the Reef Limestone Formation.

The Reef Limestone Formation itself contains distinct lithological features of reef limestone and can be found scattered throughout the southern part of the study area, accompanied by passive limestone and marl deposits. Overlying both the Reef Limestone Formation and the Holocene Volcanic Rock Formation are alluvial deposits,

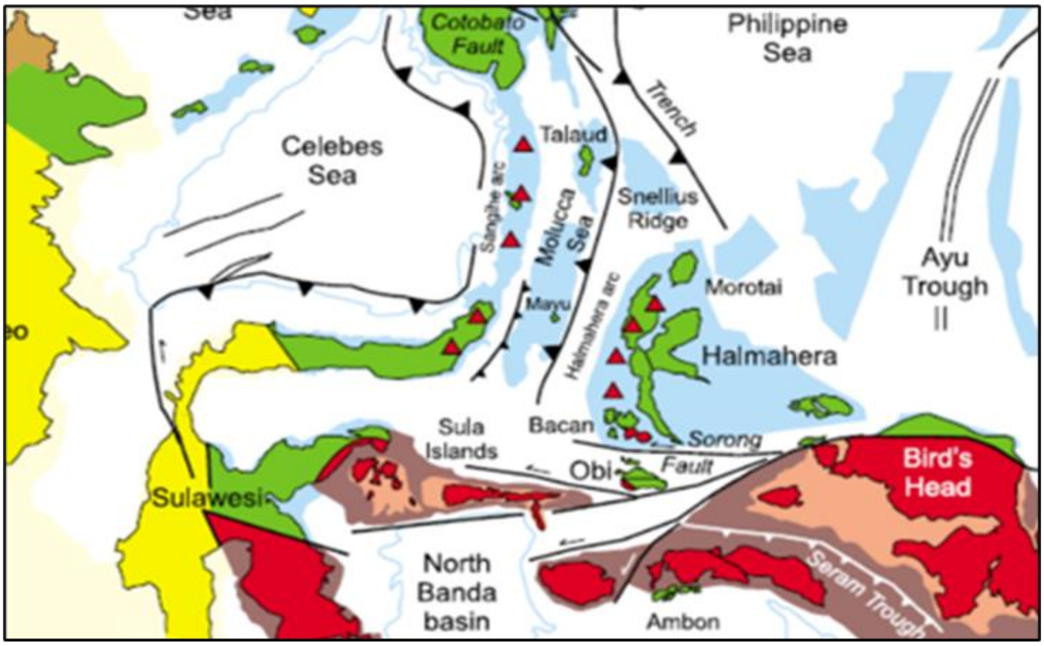

Fig 4. Recent regional tectonic system of Halmahera Island and surrounding area (modified from Hall and Spakman, 2015)

which consist of sedimentary materials that showcase a range of grain sizes, from boulders to clays, and have not undergone complete compaction, as noted by Supriatna (1980).

In terms of tectonic dynamics, North Maluku is characterized by the convergence of three major geological plates: the Eurasian, Pacific, and Indo-Australian plates. This significant interaction occurs primarily within the Halmahera region, as outlined by Ballantyne (1991). The convergence of these tectonic plates leads to a complex geological structure in the region, particularly evident in the presence of active faults, as observed by Condie (2018).

The geological characteristics of Halmahera are fundamentally linked to the tectonic interactions of the Moluccas and Sangihe sea plates, which have markedly influenced the region's tectonic activity. Recent investigations indicate that Halmahera is part of a geological extension of the Moluccas Sea that was subjected to subduction during the Neogene period, approximately between 45 and 25 million years ago. This process of subduction has resulted in the formation of the Halmahera Mountains, as highlighted by Hillis and Müller (2003).

This area is characterized by the convergence of the Moluccas Sea Plate and the southern Philippine Plate. A significant fault line extends from the Bird's Head Peninsula in Papua to the Banggai Islands in Central Sulawesi, thereby delineating a tectonic boundary between the North Maluku region, which is influenced by the Eurasian and Pacific plates, and the southern tectonic realm influenced by the Indo-Australian plate. This fault is classified as a left-lateral strike-slip fault situated in southern Halmahera and traverse various geographical regions, including the Bacan Islands, Obi Island, and Sula Islands, as illustrated in Fig. 4 (Hall and Spakman, 2015).

3. Literature Study

Igneous rock is defined as a geological formation consisting of one or multiple minerals that originate from the solidification of magma. In its most fundamental definition, magma is the parental material from which igneous rock crystallizes and is characterized as a molten rock substance. The composition of magma is largely dominated by high-temperature silica (SiO_2) and is capable of flowing (MacDonald, 1972). Consequently, the formation of igneous rocks is inherently linked to the compositional characteristics and physical properties of the magma from which they derive. According to Flint (1977), the chemical composition of magma typically ranges from 45% to 75% SiO2. Nevertheless, there are instances where certain lavas exhibit SiO_2 compositions as low as 30% and as high as 80%. Such variability can be attributed to the assimilation of magma with fragments from sedimentary rocks and volcanic materials or through the differentiation of magma, leading to alterations in its compositional structure.

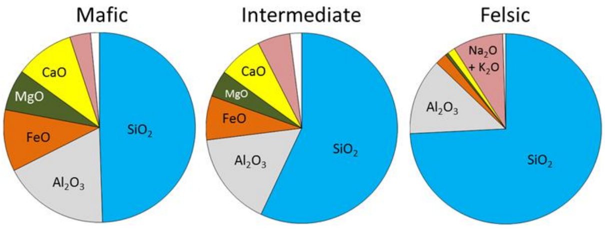

Fig. 5. Shows the composition (weight percent) of igneous rock types and differentiates them into three main groups of magma types on Earth (modified from Flint, 1977)

As illustrated in Fig. 5, Flint (1977) identifies three distinct types of magma characterized by their SiO_2 content. Magma compositions around 50% SiO_2 generally produce mafic igneous rocks, such as basalt, diabase, and gabbro. Conversely, magmas with approximately 60% SiO_2 yield intermediate rocks, including andesite and diorite, while those containing approximately 70% SiO_2 produce felsic igneous rocks, such as rhyolite and granite. The mineralogical composition of basalt and gabbro is primarily characterized by minerals that include Al_2O_2, FeO, MgO, and CaO, while rhyolite and granite predominantly contain minerals characterized by Al_2O_3, Na_2O, and K_2O.

Furthermore, Peccerillo and Taylor (1976) categorized magma based on both SiO_2 content and the combination of SiO_2 with K_2O, as depicted in Fig. 6. This classification delineates low K magma (tholeiite series), low to medium K (calc-alkaline series), high to medium K (high K calc-alkaline series), and high K (Shoshonite series), thereby elucidating the diverse compositional spectrum of igneous rocks, which includes tholeiite andesite, calc-alkaline andesite, and shoshonite andesite.

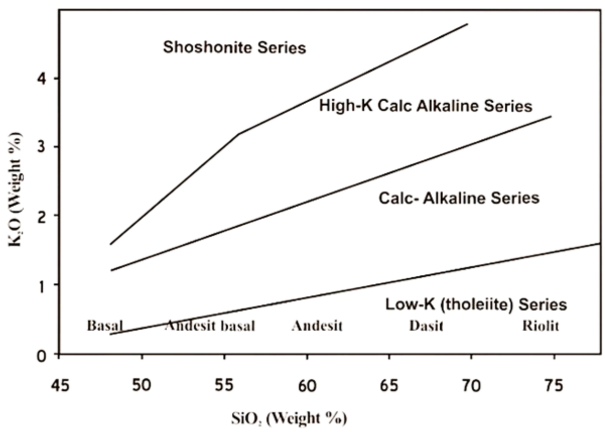

Fig. 6. Magma Composition and Affinity Diagram (Peccerillo and Taylor, 1976)

4. Methodology

The research stages followed in this study are designed to ensure a comprehensive and thorough analysis of the subject matter. Initially, a literature review and site surveys were conducted to gather foundational information about the research area and specific topics of interest. This was followed by a data collection phase that utilized secondary data obtained from previous

Table 1. Whole Rock Geochemistry

Sampel Name	Volcano Name	SiO_2	Al_2O_3	CaO	Fe_2O_3	Na_2O	MgO	K_2O	TiO_2	MnO	P_2O_5	Total
AR 001	Galela (Research Target)	52.19	17.74	12.65	9.58	3.31	1.96	1.47	0.79	0.18	0.14	100
AR 10a		52.18	16.84	13.03	8.24	3.31	2.76	2.46	0.82	0.22	0.14	100
AR 28		55.16	20.00	11.45	5.57	3.35	2.15	1.20	0.82	0.18	0.13	100
AR 013		49.87	19.39	9.25	10.14	4.22	2.95	2.60	1.06	0.31	0.22	100
GAM1	Gamalama (Badan Geologi, 2011)	66.27	17.94	5.51	5.45	4.39	2.19	2.39	1.00	0	0.24	100
GAM2		57.44	23.39	9.57	9.49	0.00	2.69	1.39	0.00	0	0.00	100
GAM3		56.56	17.29	7.25	8.99	3.45	3.49	1.56	0.84	0.18	0.19	100
GKO1	Gamkonora (Badan Geologi, 2011)	56.96	17.39	6.84	1.11	3.78	3.08	1.64	0.84	0.18	0.30	100
GKO172		70.86	15.96	2.98	0.47	4.77	0.85	2.67	0.48	0.12	0.13	100
GKO173		75.68	13.62	1.40	8.79	4.63	0.17	3.59	0.25	0.09	0.03	100
GKO2		57.66	17.69	6.95	5.00	3.74	3.20	1.50	0.78	0.18	0.25	100
IBU1	Ibu (Saing, 2014)	67.05	15.09	3.00	5.36	4.42	0.84	3.22	0.69	0.15	0.19	100
IBU2		67.05	14.89	2.97	5.00	4.38	0.85	3.20	0.70	0.15	0.18	100
IBU3		66.55	14.89	3.00	6.98	4.35	0.85	3.19	0.69	0.15	0.19	100
IBU43		55.20	20.28	9.13	7.21	3.13	3.23	1.04	0.74	0	0.16	100
IBU44		61.06	16.80	5.97	8.55	3.68	2.58	1.86	0.91	0	0.20	100
JLO10	Jailolo (Karim, 2019)	55.19	22.36	13.25	6.88	2.43	4.74	0.94	0.90	0	0.12	100
JLO11		55.76	18.49	9.19	0.00	2.85	4.71	1.00	0.69	0	0.09	100
JLO12		55.36	21.35	13.06	8.70	2.34	6.27	0.55	0.90	0	0.11	100
JLO13		50.52	20.47	12.13	8.91	2.23	4.34	0.86	0.82	0	0.11	100
JLO14		50.50	19.48	11.91	9.28	2.14	5.72	0.50	0.82	0	0.10	100
JLO5		53.04	18.43	9.97	6.04	2.38	5.00	0.61	0.81	0	0.09	100
JLO7		58.82	17.99	8.21	0.79	3.23	4.15	0.79	0.60	0	0.11	100
TOR170	Todoko-Ranu (Laratmase, 2023)	74.76	14.02	1.46	0.60	4.74	0.26	3.42	0.32	0.10	0.04	100
TOR171		74.60	13.93	1.92	0.77	4.54	0.58	3.31	0.31	0.10	0.04	100
TOR172		72.45	13.59	1.89	0.47	4.47	0.57	3.26	0.31	0.10	0.04	100
TOR173		75.68	13.62	1.40	0.50	4.63	0.17	3.59	0.25	0.09	0.03	100
TOR174		75.10	13.96	1.42	0.59	4.77	0.26	3.44	0.33	0.10	0.04	100
TOR175		73.45	13.72	1.38	0.49	4.60	0.25	3.34	0.31	0.10	0.04	100
TOR176		72.85	13.54	1.42	0.57	4.63	0.25	3.32	0.32	0.10	0.04	100

studies. The laboratory analysis was performed at the Geological Engineering Laboratory of Jenderal Soedirman University. This phase involved petrographic and geochemical analysis using an X-Ray Fluorescent (XRF) instrument. Petrographic analysis was conducted on rock samples prepared with thin sections, observed under a polarized microscope to identify various minerals, which are essential for understanding the mineral composition of the samples from the study area.

Two types of observations were made during petrographic analysis: plane polarized light (PPL) and crossed polarized light (XPL). Each sample was carefully documented to ascertain the specific mineral names, focusing primarily on igneous rocks categorized by Streckeisen (1979) into plutonic and volcanic varieties. XRF analysis was crucial for identifying the major element composition in the intrusive rock samples. This data facilitated the understanding of magma characteristics and the tectonic environment of the rocks, represented in discriminant diagrams such as AFM (Alkali, Ferro, and Magnesium), Sub-alkalic Rock diagrams, and total alkali-silica (TAS) diagrams.

Although the samples exhibited low-level alteration, normalization calculations were implemented to account for any variances in grade values resulting from mineral alterations. This correction utilized immobile elements like TiO_2, Al_2O_3, and Zr, as outlined by MacLean and Kranidiotis (1987), enabling a comparison against standard reference materials. Overall, these stages ensured a meticulous approach to the research, contributing to a better understanding of the geological characteristics of the study area.

5. Result and Discussion

The research provides a comprehensive examination of rock geochemistry and the petrogenesis of intrusive igneous rocks, emphasizing the mineral resource potential, with some outcrop (Fig. 7). The analysis of intrusive rocks involved thorough petrographic and geochemical evaluations to elucidate the mineralogical characteristics of the formations. As illustrated in Fig. 8, the classification of intrusive rocks identifies three distinct categories of diorite hornblende: fine-grain, medium-coarse grain, and coarse-grain diorite.

Fine-grain diorite is characterized by a porphyritic texture and a dark greenish ash hue. Its mineral composition predominantly includes plagioclase and hornblende as the principal phenocrysts, with grain sizes ranging from 50 to 280 μm and crystal forms varying from euhedral to anhedral. This variety exemplifies both the aesthetic diversity and geological complexity that diorite embodies. Medium-coarse grain diorite exhibits a similar porphyritic texture and coloration, with the inclusion of clinopyroxene embedded within the hornblende matrix. This aspect enhances the mineralogical diversity and reinforces the significance of plagioclase composition, aligning with the igneous rock classification framework established by Maitre (1989), which underscores the importance of plagioclase, quartz, and orthoclase in igneous rock identification. Coarse-grain diorite retains the porphyritic texture and the characteristic dark greenish ash coloration, with mineral grain sizes ranging from 100 to 320 μm. Although this type displays more pronounced mineral exposure than its finer counterparts, all diorite varieties exhibit similar compositional traits, primarily differentiated by grain size.

Further analyses have identified secondary alteration minerals, including chlorite, carbonate, and quartz, situated within veins and grains of the diorite. Additionally, disseminated opaque minerals, such as pyrite and potential magnetite, are present, indicating ongoing geochemical processes that enhance the comprehension of diorite's geochemical attributes. This extensive study contributes significantly to the classification of diorite within the discipline of igneous petrology.

The abundance of hornblende minerals across the various diorite types suggests that the magma in the studied region may possess a relatively high water content (H2O > 4%). This elevated water content is believed to facilitate the transport of copper metals, along with associated ligands such as Cl^- and HS^-, potentially leading to the formation of metal deposits.

To further substantiate these findings, four diorite igneous rock samples underwent X-ray fluorescence (XRF) analysis to determine the concentrations of major elements within the host rock. The results were subsequently compared with the major element content of nearby volcanic rocks, as reported in prior research. This comparative analysis intends to enhance the understanding of the geochemical characteristics of the region and their implications for mineralization processes.

The results of the XRF analysis as presented in Table 1, indicate a silica content that is worthy of note. According to Flint, the chemical composition of magma, as determined by analysis, ranges from 45% to 75% SiO_2. However, the analysis of samples AR 001, AR 10a, and AR 28 and AR 13, the values obtained for SiO_2 are notably high. This can be attributed to the process of mineral alteration caused by hydrothermal fluids, which resulted in the appearance of secondary minerals that are clearly visible under petrographic analysis. These minerals have led to elevated levels of SiO_2 in the samples.The presence of high levels of SiO_2 indicates the impact of silica mineral addition. The presence of these minerals can be attributed to either the alteration process or the conversion of previous minerals into silica minerals. While the presence of SiO_2 due to alteration is acknowledged, it does not preclude the possibility of increasing levels of other elements.

Fig 7. Intrusion rock outcrop and hand speciment

The characteristic geochemical analysis of the rock samples, as illustrated in Fig. 9, suggests that the specimens can be categorized as igneous rocks of the Gabbroic Diorite – Monzo-diorite type, based on the TAS (Middlemost, 1994) discriminant diagram. This classification is derived from an assessment of the SiO_2 content in relation to Na_2O + K_2O in the samples. The volcanic rocks in the vicinity of the study area exhibit a compositional range from diorite to granite, reflecting an overall transition from intermediate to felsic characteristics.

Further analysis reveals variations in SiO_2 content as it correlates with K_2O levels in several samples, which provides insights into the magmatic processes occurring within the region. Utilizing the discriminant diagram developed by Peccerillo and Taylor (1976), the geochemical data from the study area can be classified into two distinct magma series: the low-K (tholeiite) and the calc-alkaline series, as well as the high-K calc-alkaline series.

This categorization is reinforced by the AFM discriminant diagram established by Irvine and Baragar (1971), which focuses on the chemical concentrations of total alkali (Na_2O + K_2O), MgO, and total Fe (FeO + Fe_2O_3). The results from the AFM diagram indicate that the igneous rocks in this area are predominantly aligned with the calc-alkaline series, characterized by a consistent decrease in FeO relative to Na_2O + K_2O, thus underscoring the geochemical trends pertinent to the region (Irvine and Baragar, 1971).

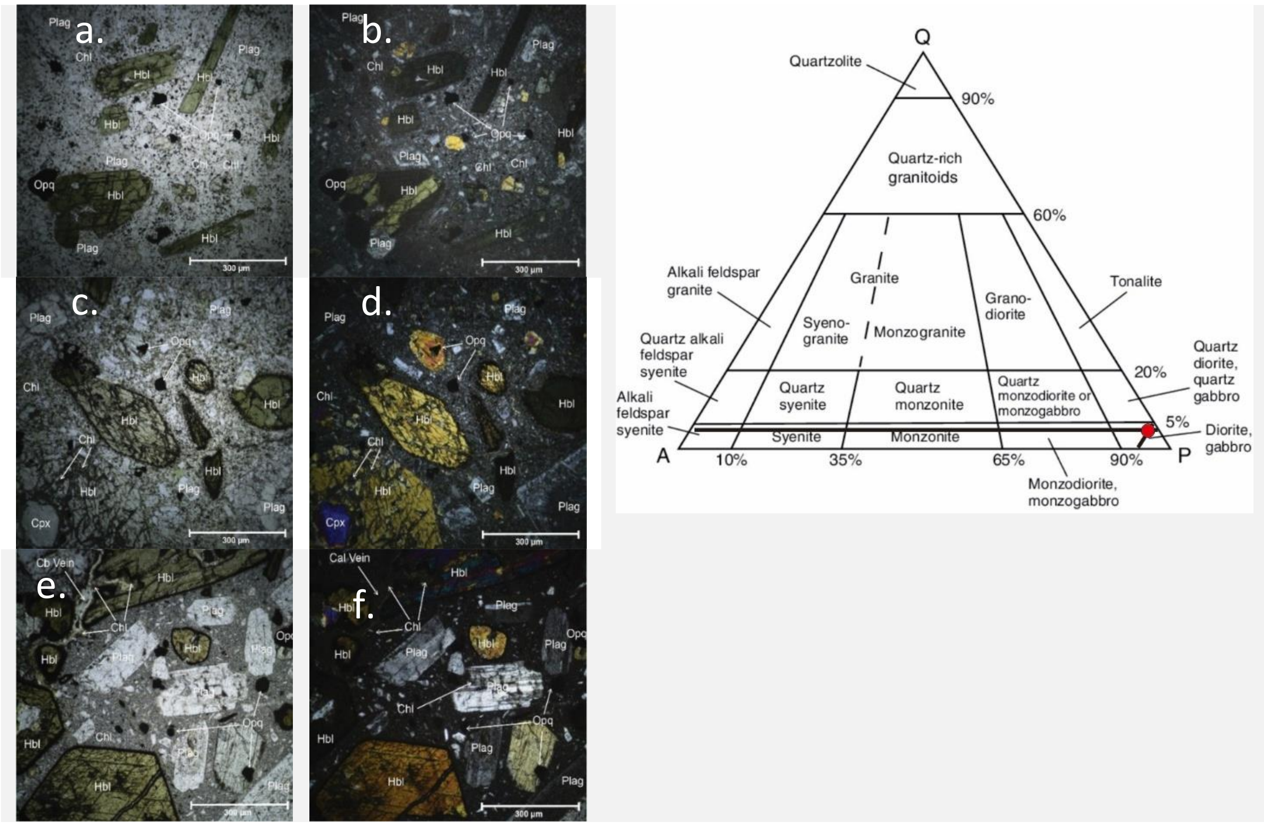

Fig. 8. The results of petrographic analysis of diorite igneous rocks, fine grain (upper), medium grain (middle) and coarse grain (bottom) which show a similar mineral composition in the form of plagioclase (Plag), hornblende (Hbl), with some secondary minerals such as chlorite (chl), calcite/carbonate (cal/cb), and opaque mineral (opq) (sulfide and oxide mineral). QAP Diagram by (Le Maitre et al., 1989) is used for classified the rock with result is Diorite

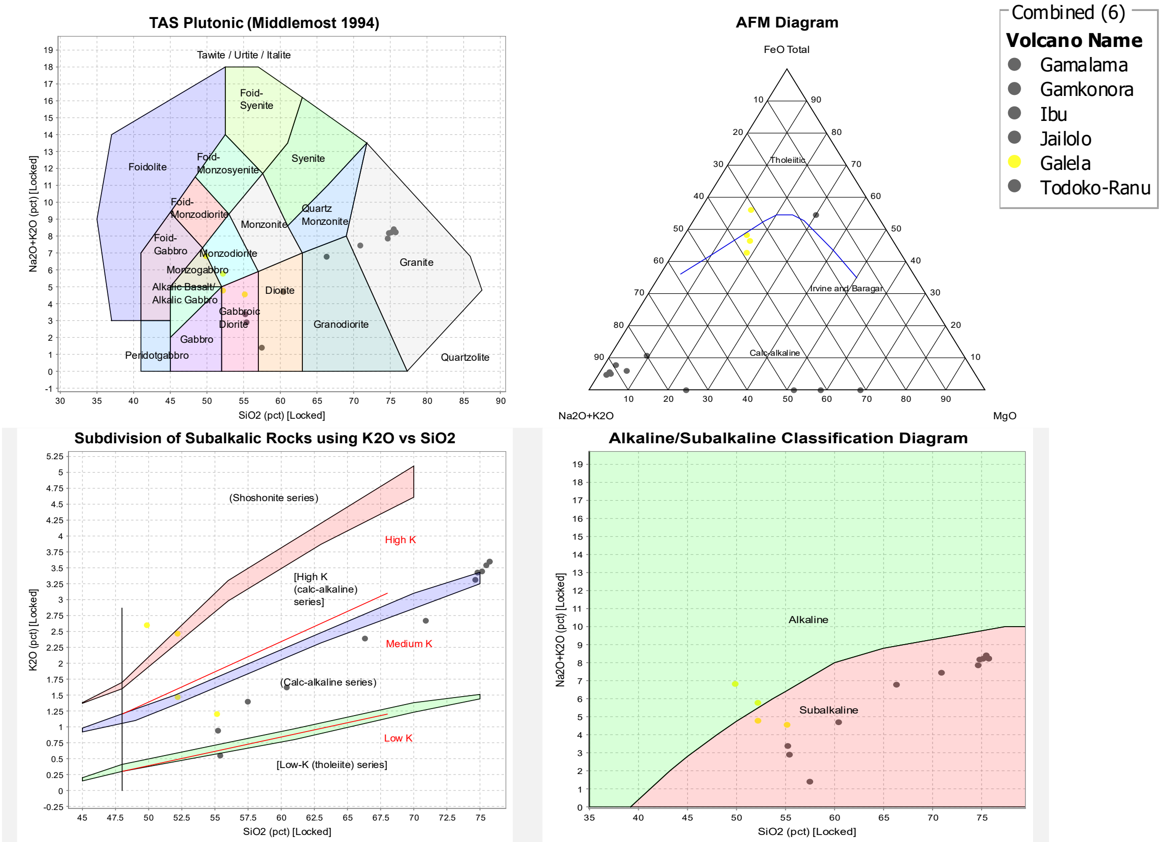

Fig 9. 1). Diagram Middlemost (1994), 2). AFM Diagram Irvine & Baragar (1979), 3). Subalkalic Rock Peccerillo & Taylor (1976). 4). Alkaline/Subalkaline Classification Irvine & Baragar (1971)

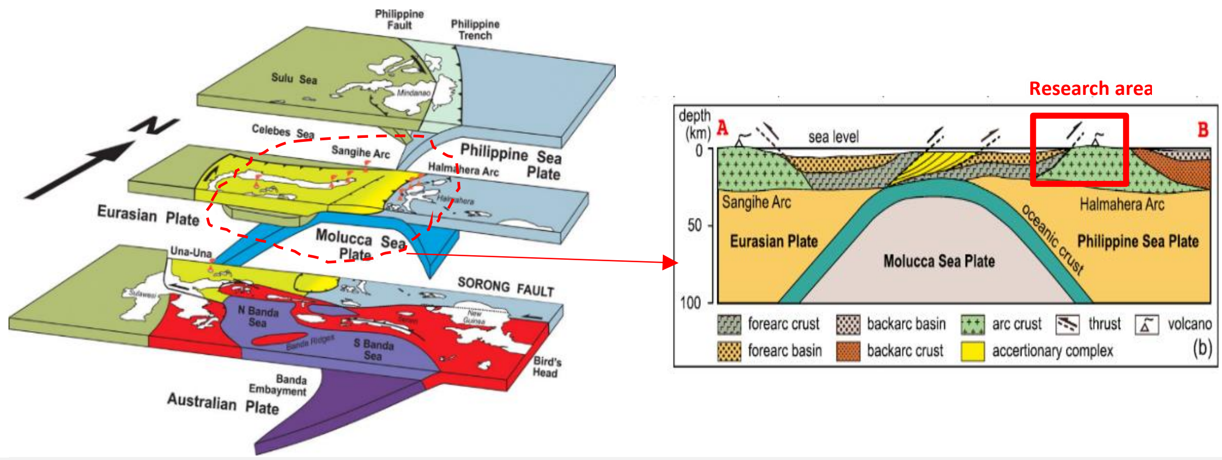

Fig 10. The tectonic environmental model in the North Maluku area shows how the influence of the meeting of three plates produces a modified Maluku Sea collision zone (Modified from Macpherson et al., 2003; Zhang et al., 2017).

The calc-alkaline magma series indicates magma that is affected by the interrelationship of moisture content and oxidation level, resulting in compositional changes. These compositional changes begin with partial melting, and calc-alkaline magmas evolve, including fractional crystallization and partial melting of continental crustal layers. Notably, rocks exhibiting a calc-alkaline composition are prevalent in arcs above subduction lines, i.e., volcanic arcs within the continental crust (Prabowo *et al.*, 2024).

Furthermore, the diagram by Peccerillo and Taylor (1976) demonstrates that the magma of medium K series, indicating that this magma possesses a high potassium element content due to the transformation of Plagioclase-Na minerals to K-feldspar minerals, which signifies the evolution of magma. The Alkaline/Subalkaline Classification diagram by Irvine and Baragar (1971) further elucidates that the diorite igneous rocks within the study area exhibit a subalkaline magma composition. The process of magma rise is initiated by the source of magma emanating from the mantle, reaching the surface temporarily delayed due to crystallization occurring in the magma chamber.

As the mafic magma, a by-product of subduction ascends through the felsic continental crust, it assimilates the rock and migrates into intermediate magma (sub-alkaline) upon reaching the surface. In particular samples, an inclination towards alkaline conditions has been observed, which may be attributed to magma with a relatively high Na_2O + K_2O composition, a consequence of the influence of the rifting process (Winter, 2014).

The results indicated that the tectonic environment responsible for the diorite formation process is a subduction environment. Previous research has demonstrated that the North Maluku region is the result of a collision process that occurred on the Maluku Sea Plate (Macpherson et al., 2003), a theory further substantiated by the presence of alkaline rocks due to the rifting process that occurred during the aforementioned collision (Sukadana, 2015). Research by Morris has shown that the concentration values of Ba, Cs, Sr, and alkali elements are positively correlated with the SiO_2 element, a characteristic commonly formed in magmas present within the Oceanic Island Arc tectonic system. The Oceanic Island Arc is present at the convergent boundary of the subduction of the oceanic plate with the ocean (Kearey *et al*., 2009), so the data and results obtained correlate to show that North Halmahera is influenced by subduction activity between oceanic plates and post-collision.

The oceanic island arc in North Halmahera is present, and three plates collide: the Philippine Sea Plate, Eurasia, and Indo-Austrlia (Macpherson et al., 2003). These three plates move together and cause a collision between the Maluku sea plate and the Sangihe sea plate Fig. 10 (Zhang et al., 2017). This is also evidenced by the results that magma-origin rocks tend tholeiitic towards calc-alkaline. The cause of this change is the magma assimilation process that occurs when magma rises through the continental crust, which tends to be alkaline (mafic) and migrates into intermediate magma when it reaches the surface. In general, tholeiitic series magmas tend to be in the initial condition of the formation of the Island Arc, which is then followed by a change in the calc-alkaline magma series (Fitton, 1971). Diorite intrusions from the research area are associated with the potential for a hydrothermal alteration system. This is associated with the analysis of the rock conditions, which show symptoms of hydrothermal activity allowing the formation of economic minerals. The petrographic results show secondary minerals. Secondary minerals such as chlorite and epidote are shown in each rock sample. In addition, many opaque isotropic minerals are found, spread at each observation point with cubic, orthogonal, and sometimes granular forms. The nature of these minerals tends to indicate that a common sulfide mineral has formed, such as pyrite. The abundance of Hornblende minerals in this rock indicates a high water content; this is one of the characteristics of fertile magma in producing economic hydrothermal fluids.

Furthermore, geochemically, diorite rocks have the characteristics of intermediate magma properties, as indicated by an increase in SiO_2, which coincides with an increase in Na_2O and K_2O. This indicates there is a change in mineral composition, which is usually influenced by plagioclase minerals. The increase in the levels of these elements is evidence that magma has a calc-alkaline series in a general hydrothermal-magmatism system as a source of hydrothermal fluids. It is also supported by the oceanic island arc, which is present as a magmatic arc. According to Sillitoe (2010), the intrusion-related metal deposit system is associated with calc-alkaline magma and plutonic rocks of intermediate to felsic type.

6. Closing

6.1 Conclusion

This study found that North Halmahera has a distribution of lithologies derived from volcanic products and magmatism that developed into various formations. One of them is diorite intrusion, which is present in the Bacan formation with various mineral size characteristics such as fine-grain diorite, medium-grain diorite, and coarse-grain diorite. The mineral characteristics present in each sample indicate that the diorite intrusion underwent multiple phases from Early to Late stages. Compositionally rock-forming minerals such as plagioclase and hornblende, as well as secondary minerals such as chlorite, epidote, and calcite, indicate that the intrusions came from hydrous magmas.

The geochemical composition of the rock shows that the rock-forming magma is an intermediate magma. Then, the magma conditions present in the form of calc-alkaline and subalkaline series indicate that the rocks are present in subduction conditions due to the magma assimilation process that changes the composition of the original magma. The subduction conditions that occur form a tectonic environment in the form of the Oceanic Island Arc, which is explained that this condition is present in the Maluku marine collision complex caused by the collision of the Philippine, Eurasian, and Indo-Australian Plates. Several alkali-series samples indicate a rifting process, proving that northern Halmahera is affected by post-collision processes.

6.2 Suggestion

These results are likely to improve the understanding of the presence of diorite intrusions in North Halmahera that have the potential to produce hydrothermal systems by improving the analysis and further study of the geochemical characteristics by understanding the presence of trace and rare earth elements in these rocks.

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