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Geology and geochemistry of the Nang Ann prospect, Noen Maprang District, Phitsanulok Province, Central Thailand

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Abstract

The Nang Ann prospect is situated approximately 35 km northeast of the Chatree gold-silver deposit in central Thailand. It is located in Ban Mung Subdistrict, Noen Maprang District, Phitsanulok Province. The mineralization at this site primarily consists of iron-copper reduced skarn, which is hosted in Late Permian-Early Triassic volcaniclastic rocks belonging to the Chatree volcanic complex. The oldest rock formation in the central part of the prospecting area is Permian limestone. In the northern part, there is a prevalent occurrence of polymictic rhyolitic sandstone and breccia, while the central part mainly contains unmineralized microdiorite. The host volcaniclastic rocks primarily comprise polymictic rhyolitic sandstone and breccia. Additionally, siltstone and quartz-phyric rhyolite intercalate within the sequence of host rocks. These rocks exhibit varying degrees of alteration, particularly in the sections intersected by diamond drill cores. The geochemistry of the intrusives in this area can be classified into two suites: the intermediate to mafic suite and the felsic suite. The intermediate to mafic suite includes andesite/basalt and basaltic andesite/andesite, suggesting a primitive magma source associated with within-plate or ocean ridge origin. The felsic suite comprises dacite, trachy-andesite, and rhyodacite/dacite, indicating a magma source related to fractional crystallization in a volcanic arc setting. Both suites are identified as part of the calc-alkaline magma series.

Keywords: Petrography, Geochemistry, Nang Ann prospect

1. Introduction

Metallic minerals play a crucial role in driving Thailand's economy, as they are widely utilized in diverse everyday applications. Industries such as construction, electronics, and jewelry heavily rely on minerals like iron, copper, and gold. Thailand has actively engaged in the production and mining of metals, with a specific emphasis on tin, zinc, iron, silver, and gold. These valuable metallic mineral deposits are primarily associated with igneous rocks and are predominantly found in the Loei-Phetchabun Fold Belt region. Within the province of Loei, notable deposits include the Phu Thap Fah gold skarn deposit and the Puthep copper-gold skarn deposit. Nong Khai province hosts the Phu Lon copper-gold skarn deposit, while Phichit province consists of the

Khao Phanom Pha gold skarn deposit and the Chatree gold-silver epithermal deposit. Nakornswan province is renowned for the Khao Lek iron skarn deposit, and the Khao Thap Kwai iron skarn deposit is located in Lop Buri province. These metallic mineral deposits make a significant contribution to Thailand's economic growth, job creation, and export potential. They not only satisfy domestic demands but also generate substantial revenue through international trade. The extraction and utilization of these metallic minerals play a pivotal role in Thailand's industrial development, securing the country's position in the global market.

The Nang Ann prospect is situated in the Ban Mung subdistrict of the Noen Maprang district, located in Phitsanulok province, which is situated in north-central Thailand. This region holds promising potential for precious metals. Although diamond drilling and rotary drilling have been conducted in this area, in-depth research is lacking. Therefore, this study aims to provide a comprehensive understanding of the geology and geochemistry of the rocks in the Nang Ann area. Furthermore, the analysis of geochemical data will aid in determining the magmatic activity and tectonic setting present in this region.

2. Geological setting

The Nang Ann prospect is located in the Loei-Phetchabun Fold Belt. The geological setting of Nang Ann is described from older to younger below (Fig. 1).

2.1 Permian sedimentary rocks

The Permian rocks in the Loei-Phetchabun range have been classified as the Saraburi Group, showing significant correlation with the Ratchaburi Group in western and southern Thailand, as well as the Ngao Group in northern Thailand. Based on the research conducted by Bunopas (1981) and Hinthong et al. (1985), the Permian sedimentary rocks found in the vicinity of the Chao Phraya basin, spanning from Uthai Thani to Saraburi province, and along the western flank of the Khorat Plateau, from Loei to Saraburi province, can be linked to the Saraburi Group. In Phetchabun province, Chonglakmani and Sattayarak (1984) identified three distinct formations within the Permian limestone: the Pha Nok Khao Formation, the Hua Na Kham Formation, and the Nam Duk Formation.

2.1.1 Pha Nok Khao Formation

The Pha Nok Khao Formation spans continuously from the southeastern part of Loei province to Phetchabun province. Its type-section is located at Pha Nok Khao in the Phu Kradung district of Loei province. Stratigraphically, the Pha Nok Khao Formation is correlated with the Nam Maholarn Formation in Loei province and the Khao Kwang Formation in Saraburi province. This formation primarily consists of gray limestone with a variety of bedding patterns, ranging from lamination to massive, and it is interbedded with gray shale. Within the limestone, lensed or laminated chert can be observed. The age of the Pha Nok Khao Formation is determined by the presence of abundant index fossils, such as fusulinids and corals, which indicate its origin during the Lower to Middle Permian era.

2.1.2 Hua Na Kham Formation

The Hua Na Kham Formation is characterized by its narrow and continuous distribution, spanning from the southeastern region of Loei province to Phetchabun province. The type-section of this formation is located at Ban Hua Na Kham in Chaiyaphum province. Within the Hua Na Kham Formation, a variety of lithologies can be observed, such as gray shale, yellowish brown sandstone, and gray laminated and socketed limestone. These rocks are dated to the Middle Permian era.

2.1.3 Nam Duk Formation

The Nam Duk Formation is characterized by its north-south trend and distribution, spanning from the southeastern part of Loei province to Phetchabun province. The type-section of this formation is located at Ban Nam Duk in the Lom Sak district of Phetchabun province. Within the Nam Duk Formation, one can find a combination of gray to black and yellowish-brown fine sandstone, as well as gray to dark gray limestone with varying thicknesses of bedding. The formation also exhibits a Bouma sequence, which is a distinctive sedimentary sequence. The presence of fusulinids and foraminifera within the formation indicates its Middle Permian age.

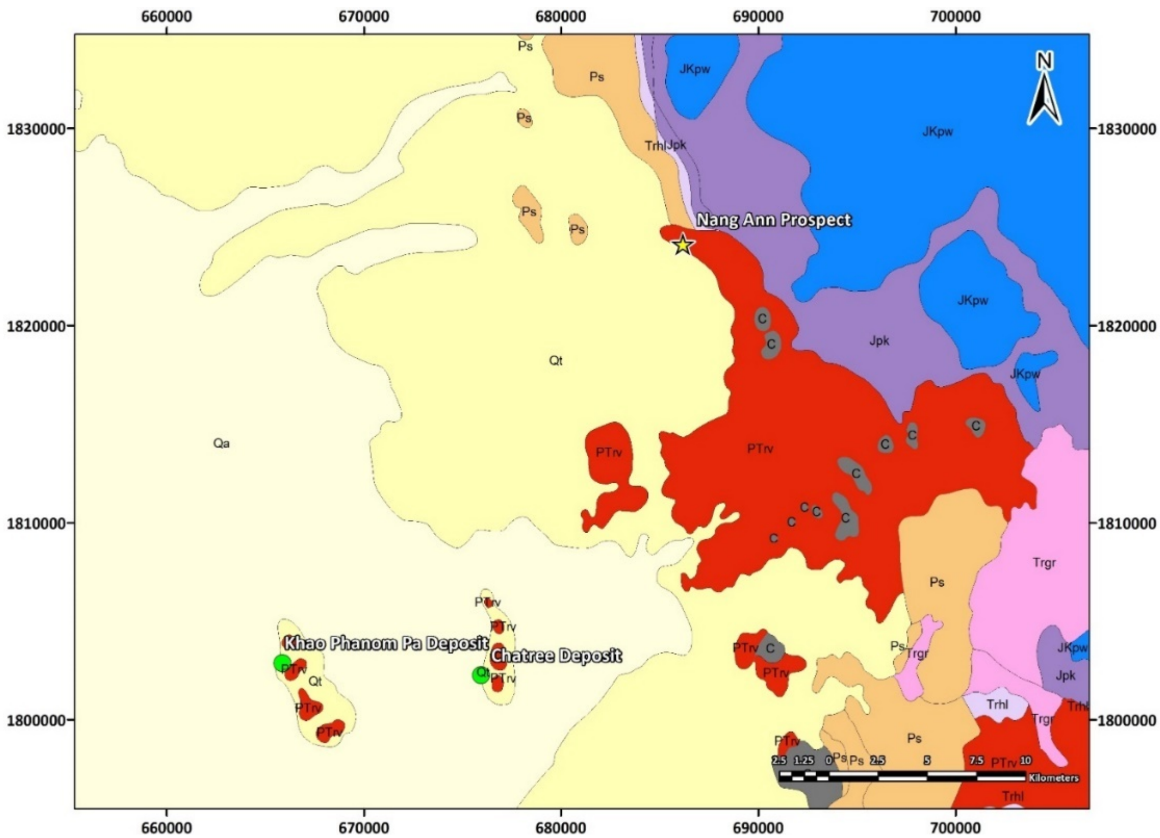

Figure 1 Regional geological map of Nang Ann prospect.

2.2 Permo-triassic volcanic rocks

The Permo-Triassic volcanic rocks extend from Phetchabun to Nakhon Nayok province, exhibiting a north-south orientation. These volcanic rocks have a regional distribution and are in contact with Permian rocks and the Khorat Group. The Permo-Triassic volcanic rocks encompass a diverse range of lithologies, including basalt, basaltic andesite, andesite, rhyolite, tuff, and agglomerate. Additionally, quartz diorite and granodiorite are found associated with the volcanic rocks. According to Salam et al. (2014), the volcanic rocks in the Chatree deposits and surrounding areas can be classified into four units: unit 1 comprises fiamme breccia, which is dated to the late Permian to Early Triassic era; unit 2 consists of volcanogenic sedimentary rocks, dating to the upper Permian to lower Triassic era; unit 3 comprises polymictic mafic to intermediate breccia, originating from the late Permian era; and unit 4 consists of plagioclase and hornblende-phyric basaltic andesite, formed during the late Permian era. In the Chatree areas, these volcanic suites overlie upper Carboniferous to lower Permian limestone, and early Carboniferous igneous rocks such as granite, rhyolite, and breccia are present (Salam et al., 2014). At the peak of Pha Daeng, phyric andesite intrusions are predominantly found within the bedding of the Permian limestone. Contact zones between the rocks are characterized by metamorphism, resulting in the formation of calc-silicate rocks and marble.

3. Methodology

3.1 Sample collection and petrographic investigation

The samples were collected from drill-coring and surface rocks. The drill core samples include least-skarn altered intrusive rocks from drill hole no. 4265DD. Samples of surface rocks consist of least-altered volcanic rocks. These samples are prepared for thin section at the Department of Science, Chulalongkorn University, Thailand. The petrographic investigation of thin section was analyzed by polarizing microscope.

3.2 X-Ray Fluorescence (XRF)

PANalytical Axios Advanced X-Ray Fluorescence (XRF) spectrometer was used for major elements analysis at Department of Mineral Resources, Thailand. Major elements were measured from fusion discs prepared at 1,200°C, 1 g sample and 5 g Flux (lithium tetraborate-metaborate; 66:34 mix). Loss on ignition (LOI) was determined by heating 1 g of sample at 900°C for 30 minutes and reweighing.

3.3 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES)

Inductively Coupled Plasma Mass Spectrometer (ICP-MS) and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) were used for trace and rare earth elements (REEs) analysis at Australian Laboratory Services (ALS).

4. Results

4.1 Petrography of Nang Ann prospect

Based on field investigation (Fig. 2) and careful analysis of drill core logging, the lithology can be classified into two distinct parts. Part A primarily comprises drill coring rocks, which are further divided into three units. Unit AI is predominantly composed of siltstone, Unit AII consists of polymictic rhyolitic sandstone/breccia, and Unit AIII exhibits a notable abundance of quartz-rich rhyolite. On the other hand, Part B encompasses the surface rocks and is subdivided into three units as well. Unit BI is identified as fossiliferous limestone, indicating the presence of fossils within the limestone formation. Unit BII shares similarities with part A, characterized by polymictic rhyolitic sandstone/breccia. Additionally, there is a distinct occurrence of a microdiorite suite in this part, signifying the presence of microdiorite rock formations. Further details about the characteristics and properties of each part will be provided below.

4.1.1 Part A: Drill coring rocks

Drill core logging serves as a fundamental method for classifying mineral deposits. Through the identification and correlation of drill core samples at Nang Ann, it has been established that the deposit rocks exhibit compositional diversity and vertical discontinuity. The focus of core logging in this case revolves around the zonation of rocks, including country rocks, intrusive rocks, alteration, and mineralization. Consequently, the rocks can be categorized into three distinct units: Unit AI: Siltstone, Unit AII: Polymictic rhyolitic sandstone/breccia, Unit AIII: Quartz-rich rhyolite

These units allow for a systematic division of the rocks based on their specific characteristics and aid in understanding their spatial distribution within the mineral deposit. This comprehensive analysis of the drill core samples contributes to a better comprehension of the deposit's geological history and the processes involved in alteration and mineralization.

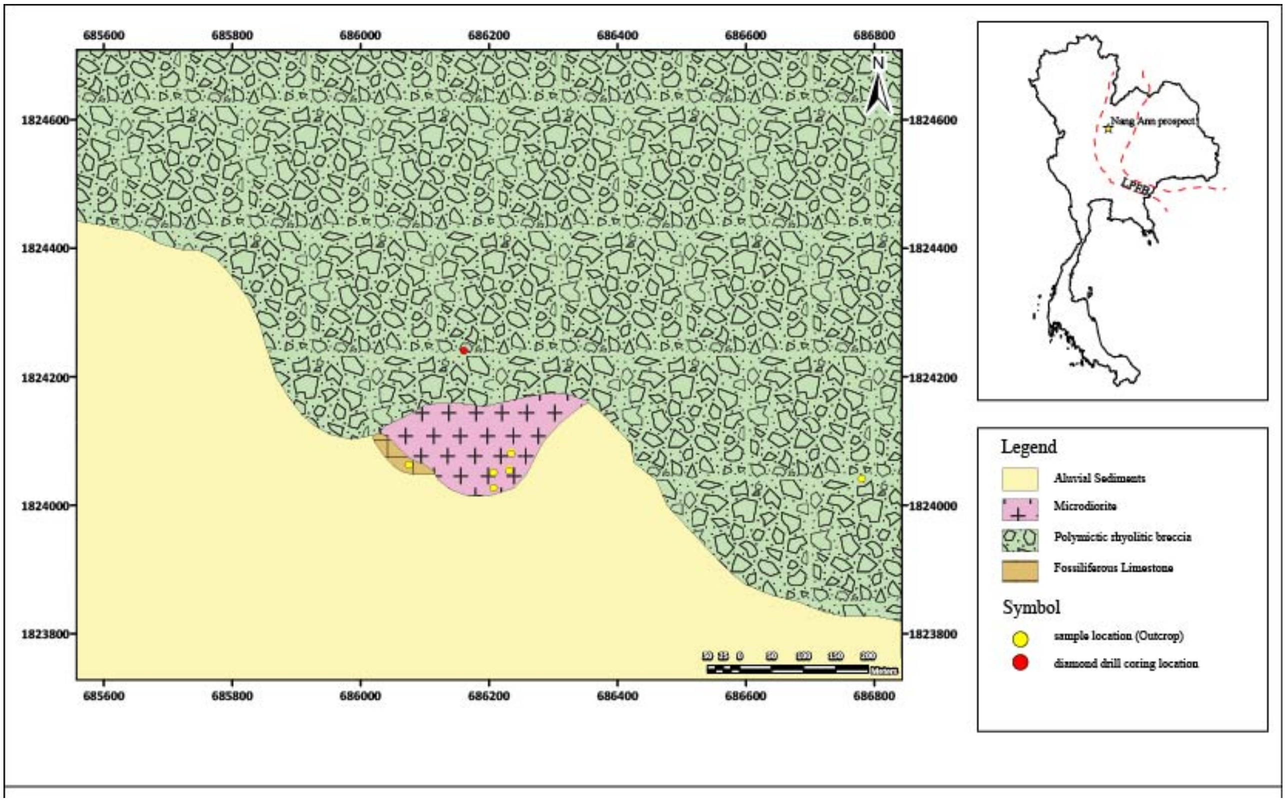

Figure 2 Geological map of Nang Ann prospect showing sample location for petrochemistry study.

Unit AI: Siltstone

Unit AI is typically found in the upper portion of the Nang Ann prospect. It generally occurs within a depth range of 37 to 44 meters and 59 to 65 meters, with some remnants observed within the skarn zone. The rocks within this unit exhibit purplish gray, dark green, and yellowish gray coloration. Siltstone is the predominant lithology, displaying a clastic texture with siliceous cement and a fine sand mixture. The mineral composition of this unit mainly comprises quartz and clay minerals. Minor veins are observed running parallel to the bedding planes. Notably, a significant portion of the siltstone exhibits alteration features.

Under microscopic study, siltstone exhibits a distinct clastic texture, comprising silt-sized clasts, matrix types, and siliceous cement. The rock also displays signs of significant weathering. Its mineral composition primarily consists of clay minerals and quartz. Notably, texture alteration is evident within the rock. Secondary minerals, including chlorite, epidote, and sericite, are present as a result of alteration processes. These secondary veins intersect the rock's texture.

Minerals such as calcite, chlorite, and epidote are identified within these veins (Fig. 3)

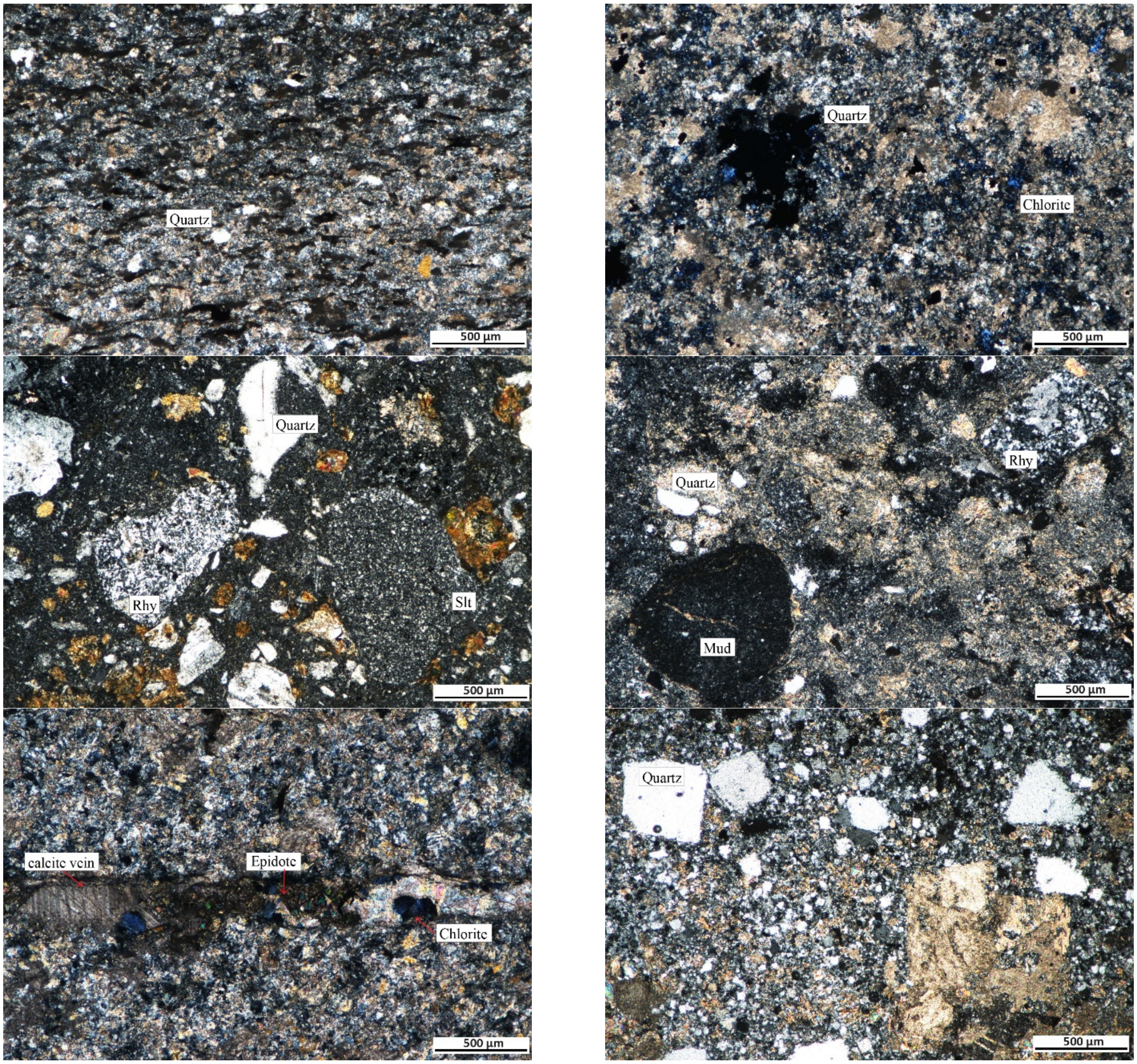

Figure 3 Characteristics of Drill core rocks. (a) Photomicrograph of siltstone showing clasts of quartz in silt-sized and flow of opaque minerals (PPL). (b) Photomicrograph of siltstone showing clasts of quartz and chlorite (XPL). (c) Photomicrograph of polymictic rhyolitic sandstone showing clasts of siltstone (Slt), rhyolite (Rhy) quartz and matrix of volcanic glass (XPL). (d) Photomicrograph of polymictic rhyolitic sandstone showing clasts of mudstone (Mud), rhyolite (Rhy) quartz and matrix of volcanic glass (XPL). (e) Photomicrograph of aphyric rhyolite showing very fined-grained quartz and calcite-epidote-chlorite vein (XPL). (f) Photomicrograph of phyric rhyolite showing very fined-grained quartz and phenocrysts of quartz (XPL).

Unit AII: polymictic rhyolitic sandstone/breccia

Unit AII can be correlated with the late Permian to early Triassic volcanic rocks. It is observed within a depth range of 81 to 97 meters in the Nang Ann area, with remnants also found within the skarn zone. This unit is characterized by greenish and light grey rocks, indicative of volcanogenic sedimentary rock. The polymictic rhyolitic sandstone within this unit exhibits a clastic texture and is primarily matrix-supported. The clasts within the sandstone range in size from 0.5 mm to 1.5 cm and display a subangular to subrounded shape. They are poorly sorted and exhibit moderate sphericity. The clasts comprise various types, including rock fragments and crystal fragments. The matrix of the sandstone is composed of clay to very fine-sized particles of quartz, feldspar, and volcanic glass. Furthermore, within the rock texture, calcite veins and pyrite can be observed. These additional features contribute to the overall characterization of the unit.

Under microscopic study, the volcanogenic sedimentary rocks display a clastic texture and are primarily matrix-supported. The rocks are composed of various clast and matrix types. The clasts range in size from 0.2 mm to 1.5 cm and can be identified as andesite, rhyolite, crystal-rich andesitic sandstone, siltstone, mudstone, quartz, orthoclase, and plagioclase. The matrix of the sedimentary rocks consists of quartz, orthoclase, plagioclase, and volcanic glass. Secondary minerals, including chlorite, sericite, and clay minerals, are also present within the rocks. These minerals contribute to the overall composition and texture of the rocks (Fig. 3).

Unit AIII: quartz-phyric rhyolite

Unit AIII can be correlated with the late Permian to early Triassic volcanic rocks. It is observed within the depth range of 23 to 24 meters, 97 to 98 meters, and 108 to 110 meters. This unit is characterized by orange to white very fine-grained massive rocks, which are identified as rhyolitic rock. The rhyolite within this unit exhibits both phyric and aphyric textures. Phyric rocks contain approximately 10 to 20% phenocrysts of quartz. Sericite is observed as a secondary mineral within the rock. Additionally, calcite-chlorite-epidote veins are present, contributing to the overall texture of the rock. At the contact with other rocks, such as unit AII and skarn rock, cross-cutting textures are observed, indicating the intrusive nature of the unit. These observations provide valuable insights into the relationships and interactions between different rock units within the studied area.

Under microscopic study, the rock-forming minerals within Unit AIII are primarily composed of quartz, orthoclase, and plagioclase. In phyric rhyolite, the phenocrysts consist of quartz and orthoclase, with phenocrysts ranging in size from 0.1 to 0.5 mm. The groundmass of the rock is predominantly fine-grained, measuring less than 0.1 mm, and composed of quartz, orthoclase, and plagioclase. This unit has undergone significant alteration, primarily characterized by the presence of quartz, chlorite, and epidote. These alteration minerals have modified the original composition of the rock. The veins observed within the rock cut across the existing texture, indicating their cross-cutting nature. Minerals found within these veins include calcite, chlorite, and epidote (Fig. 3).

4.1.2 Part B: Surface rocks

During the field investigation conducted at Nang Ann, the geology of the deposit was studied, focusing on the distribution of rocks. Through the identification and correlation of surface rocks, it was determined that the rocks in the area exhibit compositional diversity. Specifically, the rocks can be classified into two units and one intrusive suite. These include unit BI, characterized by fossiliferous limestone, unit BII, composed of polymictic rhyolitic sandstone/breccia, and the microdiorite suite. Each of these units and the intrusive suite contributes to the overall geological composition of the area.

Unit BI: Fossiliferous limestone

Unit BI, which is correlated with the Pha Nok Khao Formation described by Chonglakmani and Sattayarak in 1984, shares similarities with unit AII. This unit is predominantly present in the Nang Ann prospect, specifically occupying selected areas of the karst topography, including both the floors and hills. The limestone found within this unit displays distinctive features such as a dark grey color, a massive structure, and a non-clastic texture. Its composition primarily consists of calcite, the principal mineral component of limestone. Notably, the limestone also contains a variety of fossils, including corals, crinoid stems, and brachiopods, which offer valuable insights into the geological history and past marine environments of the region. In addition to the limestone matrix, the presence of calcite veins within its texture suggests the occurrence of mineral-rich fluid flow and subsequent vein formation processes. These characteristics collectively contribute to the comprehensive characterization of Unit BI within the Nang Ann prospect.

Under microscopic study, the carbonate rocks exhibit distinct characteristics. They are characterized by mud-sized calcite particles, known as micrite, which contribute to a non-clastic texture. The rocks are mud or matrix supported, with over two-thirds of the matrix comprising micrite. The primary components of these rocks are calcite, with less than 5% allochems present. The allochemical constituents within the carbonate rocks include oolites, foraminifera, brachiopods, and crinoids. These biological fragments provide evidence of past marine life and contribute to the overall fossil content of the rocks. Based on classification systems, the limestone falls into the category of fossiliferous biomicrite according to Folk (1959) and mudstone according to Dunham (1962). Additionally, minor calcite veins can be observed within the rock texture (Fig. 4).

Unit BII: Polymictic rhyolitic sandstone/breccia

Unit BII is correlated with the late Permian to early Triassic volcanic rocks. This unit is predominantly distributed in the northern to northeastern regions of the Nang Ann prospect, particularly in close proximity to high and steep hills. The volcanogenic sedimentary rock within this unit exhibits a moderate red and greenish grey coloration. Polymictic rhyolitic sandstone is the dominant rock type, displaying a clastic texture and being matrix supported. Clasts within the sandstone range in size from 0.5 mm to 1.5 cm and exhibit subangular to subrounded shapes. They are characterized by poor sorting and moderate sphericity. The clasts comprise various types, including rock fragments and crystal fragments. The matrix of the sandstone consists of clay particles and is primarily composed of very fine-sized quartz, feldspar, and volcanic glass. Within the rock texture, the presence of calcite veins and pyrite can be observed, indicating the occurrence of mineral-rich fluids and mineralization processes. These features collectively contribute to the overall characterization of Unit BII within the Nang Ann prospect.

Under microscopic examination, volcanogenic sedimentary rocks exhibit a clastic texture and are supported by a matrix. These rocks consist of various types of clasts and matrix materials. The clasts range in size from 0.2 mm to 1.5 cm and can be identified as andesite, rhyolite, crystal-rich andesitic sandstone, siltstone, mudstone, quartz, orthoclase, and plagioclase. The matrix of the sedimentary rocks is composed of quartz, orthoclase, plagioclase, and volcanic glass.

Additionally, secondary minerals present within the rocks include chlorite, sericite, and various clay minerals. These secondary minerals contribute to the overall composition and alteration of the rocks (Fig. 4).

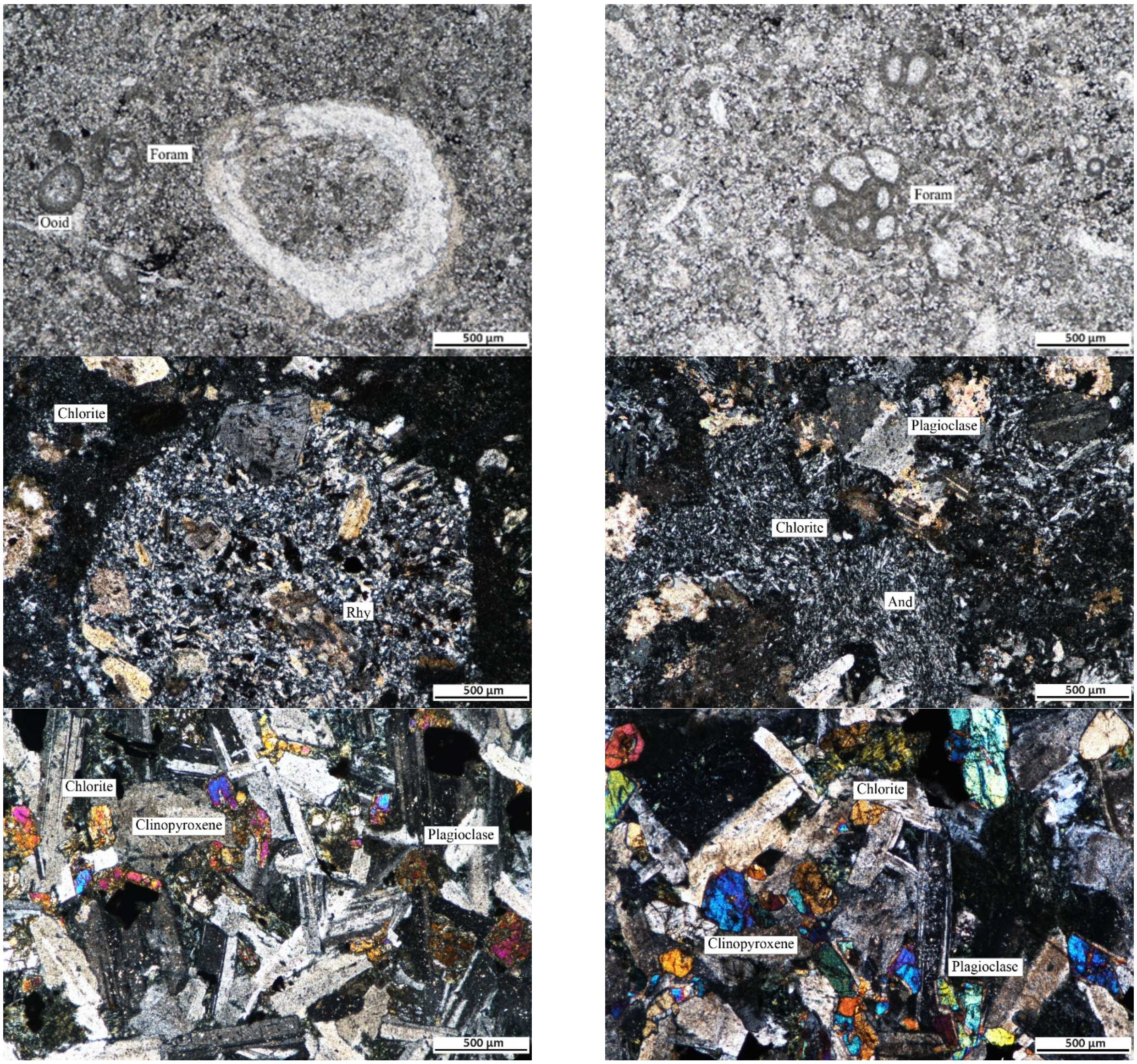

Figure 4 Characteristics of Surface rocks. (a) Photomicrograph of fossiliferous biomicrite showing oolites (Oo) and foraminifera (Foram) (PPL). (b) Photomicrograph of fossiliferous biomicrite showing foraminifera (Foram) (PPL). (c) Photomicrograph of polymictic rhyolitic sandstone showing clasts of rhyolite (Rhy), chlorite and matrix of volcanic glass (XPL). (d) Photomicrograph of polymictic rhyolitic sandstone showing clasts of andesite (And), plagioclase, chlorite and matrix of volcanic glass (XPL). (e) Photomicrograph of microdiorite showing plagioclase, clinopyroxene and chlorite (XPL). (f) Photomicrograph of microdiorite showing plagioclase, clinopyroxene and chlorite (XPL).

Microdiorite suite

The microdiorite suite is prominently found in the central area of the Nang Ann prospect, particularly in the vicinity of hills. This suite exhibits medium to fine-grained rocks with a range of colors from greenish grey to dark grey. The rocks possess a phaneritic texture, indicating that the mineral crystals are visible to the naked eye. They are classified as dioritic rock, characterized by the presence of essential minerals such as feldspar and pyroxene. The microdiorite suite reveals the abundance of feldspar and pyroxene as the primary minerals. Additionally, chlorite is observed as a secondary mineral within the suite. Furthermore, pyrite is present, adding to the textural composition of the rocks.

Under microscopic examination, the dioritic rocks exhibit a phaneritic texture, indicating that the mineral grains are visible to the naked eye. The grain sizes of minerals within the rocks range from 0.1 to 2 mm, classifying them as hypabyssal rocks, which are formed at intermediate depths beneath the Earth's surface. The rock-forming minerals in the dioritic rocks mainly consist of plagioclase, a type of feldspar, and clinopyroxene. Plagioclase minerals typically display a range of compositions between sodium-rich and calcium-rich varieties. Clinopyroxene is a silicate mineral commonly found in igneous rocks. In addition to the primary minerals, the dioritic rocks also contain secondary minerals, including chlorite, sericite, and clay minerals. These secondary minerals often form through alteration processes that occur after the rock's initial formation, indicating potential hydrothermal activity or weathering. Furthermore, upon hand specimen analysis, the presence of an opaque mineral, specifically pyrite, can be observed. Pyrite is a common sulfide mineral with a characteristic metallic luster and brass-yellow color (Fig. 4).

4.2 Geochemistry of Nang Ann prospect

Whole-rock geochemical data for Nang Ann deposit such as the intrusive rock in drill coring and the surface area are listed in Table 1 for major elements and Table 2 for trace elements and rare earth elements.

The Nb/Y - Zr/TiO_2*0.0001 discrimination diagram, proposed by Winchester and Floyd in 1979, is used to classify the rocks of Nang Ann based on their altered composition. The diagram provides valuable information about the immobile elements present in the rocks. According to the diagram, the surface rocks of Nang Ann are identified as andesite/basalt, indicating their composition and characteristics. On the other hand, the rocks obtained from drill core samples are classified as trachy-andesite and rhyodacite/dacite, suggesting a different composition compared to the surface rocks (Fig. 5).

Bivariate plots of major elements, including TiO_2, P_2O_5, Fe_2O_3, Al_2O_3, MgO, MnO, CaO, Na_2O, and K_2O, as well as immobile elements such as Zr, Zn, Y, Ce, Sc, V, Rb, Ba, Cr, Sr, Nb, Cs, Hf, Th, and U, versus FeO*/MgO, reveal the presence of three distinct geochemical suites with different major element patterns (Fig. 6). The first suite, represented by microdiorite from the surface area, exhibits specific major element characteristics. Additionally, two other geochemical suites of intrusive rocks are identified. These geochemical suites show no evidence of element remobilization resulting from fractional crystallization due to alteration processes.

Table 1 Major element compositions (in wt.%) determined by XRF analysis of intrusive and surface rocks, Nang Ann prospect, central Thailand.

No	1	2	3	4	5	6	7	8	9	10	11
Areas	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann
Sample name	NA-02	NA-03	NA-04	NA-05	NA-06	4265-02200-1	4265-02200-2	4265-09730	4265-10950-1	4265-10950-2	4265-10950-3
Rock types	microdiorite	microdiorite	microdiorite	microdiorite	microdiorite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite
SiO_2	51.61	51.09	50.46	51.83	51.24	69.4	69.95	67.55	71.14	71.43	71.23
TiO_2	2.41	2.45	2.52	2.34	2.48	0.17	0.12	0.14	0.13	0.13	0.13
Al_2O_3	14.99	14.96	14.84	15.12	15.09	13.61	13.28	13.53	13.87	14.15	13.93
Fe_2O_3	11.81	11.74	12.57	11.52	12.02	1.4	1.22	1.52	1	1.03	1.03
MnO	0.23	0.21	0.21	0.22	0.22	0.07	0.07	0.08	0.05	0.05	0.05
MgO	4.44	4.43	4.59	4.5	4.54	0.15	<0.10	0.43	0.26	0.24	0.26
CaO	5.82	5.82	6.63	5.68	5.48	5.34	5.41	5.9	4.46	4.14	4.39
Na_2O	5.77	5.79	5.26	5.81	5.8	0.15	<0.10	2.39	2.67	2.82	2.68
K_2O	0.2	0.1	0.4	0.13	0.1	2.99	3.06	2.07	1.42	1.35	1.39
P_2O_5	0.49	0.53	0.45	0.39	0.5	0.04	0.03	0.04	0.04	0.04	0.03
H_2O	0.16	0.13	0.22	0.2	0.17	0.19	0.23	0.32	0.24	0.22	0.22
LOI	1.88	2.47	1.67	2.04	2.12	6.32	6.36	5.85	4.59	4.26	4.51
sum	99.81	99.71	99.82	99.77	99.74	99.84	99.73	99.82	99.86	99.85	99.85

Table 2 Trace elements and REE compositions (in ppm) determined by ICP-MS and ICP-AES analysis of intrusive and surface rocks, Nang Ann prospect, central Thailand.

No	1	2	3	4	5	6	7	8	9	10	11
Areas	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann	Nang Ann
Sample name	NA-02	NA-03	NA-04	NA-05	NA-06	4265-02200-1	4265-02200-2	4265-09730	4265-10950-1	4265-10950-2	4265-10950-3
Rock types	microdiorite	microdiorite	microdiorite	microdiorite	microdiorite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite	quartz-phyric rhyolite
Li	10	10	10	10	10	<10	<10	10	<10	<10	<10
Sc	29	29	32	28	27	1	1	1	1	1	1
V	299	287	344	287	284	18	10	17	10	11	12
Cr	30	20	30	30	20	10	10	10	10	20	10
Ni	8	7	10	9	7	<1	<1	<1	<1	<1	<1
Cu	47	44	56	48	48	9	7	5	2	2	1
Zn	126	121	129	121	130	27	102	21	13	11	44
Ga	24.2	23.7	22.9	23	22.7	12.9	12.5	13.3	11.7	11.9	12
Rb	3.3	1.4	4.6	1.9	1.5	111	115	106	60.4	56.1	58.7
Sr	638	540	849	544	539	158	156.5	342	414	425	421
Y	63	59	51.5	51.3	58.2	8.2	7.5	9.3	7.9	7.5	7.6
Zr	246	230	196	229	231	92	85	93	96	95	90
Nb	13.7	11.4	9.6	9.8	10	6.3	5.6	4.7	5.4	5.4	5.3
Mo	1	1	1	1	1	36	26	<1	24	14	17
Sn	622	233	174	111	103	226	150	30	67	80	76
Cs	0.11	0.09	0.13	0.06	0.05	1.31	1.43	2.12	1.51	1.4	1.47
Co	26	27	30	27	26	<1	<1	<1	<1	<1	<1
Ba	91.4	79.3	182	73.8	132.5	245	263	64.4	68.5	64.1	65.2
La	17.3	17.3	14.8	15.3	16.2	21.1	30.8	19.2	18.6	15	17
Ce	43.7	42.9	37.4	38.4	40	40.1	58.6	36	35.5	29.1	32.2
Pr	6.47	6.68	5.79	5.82	6.17	4.63	6.48	4.06	4.05	3.41	3.87
Nd	31.7	32.6	27.9	28.5	29.9	16.5	22	14.8	14.4	12.3	13.7
Sm	8.89	9.16	8.25	8.11	8.7	2.49	3.09	2.4	2.36	1.97	2.14
Eu	3.22	3.44	3.09	3.1	3.24	0.4	0.37	0.7	0.44	0.4	0.45
Gd	11.1	11.3	9.43	9.57	10.7	1.76	1.96	1.82	1.69	1.52	1.59
Tb	1.73	1.77	1.5	1.59	1.76	0.25	0.26	0.25	0.21	0.21	0.23
Dy	11	10.4	9.25	9.41	10.65	1.35	1.23	1.42	1.24	1.19	1.2
Ho	2.3	2.14	1.86	1.95	2.23	0.28	0.26	0.31	0.26	0.25	0.24
Er	6.49	5.97	5.21	5.3	6.02	0.87	0.79	0.92	0.78	0.76	0.77
Tm	0.92	0.83	0.74	0.79	0.87	0.14	0.13	0.15	0.11	0.12	0.12
Yb	5.41	4.99	4.37	4.78	5.22	1.04	0.98	0.99	0.89	0.82	0.82
Lu	0.84	0.78	0.7	0.74	0.8	0.19	0.18	0.19	0.16	0.17	0.15
Hf	5.6	5.3	4.7	5.5	5.3	2.6	2.4	2.5	2.6	2.5	2.5
Ta	9.1	3.8	2.9	2.1	2.1	3.4	2.3	0.7	1.2	1.4	1.5
Tl	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	10
Pb	<2	5	2	3	6	<2	<2	5	<2	2	<2
Th	2.08	1.5	1.17	1.27	1.19	3.33	3.48	2.91	3.34	3.22	3.36
U	1.49	0.9	0.72	0.7	0.63	1.27	1.24	2.05	1.17	1.06	0

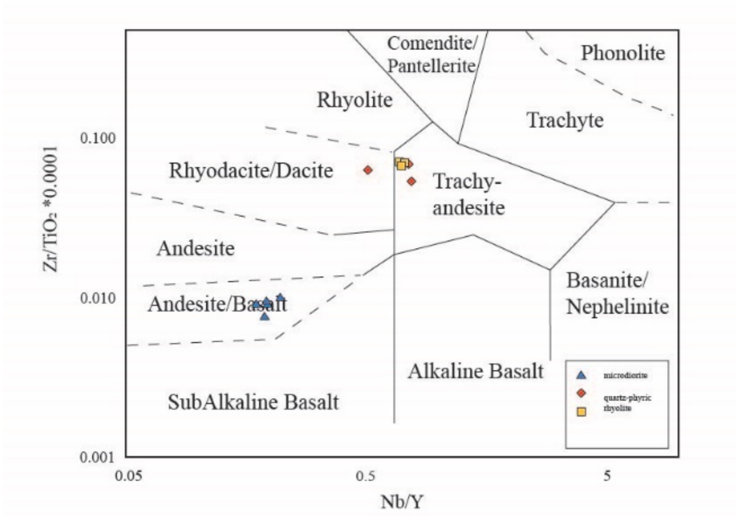

Figure 5 Nb/Y - Zr/TiO_2 discrimination diagram for the Nang Ann intrusive and surface rocks from Winchester and Floyd (1979).

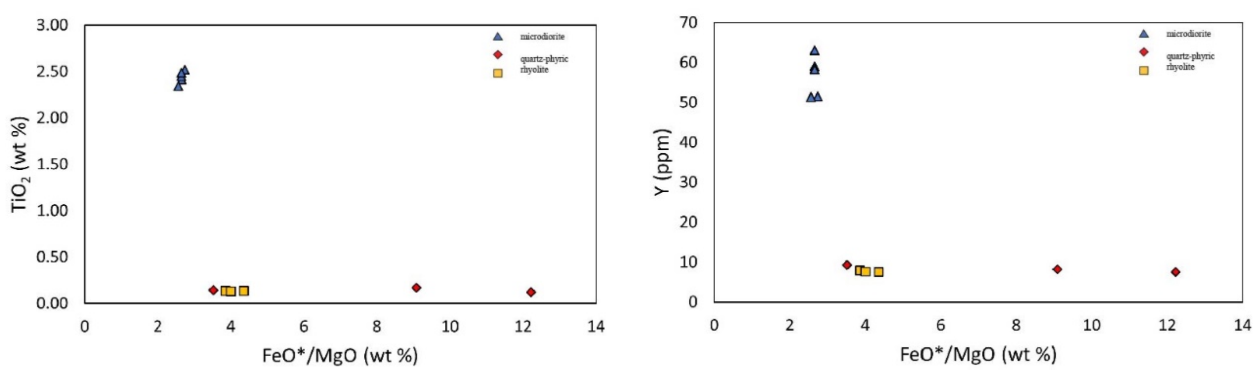

Figure 6 Major elements and selected high field strength elements (HFSE), trace elements and LREE bivariate diagram plotted as function of FeO*/MgO for the intrusive and surface rocks from the Nang Ann prospect. A. TiO2 - FeO*/MgO, B. Y - FeO*/MgO.

The chondrite-normalized plot provides further evidence of the existence of at least three distinct magmatic suites within the Nang Ann area (Fig. 7). The microdiorite samples display distinctive flat patterns, suggesting that they were derived from primitive magma sources. On the other hand, the quartz-phyric rhyolite samples exhibit pronounced enrichment in light rare earth elements (LREE) and depletion in heavy rare earth elements (HREE), along with a negative europium (Eu) anomaly. This pattern suggests that these intrusives originated from fractionated magma sources. Interestingly, one of the rhyolite samples displays a similar pattern to the quartz-phyric rhyolite but lacks the Eu anomaly. This variation may indicate a slight difference in the magma source or evolution. Overall, microdiorite samples tend to exhibit higher abundances of rare earth elements (REE) compared to quartz-phyric rhyolite samples.

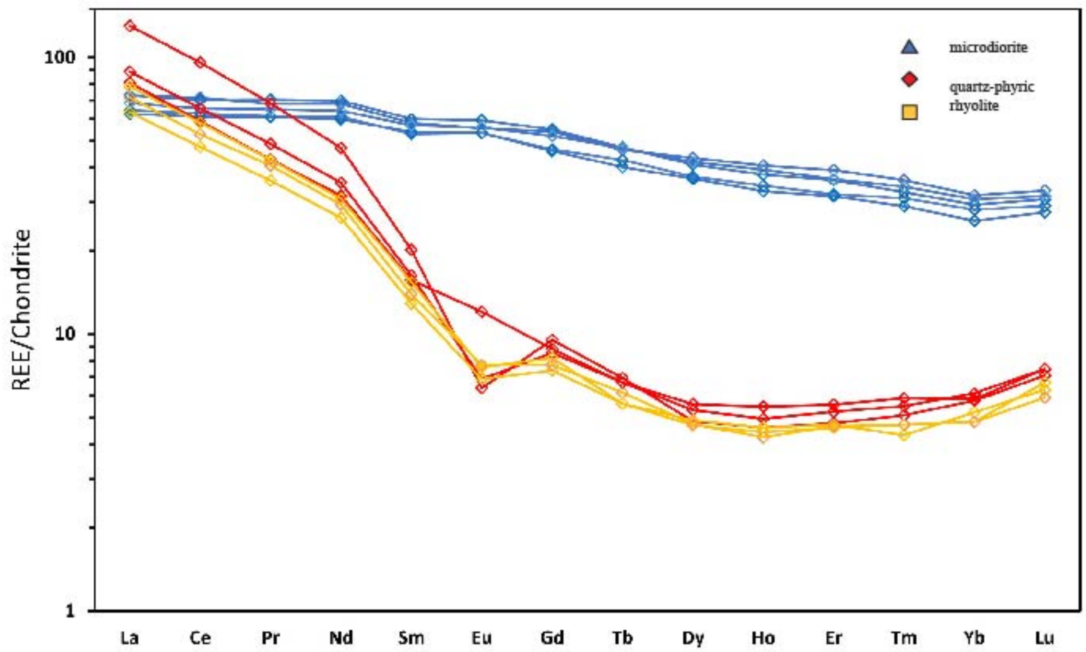

Figure 7 Chondrite-normalized REE patterns of representative intrusive volcanic and surface rocks plotted using normalizing values of Sun and McDonough (1989).

The AFM (alkali oxide - iron oxide - magnesium oxide) diagram is utilized to assess the relative proportions of alkali oxide (Al_2O_3), iron oxide (Fe_2O_3), and magnesium oxide (MgO) in order to determine the magma series. In the case of Nang Ann, both the microdiorite and quartz-phyric rhyolite samples are classified as belonging to the calc-alkaline series based on their positions in the AFM diagram (Fig. 8).

The Co - Th diagram proves to be a valuable tool in the classification and determination of magma series for the Nang Ann rocks. Based on the analysis, the microdiorite sample is classified as basaltic andesite within the calc-alkaline series. The quartz-phyric rhyolite samples, on the other hand, are identified as dacite and rhyolite, both falling under the calc-alkaline series. Dacite represents an intermediate volcanic rock composition, while rhyolite represents a felsic volcanic rock composition. (Fig. 9).

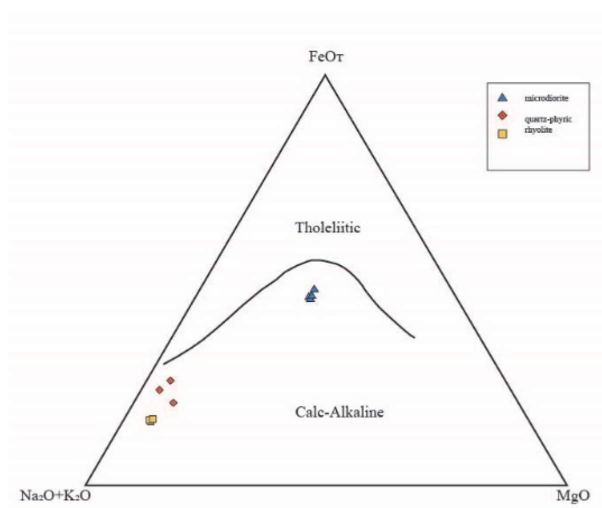

Figure 8 AFM diagram of the intrusive and surface rocks at the Nang Ann prospect from Irvine & Baragar (1979).

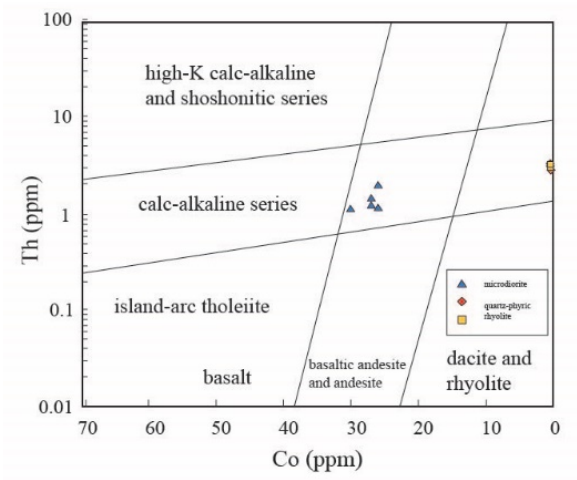

Figure 9 Co - Th diagram of the intrusive and surface rocks at the Nang Ann prospect from Wang et al. (2010).

The discrimination diagram proposed by Pearce et al. (1984) serves as a valuable tool for determining the tectonic setting of granitic rocks, but it can also be applied to more mafic intrusive and volcanic rocks. By examining the plots of Nb versus Y, we can gain insights into the origins of the microdiorite samples. The analysis reveals that one microdiorite sample originated from both within-plate and ocean ridge settings. Another sample exhibits characteristics indicative of a volcanic arc origin and a syn-collision origin, suggesting its formation in a setting related to subduction or collision events. Moreover, by examining the plots of Rb versus Y+Nb, we can further determine the tectonic affinities of the microdiorite samples. One sample displays an A-type affinity, suggesting its within-plate origin with alkaline characteristics, while also exhibiting an OR-type affinity associated with processes occurring along ocean ridges. The other sample exhibits an I-type affinity, indicating its formation within a volcanic arc setting (Figs. 10 and 11).

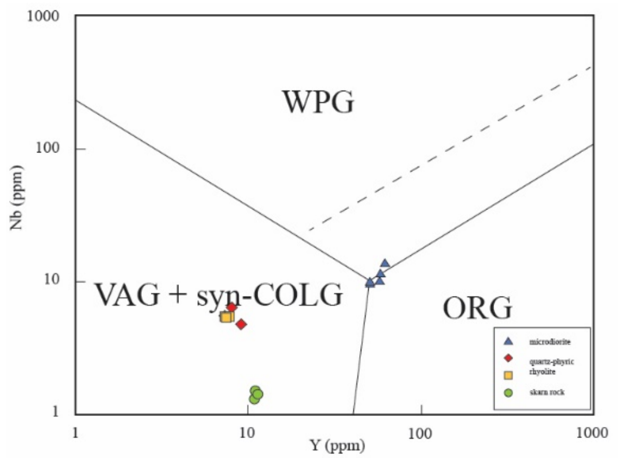

Figure 10 Nb – Y discrimination diagram of the intrusive and surface rocks at the Nang Ann prospect (after Pearce et al., 1984).

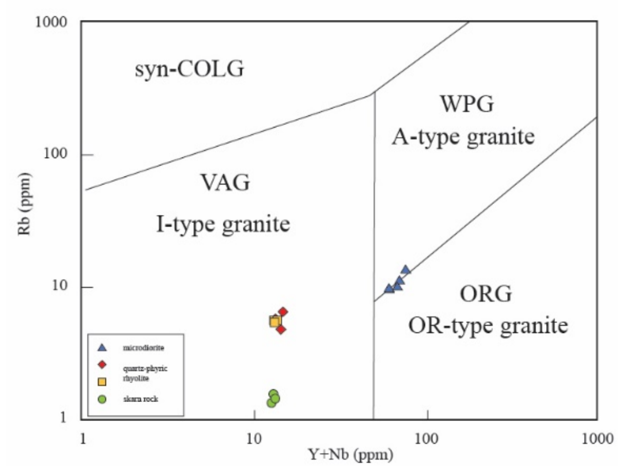

Figure 11 Rb - (Y + Nb) discrimination diagram of the intrusive and surface rocks at the Nang Ann prospect (after Pearce et al., 1984).

5. Discussion

5.1 Geology of Nang Ann prospect

The geological setting of the Nang Ann prospect can be divided into four units and one suite: Fossiliferous limestone unit, Siltstone unit, Polymictic rhyolitic sandstone/breccia unit, Quartz-phyric rhyolite unit and Microdiorite suite.

The fossiliferous limestone unit has been discovered at the center of the study area. This unit is composed of limestone containing various fossils. It consists of micrite, which is a fine-grained carbonate mud, and allochems, which are fossil fragments within the rock. The allochemical constituents include oolites, foraminifera, brachiopods, and crinoid stems. This particular unit is classified as a fossiliferous biomicrite according to Folk (1959) and as a mudstone according to Dunham (1962). It is correlated with the Pha Nok Khao Formation, as identified by Chonglakmani and Sattayarak (1984). The age of this formation is determined based on the presence of abundant index fossils, such as fusulinids and corals, which indicate its deposition during the lower to middle Permian era.

The siltstone unit is a type of sedimentary rock found in the subsurface, intercalated with polymictic rhyolitic sandstone/breccia units. This unit primarily consists of siltstone with various types of alteration. Siltstone is a fine-grained rock composed of predominantly clay minerals and quartz.

The polymictic rhyolitic sandstone/breccia units are a type of volcanogenic sedimentary rock that exhibit a variety of clast sources. These units contain volcanic clasts, including andesite, rhyolite, and crystal-rich andesitic sandstone. Additionally, sedimentary clasts such as siltstone and mudstone are present. The crystal clasts consist of quartz, orthoclase, and plagioclase minerals. The matrix of the rock is composed of quartz, orthoclase, plagioclase, and volcanic glass. Notably, calcite veins and pyrite are observed within the rock, adding to its overall texture.

The quartz-phyric rhyolite unit is a coherent volcanic rock that intrudes as part of the Polymictic rhyolitic sandstone/breccia units and Siltstone unit. This unit exhibits both phyric (containing phenocrysts) and aphyric (without phenocrysts) rhyolite compositions. Quartz is a prominent phenocryst present in the phyric rocks. The primary rock-forming minerals within this unit include quartz, orthoclase, and plagioclase. The unit has undergone significant alteration, with quartz, chlorite, and epidote being the major secondary minerals observed. Additionally, this unit has been classified as trachy-andesite and rhyodacite/dacite according to the classification proposed by Winchester and Floyd in 1979. Another classification by Wang et al. (2010) identifies it as dacite/rhyolite.

The three mentioned units can be correlated with volcanic or volcanogenic sedimentary rocks dating back to the late Permian to early Triassic period. Based on the available evidence, the age of these units is inferred to range from the late Permian to the lower Triassic era (Salam et al., 2014).

The microdiorite suite is a coherent volcanic rock found at the central region. It exhibits a phaneritic and hypabyssal texture, indicating its intermediate cooling history. The dominant rock-forming minerals in the microdiorite are plagioclase and clinopyroxene. Additionally, pyrite is disseminated within the rock texture, adding to its mineral composition. The age of microdiorite inferred as late Triassic era (Salam et al., 2014). The microdiorite suite is classified as andesite/basalt (Winchester and Floyd, 1979) and basaltic andesite/andesite (Wang et al., 2010).

5.2 Magma affinity and tectonic implication of Nang Ann prospect

The magmatic suite at the Nang Ann prospect can be classified into two distinct groups: an intermediate to mafic suite and a felsic suite, as determined by bivariate plots of major elements and immobile elements relative to FeO*/MgO. The first suite is exemplified by the microdiorite samples obtained from the surface area, which display distinct major element patterns. Furthermore, two additional geochemical suites of intrusive rocks have been identified. These suites exhibit geochemical characteristics that indicate the absence of element remobilization resulting from alteration processes or fractional crystallization.

The chondrite-normalized patterns of rare earth elements (REEs) show distinct characteristics for the intermediate to mafic suite and the felsic suite. The intermediate to mafic suite exhibits flat REE patterns, indicating a primitive magma source. On the other hand, the felsic suite shows high light rare earth elements (LREE) and low heavy rare earth elements (HREE) patterns, along with a negative europium (Eu) anomaly, suggesting a source that underwent fractionation processes. The REE patterns were plotted using normalization values provided by Sun and McDonough (1989).

The magma affinity of the Nang Ann predominantly suggests a calc-alkaline series, as indicated by Irvine and Baragar (1979) and Wang et al. (2010). The calc-alkaline series is characterized by magmas with elevated levels of alkali oxides and iron oxides and is commonly associated with subduction zones and volcanic arcs.

Based on the magma affinity, the tectonic setting of the Nang Ann region indicates the presence of two distinct origins within the mafic to intermediate suite. One suite displays features consistent with within-plate and ocean ridge settings. The other suite exhibits characteristics associated with volcanic arcs and syn-collision settings, suggesting its formation in areas influenced by subduction or collision processes. These findings align with the classification proposed by Pearce et al. (1984).

6. Conclusion

1. The Nang Ann prospect is characterized by the presence of five distinct geological units: the fossiliferous limestone unit, siltstone unit, polymictic rhyolitic sandstone/breccia units, quartz-phyric rhyolite unit, and Microdiorite suite. The fossiliferous limestone unit is dated to the lower to middle Permian era and is correlated with the Pha Nok Khao Formation. The siltstone unit, polymictic rhyolitic sandstone/breccia units, and quartz-phyric rhyolite unit are inferred to be from the upper Permian to late Triassic era and are correlated with the Permo-Triassic volcanic rocks. The Microdiorite suite, on the other hand, is determined to be of late Triassic age.

2. The geochemistry of the Nang Ann prospect can be categorized into two distinct suites: the intermediate to mafic suite and the felsic suite. The intermediate to mafic suite encompasses trachy-basalt and andesite/basalt compositions. These rocks exhibit flat patterns in their rare earth element (REE) distribution, indicating a primitive magma source. The tectonic setting for this suite suggests formation within a plate origin and/or an ocean ridge origin. On the other hand, the felsic suite consists of dacite, trachy-andesite, and rhyodacite/dacite compositions. These rocks exhibit high light rare earth element (LREE) and low heavy rare earth element (HREE) patterns, along with a negative Eu anomaly, which indicates a magma source influenced by fractionation processes. The tectonic setting associated with this suite suggests formation in a volcanic arc origin. Overall, both suites predominantly exhibit characteristics that align with the calc-alkaline series, which is indicative of their magma affinity.

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