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PETROGRAPHY OF IRON SKARN AT KHAO LEK, AMPHOE NONG BUA, CHANGWAT NAKHON SAWAN

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Project Advisor	Associate Professor Pitsanupong Kanjanapayont, Ph.D.

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(Associate Professor Pitsanupong Kanjanapayont, Ph.D.)

นาถมงคล ส่งเสริม: ศิลาวรรณาของหินเหล็กสการ์นบริเวณเขาเหล็ก อำเภอหนองบัว จังหวัดนครสวรรค์. (PETROGRAPHY OF IRON SKARN AT KHAO LEK, AMPHOE NONG BUA, CHANGWAT NAKHON SAWAN).
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สการ์นเป็นหินแปรที่เกิดจากกระบวนการแปรสัมผัสแบบมีการแลกเปลี่ยนไอออนระหว่างมวลหินอัคนีกับหินท้องที่ ซึ่งโดยทั่วไปแล้วมักเป็นหินคาร์บอเนต หินสการ์น มักเกิดแบบแทนที่อยู่ในหินอัคนี เรียกว่า เอนโดสการ์น และในหินท้องที่ เรียกว่า เอกโซสการ์น เอกโซสการ์นจะให้โซนแร่ต่าง ๆไป ซึ่งจะเรียกชื่อขึ้นตามแร่ที่เด่น ๆในแต่โซน โซนแร่ที่มักพบทั่วไปในหินสการ์นได้แก่ การ์เนตโซน ไพรอกซีนโซน และโวลาสโทไนต์โซน หรือ ไพรอกซีนอยด์โซน จากงานวิจัยในอดีตพบว่า การเกิดสินแร่มีค่าของแหล่งแร่แบบสการ์น มักเกิดตามแนวรอยต่อระหว่างสการ์นกับหินสการ์น หรือ ระหว่างสการ์นกับหินท้องที่ที่ไม่โดนแปรสภาพ หินสการ์นบริเวณเขาเหล็กเกิดอยู่ในหินสองประเภทคือ หินภูเขาไฟ และหินคาร์บอเนต ซึ่งต่างจากสการ์นทั่วไปที่พบ ดังนั้นการศึกษาโซนแร่ของสการ์นและวิวัฒนาการของสการ์น จะแสดงตำแหน่งของโซนแร่ให้ชัดเจนยิ่งขึ้น

จากการศึกษาทางศิลาวรรณาและการสำรวจในภาคสนาม พบว่าเขาเหล็กสการ์นเป็นแหล่งแร่เหล็กสการ์น ซึ่งจากผลศึกษาพบว่าประเภทของหินท้องที่ส่งผลต่อการเกิดโซนแร่และการแผ่ขยายของหินสการ์น โดยหินสการ์นจะแผ่ขยายในหินท้องที่ภูเขาไฟน้อยกว่าในหินท้องที่คาร์บอเนต จากการสังเกตในระดับจุลภาค พบว่าระยะความห่างกับหินอัคนีส่งผลต่อลักษณะทางศิลาวรรณาของผลึกแร่การ์เนต โดยบริเวณที่ใกล้กับหินอัคนี สการ์นจะมีปริมาณของ แอนไอโซทรอปิกการ์เนต และแสดงลักษณะของโซนนิ่งมากกว่าในบริเวณที่ห่างออกไปซึ่งจะมีแค่ไอโซทรอปิกการ์เนต จากผลการศึกษาและข้อมูลทั้งหมด นำไปสู่การแปลความหมายถึงวิวัฒนาการของหินสการ์นในพื้นที่ ซึ่งสันนิษฐานว่าแมกมาที่ทำให้เกิดสการ์นน่าจะมีขนาดเล็ก เนื่องจากพบสการ์นกระจายตัวอยู่แค่ในบริเวณพื้นที่ศึกษาเขาเหล็กเท่านั้น

ภาควิชา ธรณีวิทยา ลายมือชื่อนิสิต ....
สาขาวิชา ธรณีวิทยา ลายมือชื่อ อ.ที่ปรึกษาโครงงาน ....
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NARTMONGKHOL SONGSERM : PETROGRAPHY OF IRON SKARN AT KHAO LEK, AMPHOE NONG BUA, CHANGWAT NAKHON SAWAN.
ADVISOR: ASSOCIATE PROFESSOR PITSANUPONG KANJANAPAYONT, Ph.D., 66 pp.

Skarn is a metamorphic rock occurred by contact metasomatism between igneous and country rocks which generally is carbonate host. It usually forms as replacement both in igneous, endoskarn, and in country rocks, exoskarn. In exoskarn, it commonly has mineral zonation based on dominant minerals in each zone. Those zones commonly consist of garnet skarn, pyroxene skarn and wollastonite or pyroxenoid skarn. Moreover, from previous works, they found that ore mineralization is commonly formed at boundary between endo- and exoskarn or between exoskarn and non-metasomatized rocks. Khao Lek Fe skarn deposit situates in the western part of Loei Fold Belt. Its host rocks of Khao Lek skarn consists of volcanic and carbonate rocks. So, study about skarn zonation in different types of host rock and its evolution maybe help us to interpret and identify location of ore zone.

According to petrographic study and field observation, the result that Khao Lek skarn is iron skarn deposit. The result shows that types of host affected to skarn extension and mineralization also. Skarn in volcanic host commonly extended less than in carbonate host. Moreover, from microscopic observation, the proximity of skarn caused petrographical variation in garnet crystals. The proximal zone is usually containing anisotropic and zoned garnet rather than in distal zone. The interpretation of Khao Lek skarn evolution and is that the magma causing iron skarn deposit should come as small intrusive body because it is occurred as local scale.

Department: Geology Student's Signature ....
Field of Study: Geology Advisor's Signature ....
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Secondly, I would like to thank Mr. Arthit and S.K. mineral company for convenience to go to quarry section in study area and others facilitation during working in the field.

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Finally, I would like to thank my classmates for their willingly helping and wonderful suggestion.

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CHAPTER 1
INTRODUCTION

1.1 Background

Skarn is a metamorphic rock which generally occurred by contact metasomatism between igneous and carbonate rocks. Exchanging chemical composition of each other caused skarn formation at contact boundary. This rock composed elements that came from both magma and country rock and formed to new minerals. Those minerals mostly were calcsilicate group such as garnet, wollastonite. Evolution of skarn began with isochemical metamorphism and then followed with bimetasomatism which caused circulation of hydrothermal fluid around contact boundary and gave "reaction or prograde skarn." Finally, it will occur hydrothermal alteration and form "retrograde skarn." Reaction skarn that occurred can be divided into mineral zones following a dominated mineral in that zone. Those zones commonly consisted of garnet skarn, pyroxene skarn and wollastonite or pyroxenoid skarn (Meinert et al. 2005). However, these zones may not be found completely all zones and some minerals can be altered to lower temperature minerals; for example, garnet-pyroxene changed to epidote-chlorite.

Skarn is important to economy because they usually give many types of ore. Common metals which are found with skarn may include iron, tungsten, tin, molybdenite and base metals (copper lead zinc). We call this ore deposit as "skarn deposit". In Thailand, there are many skarn deposits in central and northeastern regions along Loei fold belt which both be mining or just prospecting such as Phu Hin Lek Fai (copper-gold prospect), Phu Thap Fah (gold mine), Khao Phanom Pha (gold mine), Khao Phra Ngam (copper prospect), Singto (iron-copper prospect) etc. (Zaw K. 2014). In Loei fold belt, ages of skarn host rocks mostly are Ordovician, Carboniferous or Permian which usually are carbonate rock but there are some other rocks too such siliclastic rocks or volcaniclastic rocks. For igneous rocks of skarn deposit in this belt mostly are felsic to intermediate composition and have age in late Permian to Triassic (Kromkhun et al. 2013).

Khao Lek have been found skarn which also gave iron ore and opened mine. Skarn of this area occurred in carbonate rock associated with volcanic rock that special than other deposits in Loei belt. For this reason, researcher is interested to study about mineral zone that may be affected from associating with volcanic rock. In this project, will focus on studying petrographical characteristics of this skarn to classify the mineral zone.

1.2 Objectives

a) To classify mineral zonation of iron skarn by using petrographical characteristics.
b) To create a simple model describing the formation of iron skarn at Khao Lek, Nakhon Sawan province.

1.3 Study Area

The study area situates in mine of S.K. mineral Co., Ltd. which is located in Khao Lek, Tung Thong sub district, Nong Bua district, Nakhon Sawan province. Khao Lek is isolated mountain which conform from ridge located in southwestern part of Loei fold belt at boundary between Nakhon Sawan and Phetchabun. The area covers latitude 15°53’30”N to 15°54’02”N and longitude 100°56’24”E to 100°47’14”E. Khao Lek covers area approximately 48 kilometers’ square. Accessing study area can get by going to north of Bangkok along Phahon Yothin road. Then move to northwest toward highway number 32 and turn to northeast entering to highway number 11. Following the path and then turn to east again toward highway number 225 and follow the road. Finally, turn to the north and enter to Tung Thong sub district, Nong Bua district, Nakhon Sawan province. Total distance from Bangkok to the study area around 300 kilometers.

1.4 Scope of Study

This project focuses on studying formation and classifying mineral zonation of iron skarn at Khao Lek, Nakhon Sawan province by using petrographical data. However, the study will ignore ore genesis that associated with skarn. This work takes 8 months from September, 2016 to May, 2017. The independent variable in this study is type of country rock and the dependent variable is mineral zonation of skarn.

1.5 Expected Results

a) Mineral zonation of iron skarn from petrographical characteristics.
b) Simple model describing the formation of iron skarn at Khao Lek,
Nakhon Sawan province.

1.6 Method of Investigation

The method of study can be divided into 6 phases as showing in figure 1.2. Firstly, it began with selection the suitable area and then specifying boundaries and objective of project. Secondly, we would be planning and reviewing data from previous works which related to geology of Khao Lek area or nearby area, definition of skarn and also general model of skarn formation, deposit geology in Loei fold belt.

Next phase of study is filed investigation which was carried out during September, 2016 and again in January, 2017. This step included collecting sample and orientation data of skarn zone. Rocks that was collected are 20 samples which composed of volcanic rocks, carbonate rocks and skarns. Each sample has size about 15 x 15 x15 cubic centimeters. Following this step, we will study petrographical features of those rocks by using slab for mesoscopic scale and thin section for microscopic scale. Then evaluating data both from the field and laboratory for interpreting skarn formation, analyzing their mineralogy and creating conceptual model of skarn deposit in Khao Lek area. Finally, it would be discussion and conclusion also writing report and presentation.

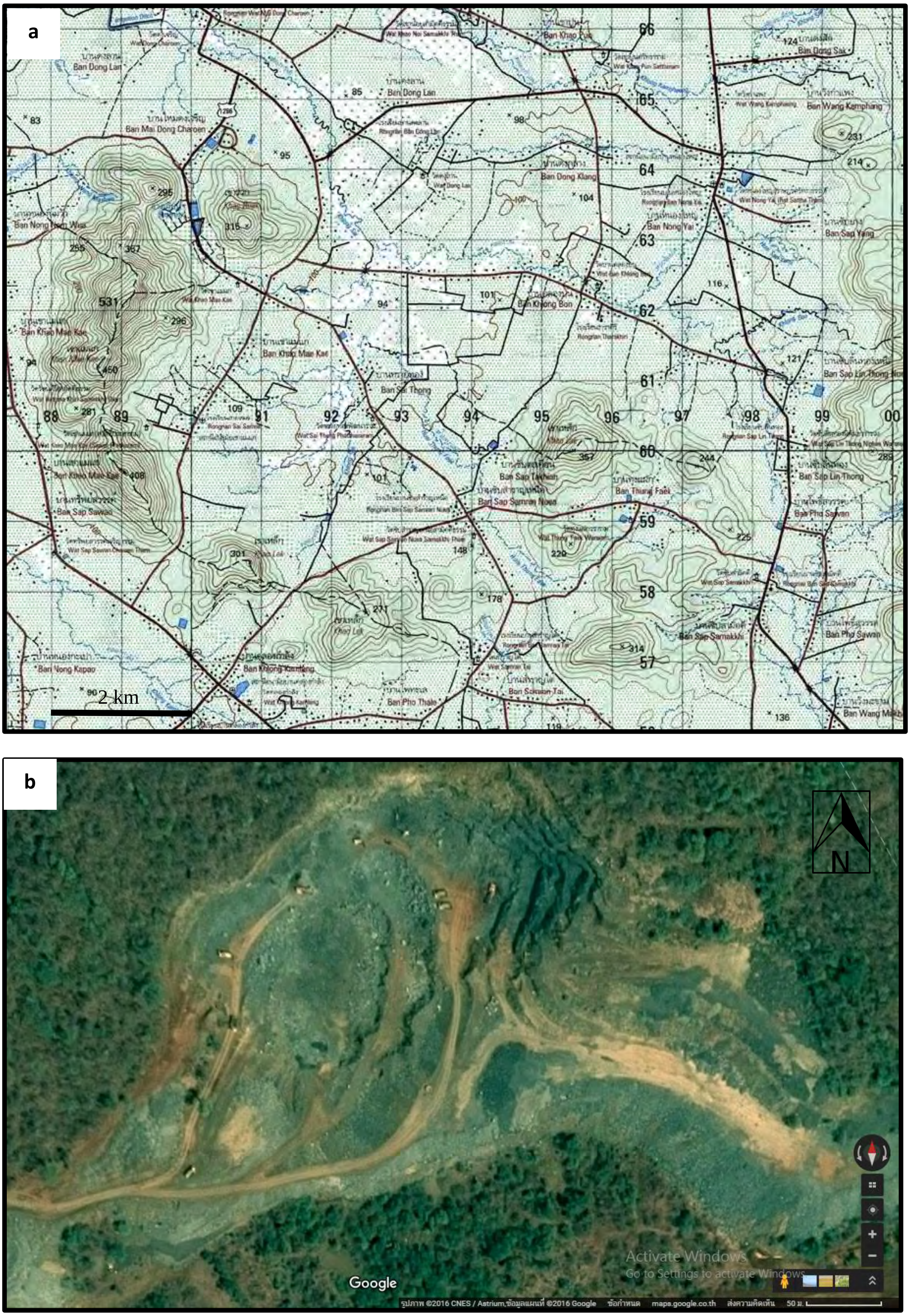


Figure 1.1 a.) Topographic map. b.) Google earth image of study area.

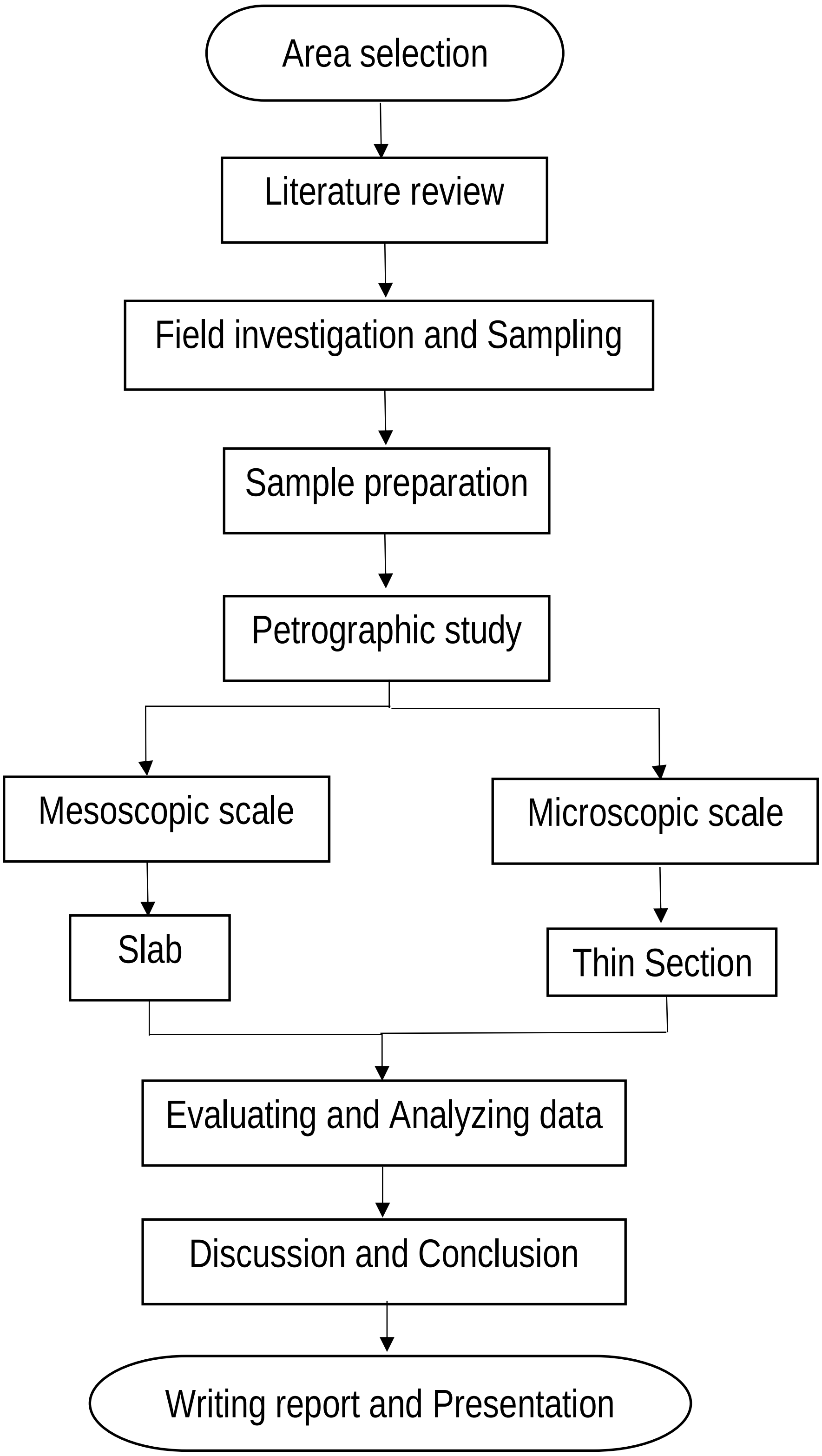


Figure 1.2 Flow chart summarized the method of study.

CHAPTER 2
GENERAL GEOLOGY

2.1 Tectonic Setting

Khao Lek Fe skarn deposit situated in the western part of Loei Fold Belt which is in North-South trending along western margin of Indochina terrane bounded with Nan-Sra Kaeo suture and extending from Laos trough Loei-Phetchabun provinces in Thailand to Sra Kaeo and continuing to the west of Cambodia. This belt has many ore deposits such as Phu Kham (Cu-Au skarn), Chartree (Au-Ag epithermal), Khao Phanom Pha (Cu-Au skarn), Khao Phra Ngam (Cu skarn) and Khao Lek (Fe skarn).

In Thailand, there are two microcontinents rifted from Gondwana. Indochina rifted from northwestern part in the Devonian and Shan-Thai rifted from northeastern part in the Early Permian (Metcalfe, 2005), they drifted northwards to merge together in the Triassic forming Loei Fold Belt and causing arc magmatism along the belt.

Salam (2014) proposed tectonic evolution of Loei Fold Belt that formed as subduction of Paleotethys which is in between two terranes beneath Indochina terrane beginning in Late Permain. Early subduction caused emplacement of igneous rocks along central part of Loei Fold Belt that gave Au-Ag epithermal mineralization in that area. Afterwards, they continually have partial melting created intrusion in Middle Triassic and provided Cu-Mo porphyry mineralization. After that, when Shan-Thai and Indochina terranes have collided and come to close together, there was post-collision granitoids (210 Ma) emplaced into Sukhothai Fold Belt.

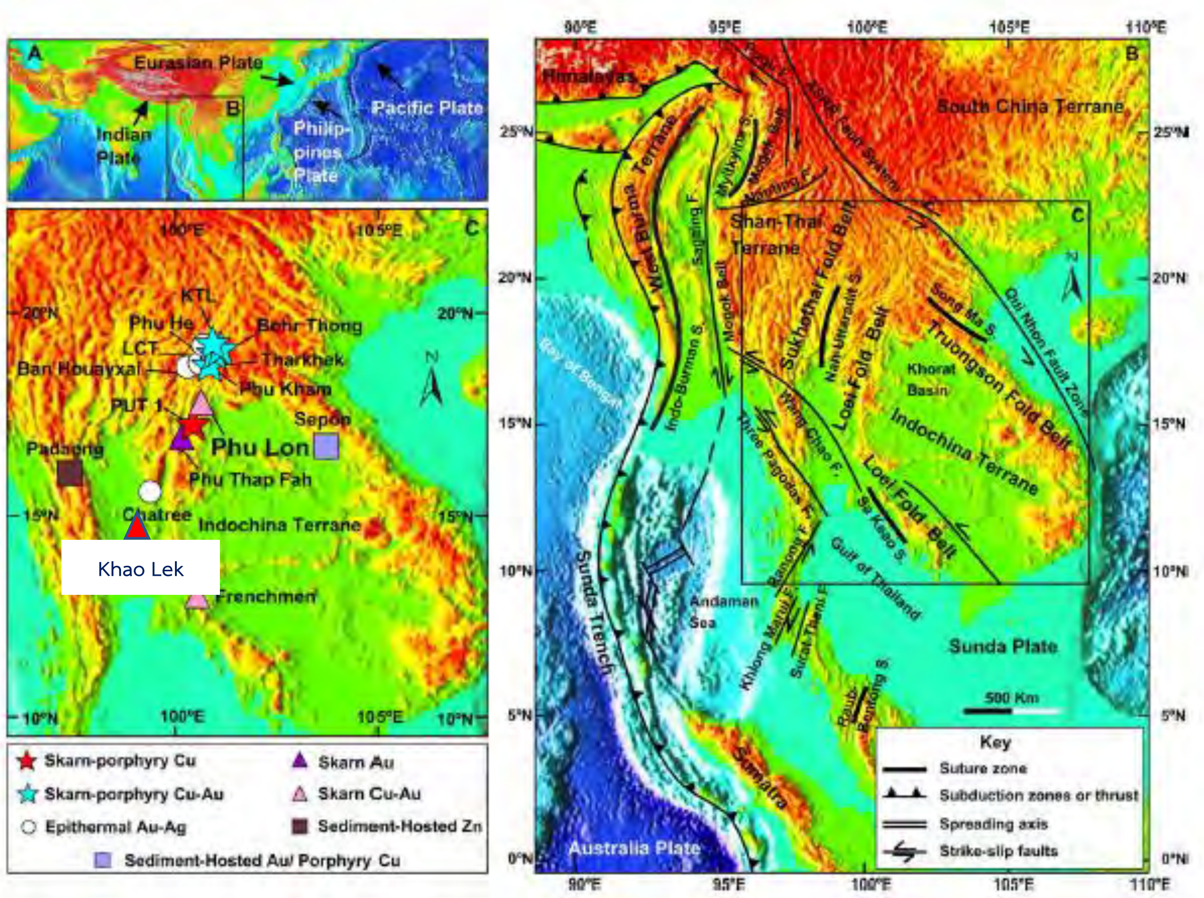


Figure 2.1 Tectonic setting in study area.

a.) Map is illustrating the tectonic plates in Asia and their relative movement.

b.) Map is illustrating major terranes, suture, faults and active subduction zone in Southeast Asia mainland.

c.) Map is illustrating location of major ore deposit along Loei Fold Belt. (Modified from Kamvong & Zaw, 2009)

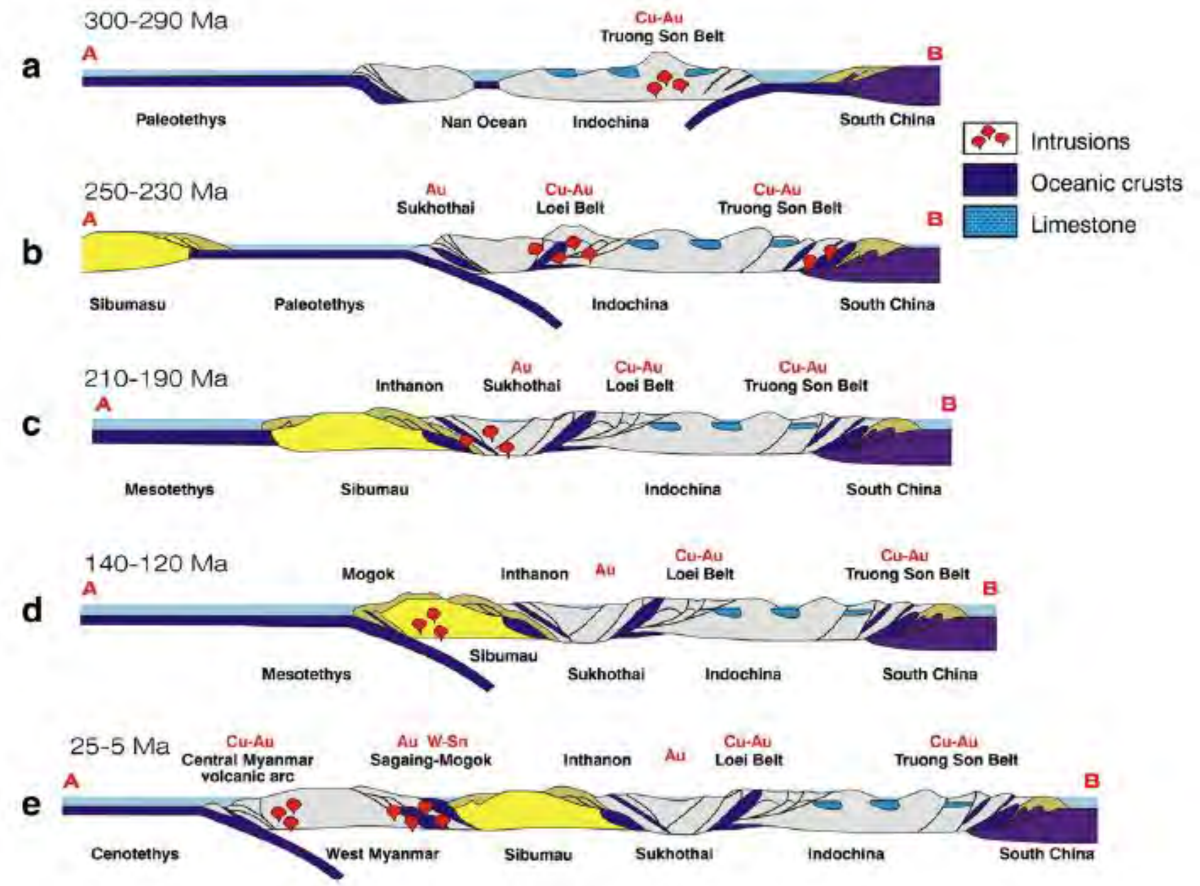


Figure 2.2 Schematic diagram of tectonic evolution of Loei Fold Belt. (Salam, 2014)

2.2 Regional Geology

The geology around Khao Lek area covers both in the eastern part of Nakhon Sawan and western part of Phetchabun. The most up-to-date geological data that related with study area is geological map complied by Khositanont (2008). The regional area that we are concerning lay between latitude 15° 50' N to 16° 00' N and longitudes 100° 45' E to 101° 00' E which is including Ban Sap Samran, Ban Khao Mae Kae and Ban Thung Faeg. Moreover, we also have another geological map that related with study area complied by Nakornsri (1977) and mineral resource maps made by Premmanee et al. (2001). In this area, rocks consist of the sedimentary rocks which is mainly in Permian age and the igneous rocks in Permian to Triassic age. It also developed Quaternary terraces covering about 40% of the regional area

The Permian rocks are abundant in carbonate rocks of Saraburi Group distributed in eastern part of the area, at Phetchabun province mainly found Tak Fa formations. The igneous rocks are predominated with volcanic rocks of Permo-Triassic age and some plutonic rocks in Triassic age. The description of the main rock units that found in the area is in following paragraph.

The volcanic rocks in the Phetchabun area are mainly consisted of intermediate to basic rocks. They are extensively distributed in the Phetchabun and Phichit Provinces. Two volcanic units as well as two plutonic units mostly represent the volcanic and plutonic rocks in the regional area, Phetchabun area. Those units composed of Thung Faeg volcaniclastic, Sap Samran basalt and diabase, Khao Lek diorite, and Khao Mae Kae diorite units (Khositanont, 2008).

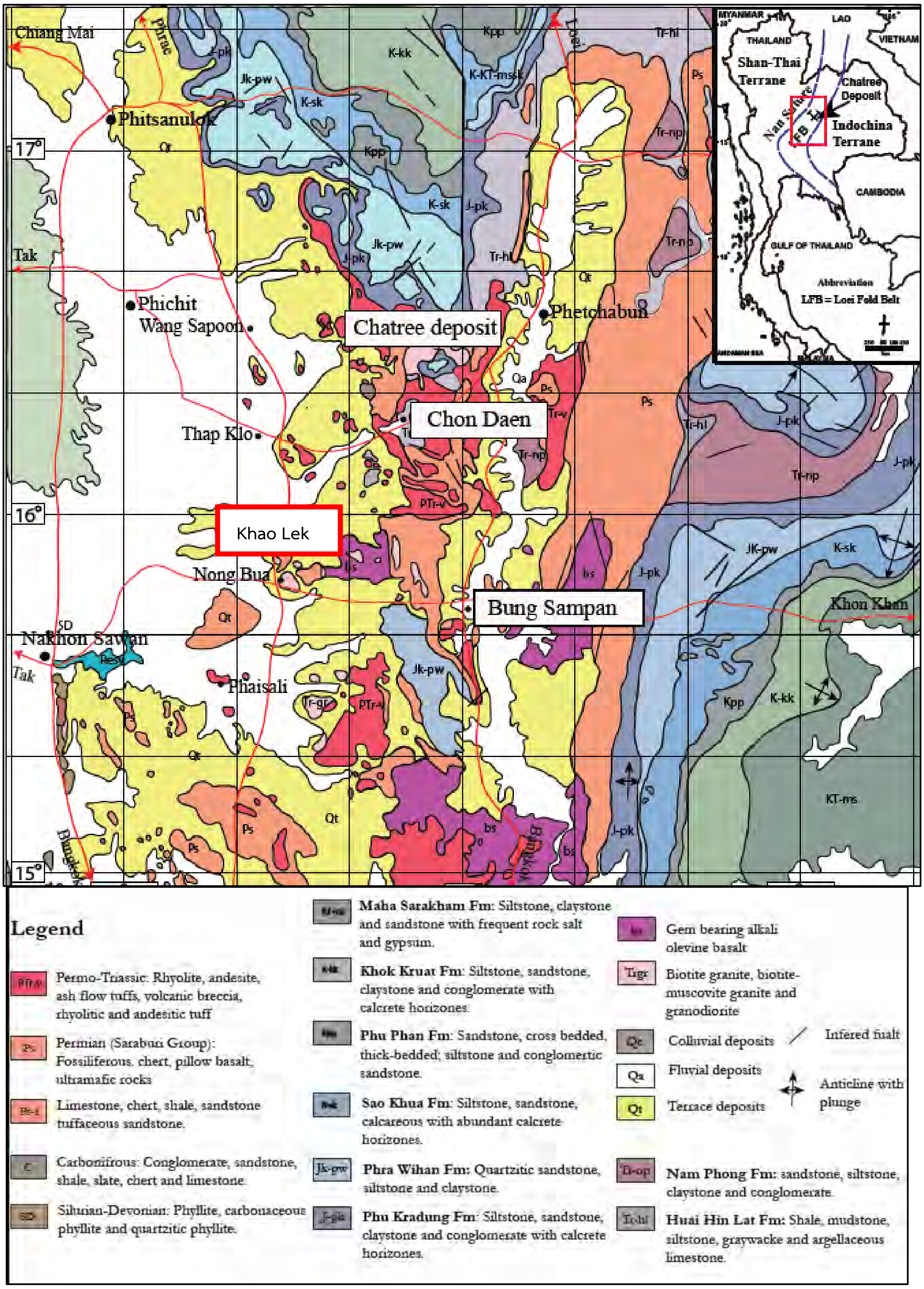


Figure 2.3 Regional geologic map showing Khao Lek area compared with Chatree, Bung Sampan and Chon Daen rocks. (Modified from Salam, 2014)

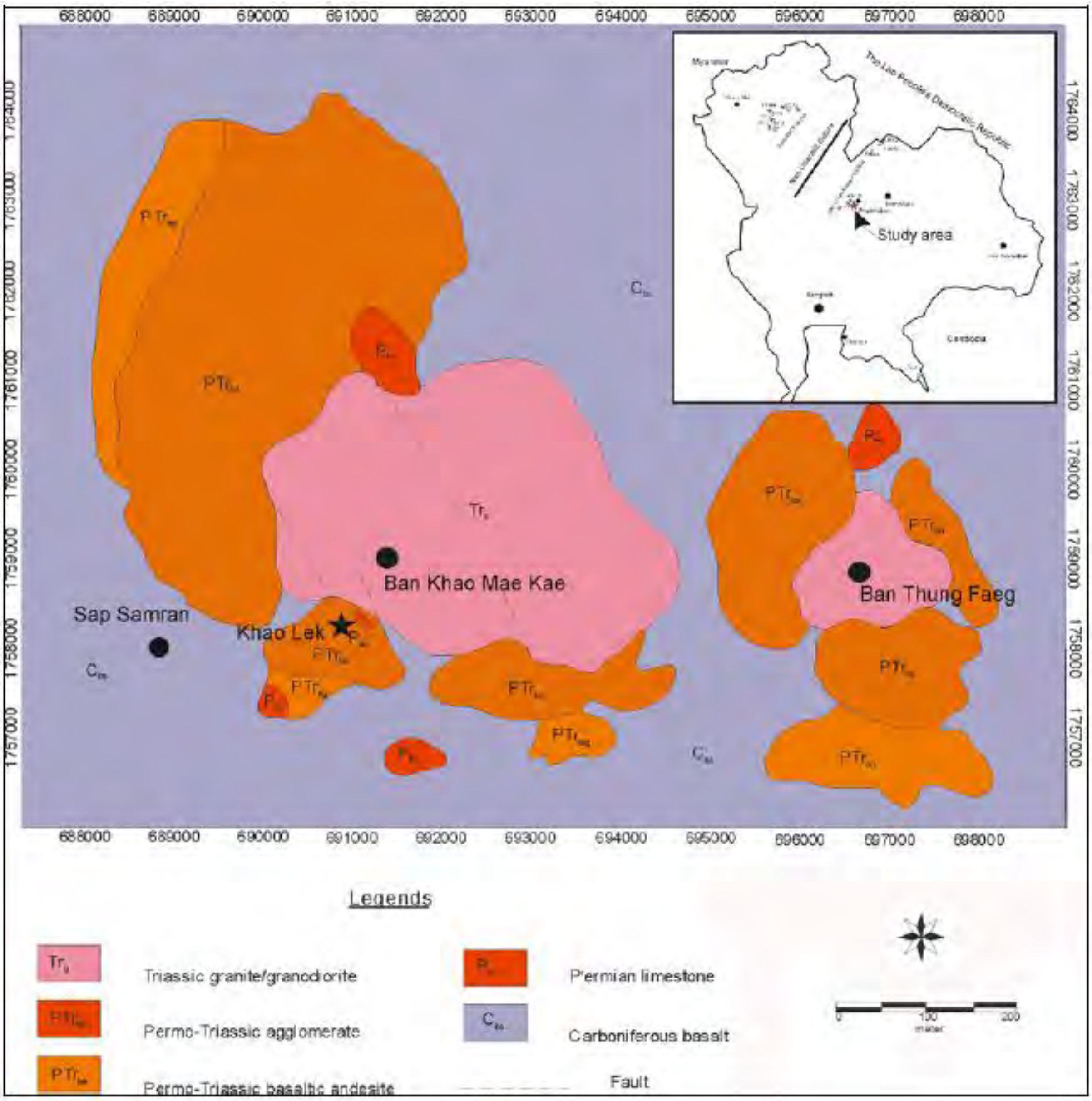


Figure 2.4 Geological map of Khao Lek and Khao Mae Kae areas showing distribution of volcanic and plutonic rocks in the Khao Lek and Ban Thung Faeg area. (prepared by Khositanont, 2008)

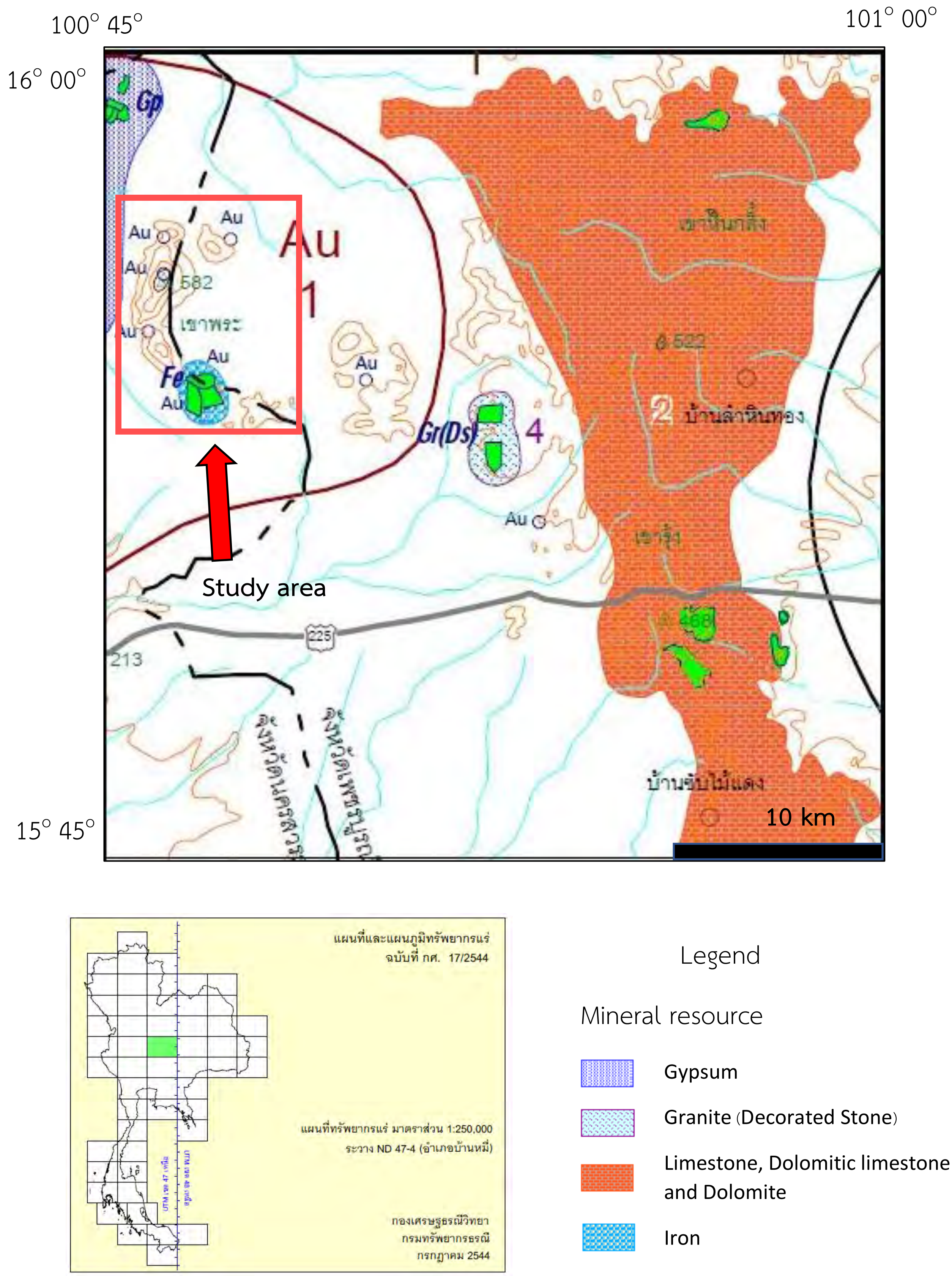
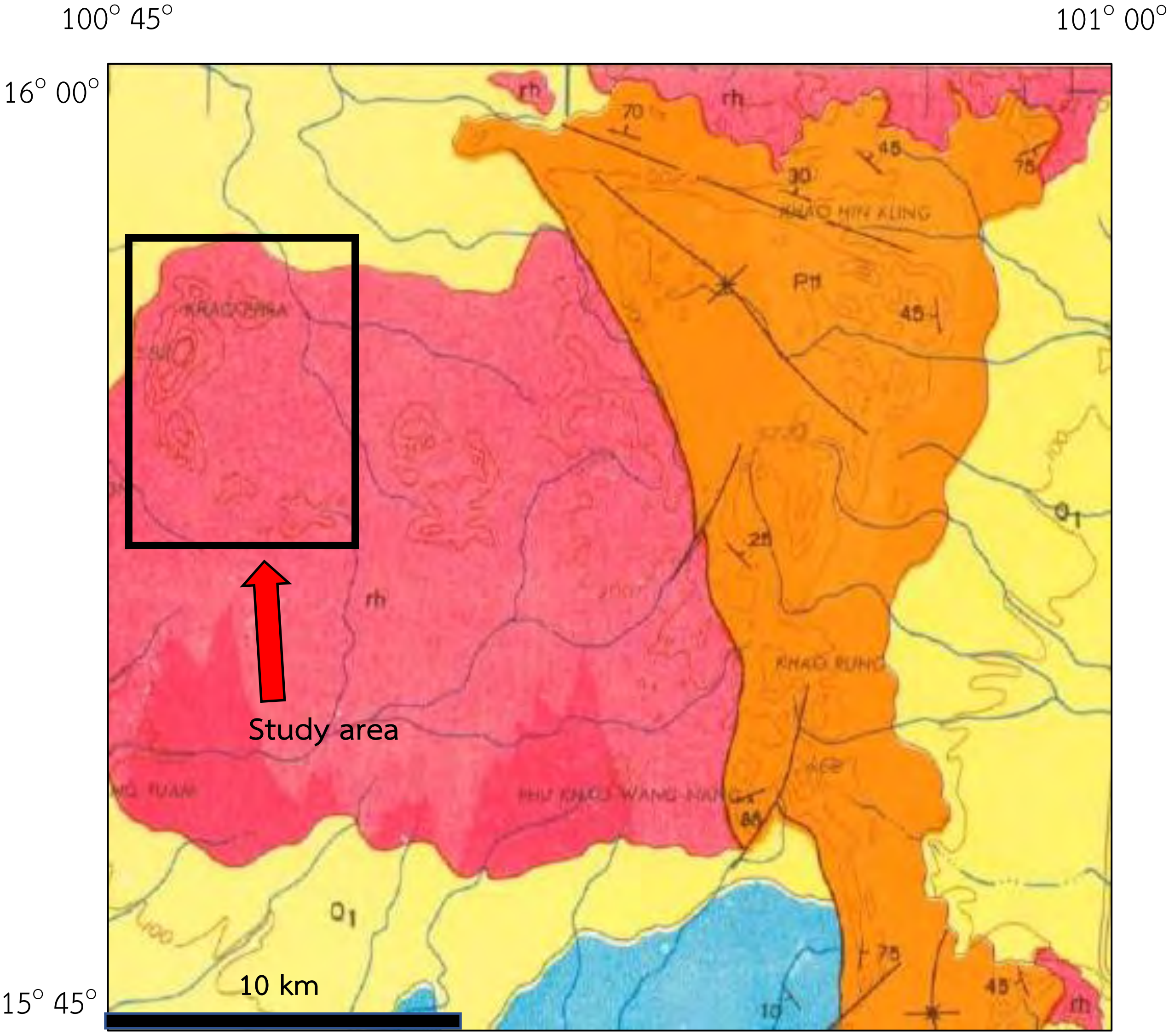


Figure 2.5 Mineral resources map of Amphoe Ban Mi that covered the study area. (Modified from DMR, 2001)



		Formation	Age
Q1	Terrace deposit		Pleistocene
Jsm	Pebbly sandstone with volcanic and Limestone pebbles.	SAP MAI DAENG (SANDSTONE)	Jurassic
rh	Rhyolite, tuff, agglomerate and andesite	LOEI - PETCHABUN VOLCANICS	Permo-Triassic
Ptf	Massive to well bedded limestone	TAK FA	Permian

Figure 2.6 Geologic map of Amphoe Ban Mi that covered the study area. (Modified from DMR, 1972)

2.2.1 Tak Fa Formation

This formation is mainly in eastern part of the study area. It extended from Lop Buri and Nakhon Sawan northeastwards to Phetchabun Province (Nakornsri, 1976) as showing in figure 2.7. These areas are the northern part of Khao Khwang Platform on western Nam Duk Basin illustrated in figure 2.8. Lithology of this formation mainly consisted of massive to well-bedded limestone with some shale and sandstone.

2.2.2 Igneous Rocks

This unit approximately covered 80% of regional area and dominated with three types of rocks which intruded into Permian carbonate rocks. Extrusion in the area mainly occurred during the Late Permian and Early Triassic (Kamvong et al., 2006). These types of rocks will be described in next paragraph. From the study by Khositanot in 2008, he found that plutonic rocks at Phetchabun area can be divided into Khao Mae Khae and Khao Lek units and the volcanic rocks are consisted of Thung Faeg and Sap Samran units.

(1.) Thung Faeg volcaniclastic unit

This unit occurred as ring shape around the intrusion at Ban Thung Faeg and Ban Khao Mae Kae, Bung Samphan, District, Phetchabun Province. This unit dominated with dark greenish grey lapilli tuff, and coarse tuff. Under thin-section, they found that it is composed mostly consisted of lapilli and subordinate coarse ash grains. Coarse ash grains and lapilli mostly are plagioclase, clinopyroxene crystal fragments and basaltic or andesite rock fragments.

(2.) Sap Samran basalt and diabase unit

Sap Samran basalt and diabase unit located in the western part of Thung Faeg basalt unit. Basalt are usually found as a low land plain, whereas the diabase presented as small hills around Khao Lek hill in western side of Ban Khao Mae Kae. Diabase shows dark greenish grey color and fine- to medium-grained seriate texture. Under thin-section they found that it mainly composed of plagioclase and clinopyroxene. The plagioclase grains are subhedral to euhedral, with short prismatic forms. The clinopyroxene grains are mostly subhedral.

(3.) Khao Mae Khae diorite unit

It intruded into volcanic unit which are the Thung Faeg and Sap Samran basalts. Rock in this unit is grey to pale grey in color and medium- to coarse-grained.

It shows plagioclase phenocrysts and inequigranular to porphyritic textures. Plagioclase phenocrysts are 1-2 cm and pale grey. Crystals are usually subhedral to euhedral and have short tabular forms. From microscopic study, groundmass consisted of amphibole, biotite, K-feldspar, plagioclase which are 1-2 mm in size. Amphibole crystals commonly are subhedral and stubby forms. It was contained up to 5%. Biotite are mostly flakes and up to 3 percent in the rock. Plagioclase are the most abundant. They show subhedral to anhedral and short tabular crystals, with size 1-5 mm. K-feldspar are up to 10%, with sizes 1-5 mm. They usually are subhedral to anhedral, and have tabular forms. Moreover, they found that plagioclase grains is some locally replaced by quartz at rims.

(4.) Khao Lek diorite unit

This unit was exposed in between Sap Samran basalt and Khao Mae Kae diorite. It showed dark grey and porphyritic texture, with plagioclase phenocrysts and medium-grained groundmass. Under thin-section, the rock showed short tabular phenocrysts of plagioclase. Groundmass composed of amphibole, plagioclase and quartz which they commonly are 1-2 mm in size. Amphibole shows stubby subhedral crystals and contained up to 5%. Its grains also commonly were altered by epidote (pumpellyite) and chlorite alteration. Plagioclase are the most abundant felsic mineral constituent. They usually have euhedral to subhedral shape and short tabular forms. The An content in the plagioclase ranges from 30 to 50% (Andesine). Anhedral quartz crystals commonly are interstitial to plagioclase crystals, suggesting they were crystallized later than plagioclase groundmass.

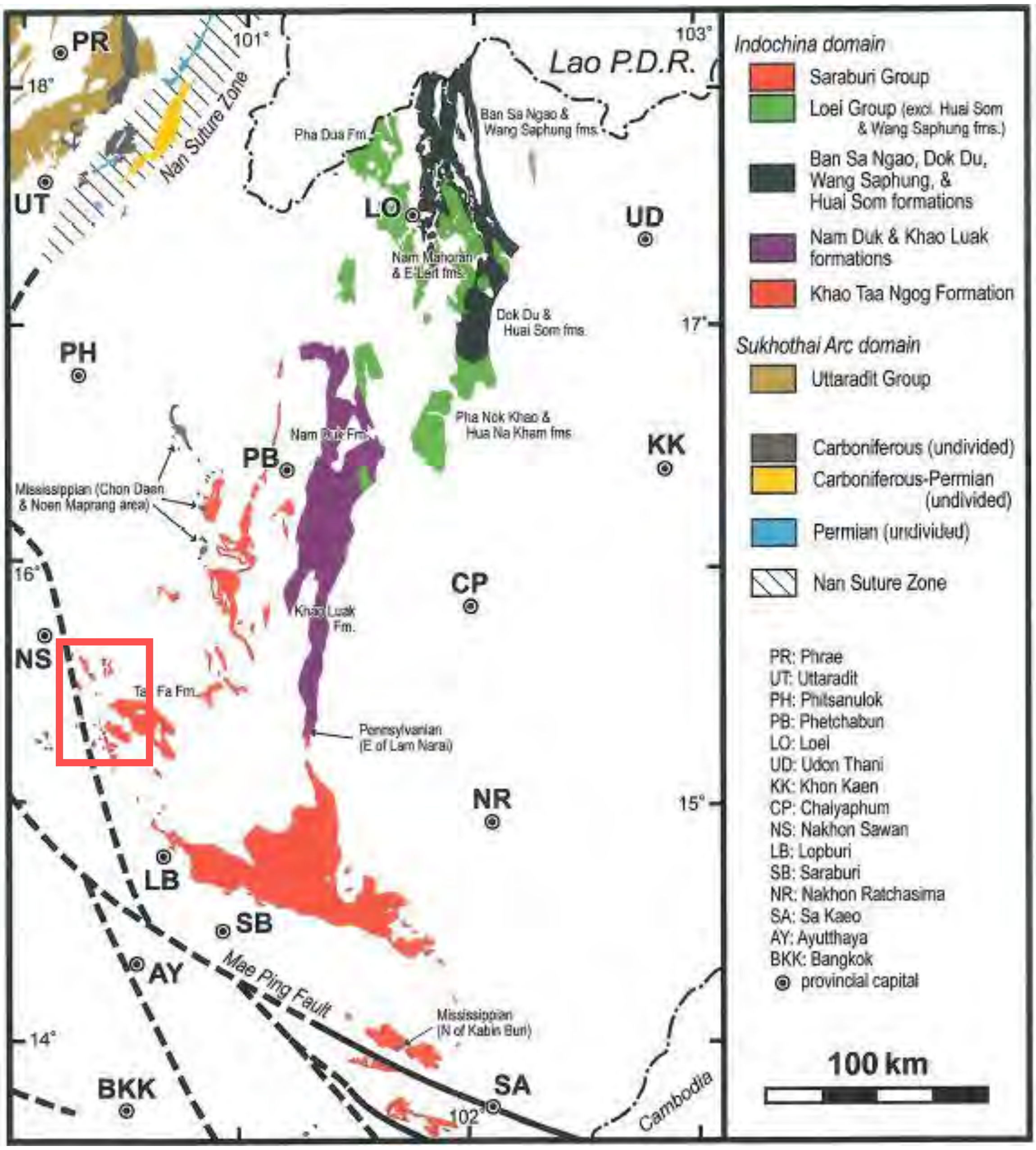


Figure 2.7 Distribution of Upper Paleozoic rocks in NE Thailand (After DMR, 1999)

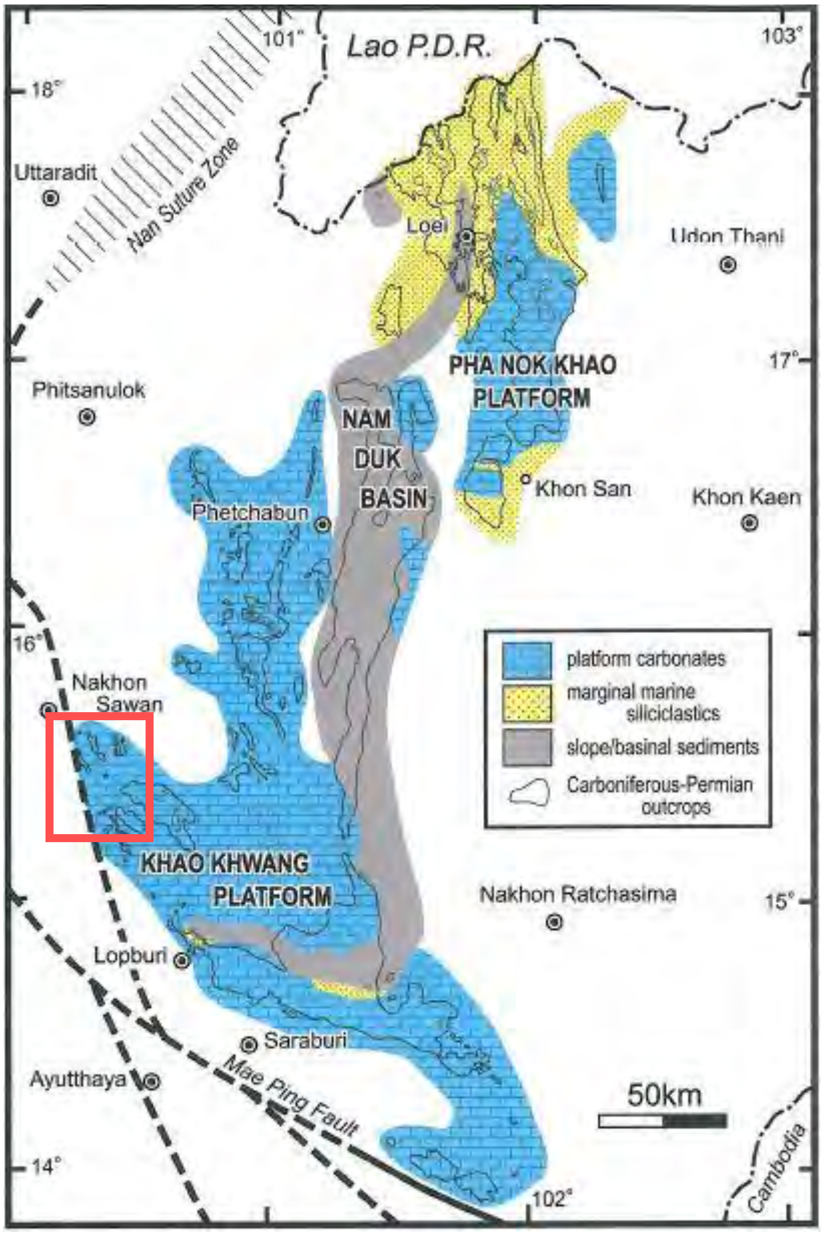


Figure 2.8 Illustration of Late Paleozoic major facies subdivisions on Loei fold belt (After Ueno and Charoentitirat, 2014)

2.3 Skarn Deposit and Occurrence

From Zaw's work, many skarn deposits in mainland SE Asia are mostly found along Ttuong Son and Loei fold belts in Laos and Thailand. These deposits can be divided into two main categories which are oxidized and reduced skarn (Zaw et al., 2014). Skarn deposits which occurred in Loei Fold Belt and had some features related to skarn in the study area or had location near to the area will be described in next paragraph.

2.3.1 Oxidized Skarns

a. Khao Pha Ngam Fe-Cu Skarn Deposit

Intayot (2000) studied mineralogy and petrography of skarn at Khao Phra Ngam, Muang distinct, Lop Buri province. He found that skarn in the area occurred from contact metasomatism between diorite which have age in Permian to Triassic and Khao Khad carbonate. Zonation of skarn in Khao Phra Ngam ordered from marble, diopsidic marble, wollastonite skarn, garnet-clinopyroxene skarn and contaminated diorite. Skarn in this area occurred as narrow zone conformed with contact boundary and rarely to have retrograde alteration so he used this reason to imply that skarn formation occurred deep down from earth's surface.

b. Frenchmen Au-Cu Skarn Deposit

In 1999, Muller et al. studied about skarn system at French Mine, Prachinburi that situated in Loei fold belt like Khao Lek area. In this area, the skarn formed in volcaniclastic host sequence associated with hornblende phyric andesite which occurred comformably with limestone and other sedimentary facies. These host rocks were considered that they occurred from arc magmatism. The Late Triassic diorite intruded after that magmatism and caused skarn formation in the area. Because volcaniclastic facies have permeability compared with others, so they gave a favorable layer for ore deposition.

c. Phu Lon Cu-Au Skarn Deposit

In 2009, Kamvong and Zaw studied about the origin and evolution of skarn-forming fluids from the Phu Lon deposit in northern Loei fold belt by using evidence from fluid inclusion and sulfur isotope. They found that Phu Lon is a Cu skarn which is classified following Einaudiet et al. (1981) and Mienert (2000). This deposit is also classified as a calcic skarn and mineralogy is dominated with andradite-diopside-epidote-amphibole assemblages.

Prograde skarn in Phu Lon, dominated with massive andradite and diopside which associated with magnetite. Retrograde skarn alteration had been overprinting on prograde skarn indicated by hydrous mineral formation. From those studies, they found that magmatic fluid is high temperature and moderate salinity by using evidence from fluid inclusions in prograde skarn garnet crystals and they also found that those garnets contain hematite daughters which indicated to oxidizing environment while fluid inclusion was trapped. Whereas inclusions in retrograde skarn epidote indicate both in low temperature and salinity which are caused by inputting of external fluid source.

2.3.2 Reduced Skarns

Phu Thap Fah Au (Cu) Skarn Deposit

From study of geology and genesis of Phu Thap Fah gold skarn deposit which made by Zaw et al. in 2006, the Phu Thap Fah deposit has been located in Loei Province. Skarn is hosted in Permian sedimentary package which is limestone, siltstone and carbonaceous shale which these host rock caused to form reducing skarn. The intrusion in this area consisted of Triassic granodiorite and microdiorite dike.

This deposit was beginning with early development of andraditic garnet and clinopyroxene skarn and then it was followed by retrograde alteration and ore genesis. The alteration assemblages are dominated by amphiboles, epidote, chlorite, carbonate and quartz. However, both prograde and retrograde skarn were formed as proximal exoskarn assemblages. Moreover, they found that gold-bismuth-tellurium mineralization is mostly associated with retrograde reduced pyrrhotite-rich massive sulphide and quartz veins.

CHAPTER 3
GEOLOGY IN THE STUDY AREA

This chapter concern about host rocks and skarn units which exposed in the mine area. Rocks in each unit will be described in petrographic features, both mesoscopic and microscopic scales. Geology in the study area can be categorized into 2 sections: deposit geology, concerning about host rock units and skarn alteration, concerning to skarn zonation.

3.1 Deposit Geology

In the quarry at Khao Lek, we found that volcanic rocks are underlain by carbonate rocks which unconformably along volcanic rocks. In this section, we divided rock units based on type of host rock. So, we will ignore any changing of rocks and classify them followed their original features. There are 2 main rock units in Khao Lek area; volcanic and carbonate units. In each unit, it maybe composes one or more types of rock which its detail will be mentioned in following paragraphs.

3.1.1 Carbonate Unit

This unit mainly extensively distributed on eastern side of study area. It mainly consisted of limestone which mostly were metamorphosed into marble. In the most eastern of area, we found uncontaminated limestone which should be some metamorphosed because it showed some recrystallized feature of calcite but not intense as marble.

3.1.2 Volcanic Unit

This unit mostly extended on northern to western side whereas rarely to be found on eastern side of the mining section. Volcanic rocks are usually found closed to ore zone. Rocks in this unit can be classified into 3 types. They are both volcaniclastic and lava flow type as being described below.

Basaltic Andesite

The andesite is usually light to dark gray in color (figure 3.3). In rock slab, it shows porphyritic texture which phenocrysts are long about 0.5 to 2 millimeters. The rock is more mafic than general andesite because its color index is about 47-52 percent.

In thin section, it shows hypocrystalline and hypidomorphic, fine to medium-grained and varying size of phenocryst. Moreover, it also has glomeroporphyritic texture of pyroxene and plagioclase. Phenocrysts mainly compose of plagioclase and some clinopyroxene. Groundmass is plagioclase microlite associated with volcanic glasses. Plagioclase has prismatic crystals, subhedral to euhedral grains which have An content about 45 to 55% and also, formed zoning, antiperthitic texture and Carlsbad twin (figure 3.3). Moreover, we found that some plagioclase phenocrysts were altered to sericite but they still showed relic texture of former plagioclase. Clinopyroxene is mostly subhedral crystals which size and amount are smaller than plagioclase. they also formed zoning and showed reaction rim.

Andesitic Breccia

It found as dike cut through andesite. All volcanic clasts are andesite varying size from 10 to 70 centimeters. The cementing material was altered to clay as you will see in figure 3.5b. The volcanic clast is green to gray in color, low sphericity and high angularity and also has porphyritic texture with larger phenocryst than in basaltic andesite unit. Matrix and cementing material are clay which has pink to cream in color. This unit is strongly weathered and can be broken by hand.

Andesitic Sandstone

They usually are closed to ore zone. Outcrops on the western flank are massive and jointed in NW-SE trending. Width of outcrop ranges from 5 to 15 meters. Their hand specimens are greenish gray, light gray and black in color. In rock slabs, it is gray color and showing some pinkish zone. The pinkish zone is usually containing very small black spots. Moreover, its slab showed fine-grained sulfide minerals such as pyrite disseminated in pinkish zone. It also was observed in outermost flanks of eastern flank and adjacent to marble. It is bluish to dark gray in color and showing some black bands.

In thin section, it is very dirty and containing cryptocrystalline quartz and microcrystalline of calcite, plagioclase and pyroxene. Those grains commonly are medium to very fine sand sizes. Mineral grains in this rock is very hard to identify shape and grain boundary. Rock also showed veinlet of clinopyroxene which some was altered. It also showed feature like spotted texture which is evidence of contact metamorphism.

Figure 3.1 Simplified geology of Khao Lek deposit showing host rocks unit distribution.

Figure 3.2 Outcrop exposure of volcanic rocks at Khao Lek area.

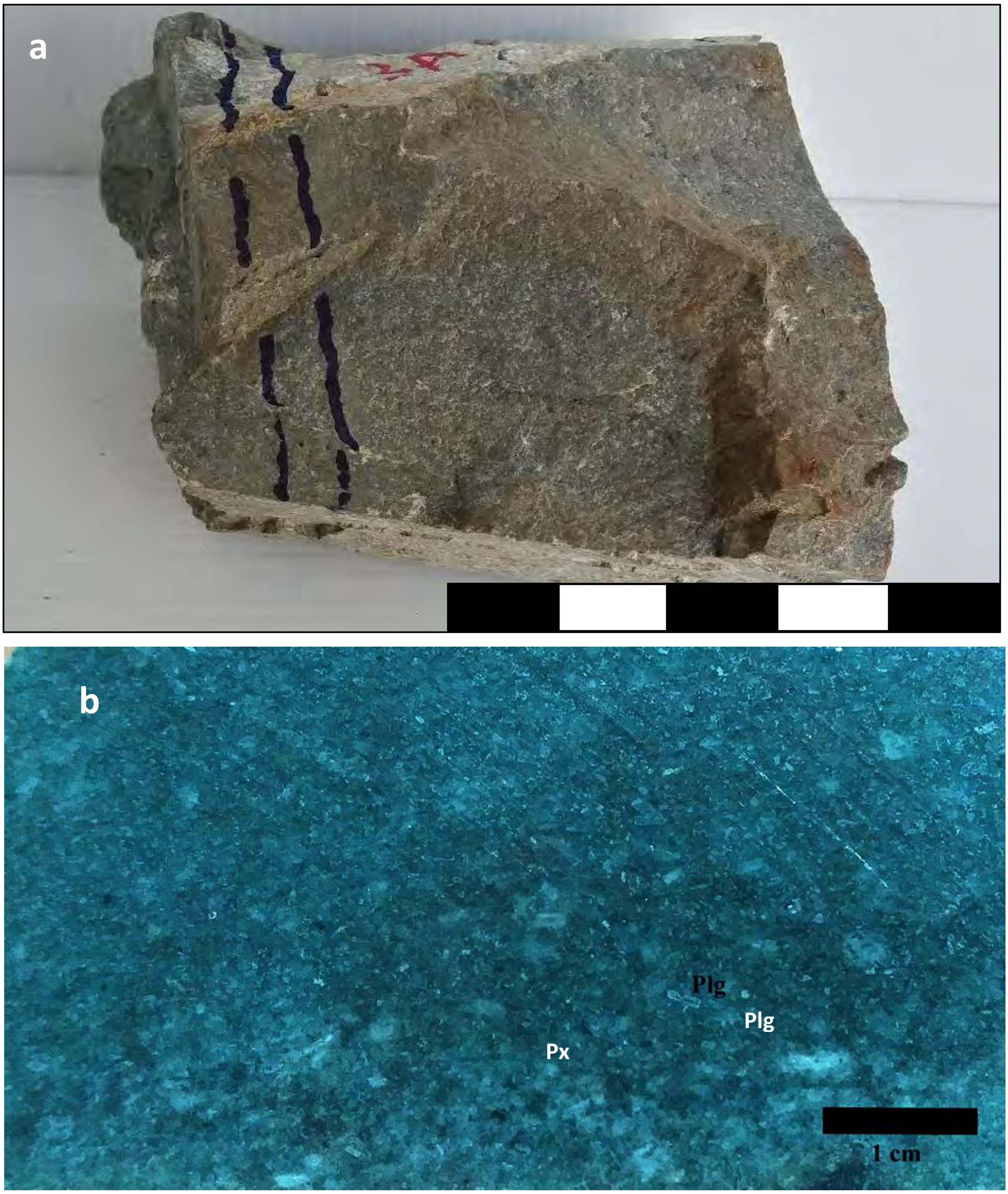


Figure 3.3 Rock sample of basaltic andesite

a.) Hand specimens containing dark gray in color and medium-grained black phenocrysts.

b.) Rock slab shows porphyritic texture containing medium-grained of plagioclase and medium- to fine-grained pyroxene as phenocrysts.

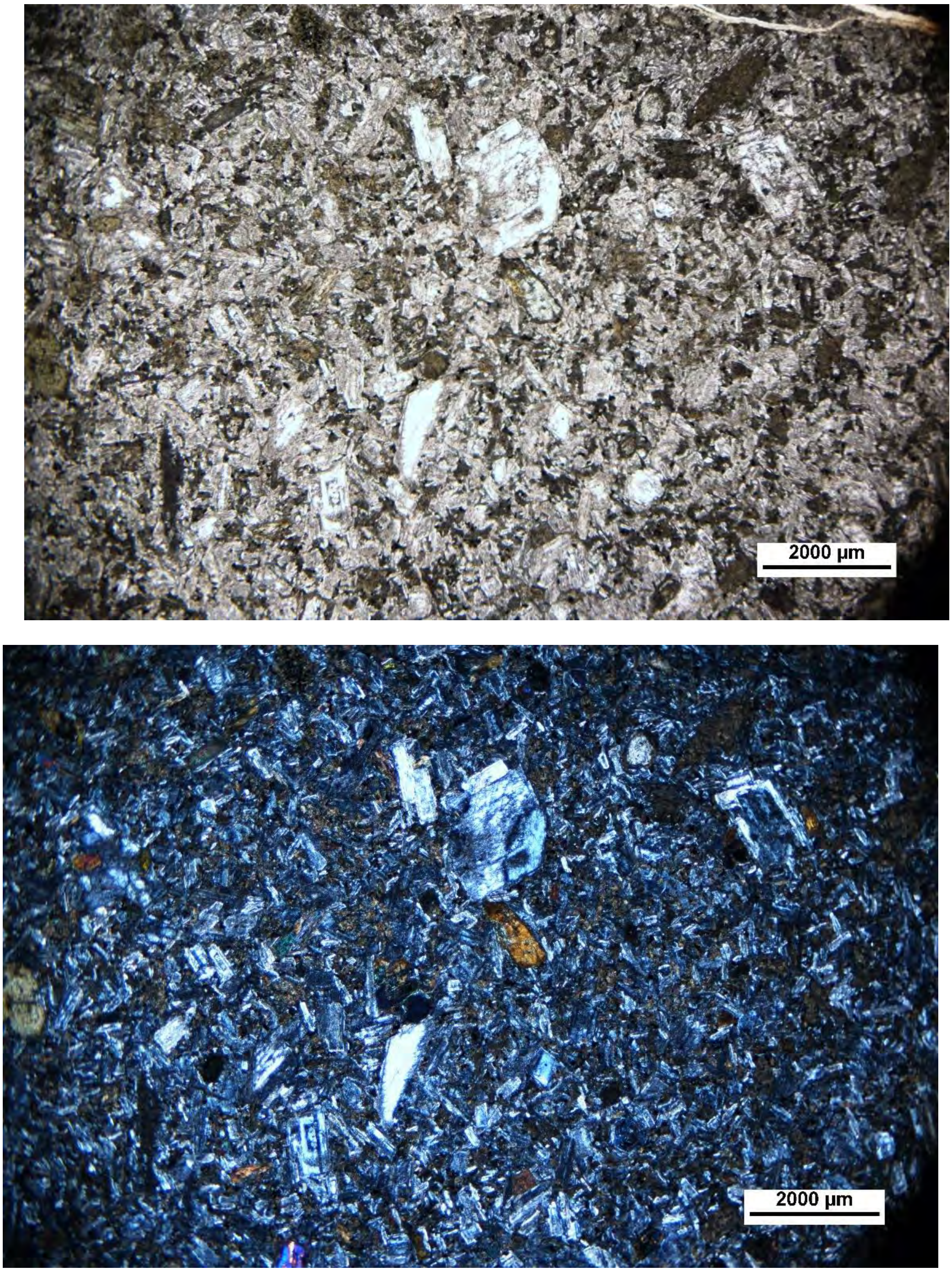


Figure 3.4 Photomicrograph of basaltic andesite showing zoning plagioclase and pyroxene phenocrysts in the groundmass of microcrystalline plagioclase, pyroxene and volcanic glasses (upper photo: PPL, lower photo: XPL)

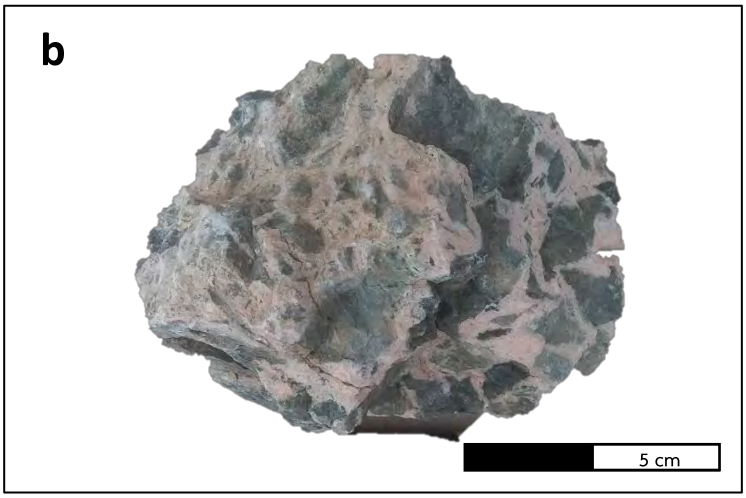


Figure 3.5 Andesitic breccia

a.) Outcrop exposure of volcanic breccia in study area.

b.) A hand specimen of andesitic breccia containing green andesite clasts and pink clay as matrix and cementing material.

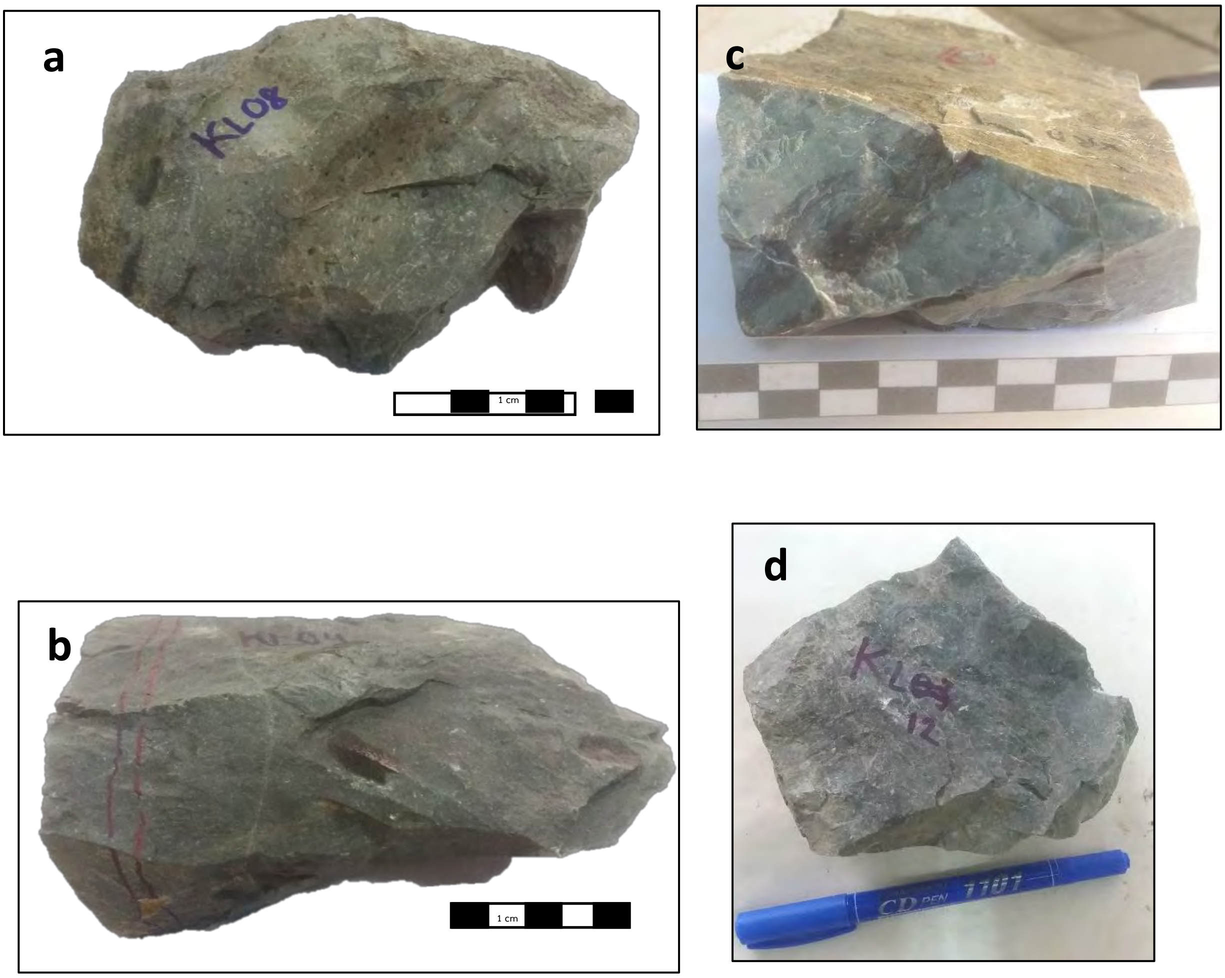


Figure 3.6 Hand specimens of andesitic sandstone. Upper photo has greenish gray in color and it also shows some phenocrysts of sulfide minerals in the sample. Lower photo is darker color and showing aphanitic texture. (a: KL08, b: KL04 c: SN10, d: KL12)

Figure 3.7 Outcrops of andesitic sandstone [Upper photo] showing joint set in NW-SE trending and dipping to SW direction whereas, andesitic sandstone [Lower photo] is showing orientation with strike in NW-SE trending and dipping to NE direction.

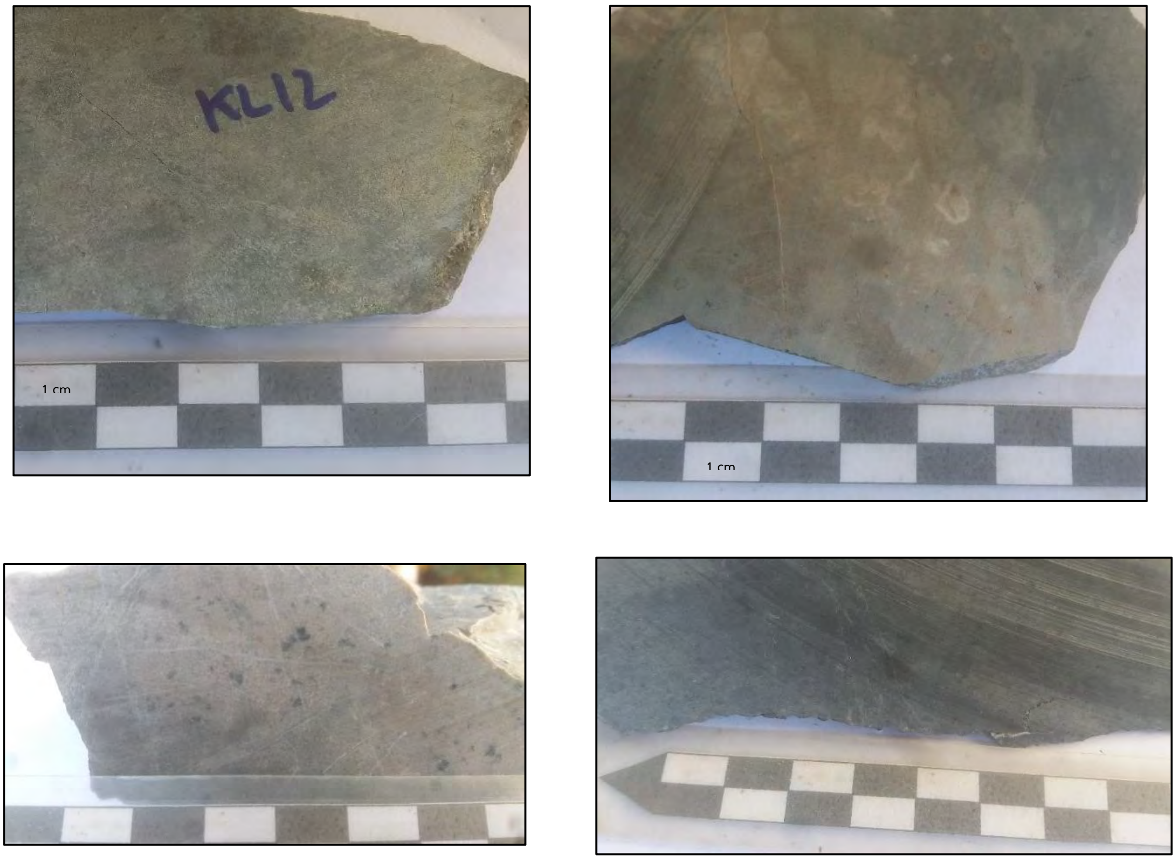


Figure 3.8 Rock slabs of andesitic sandstone [Lower photos] and sulfide mineral in andesitic siltstone [Upper photos].

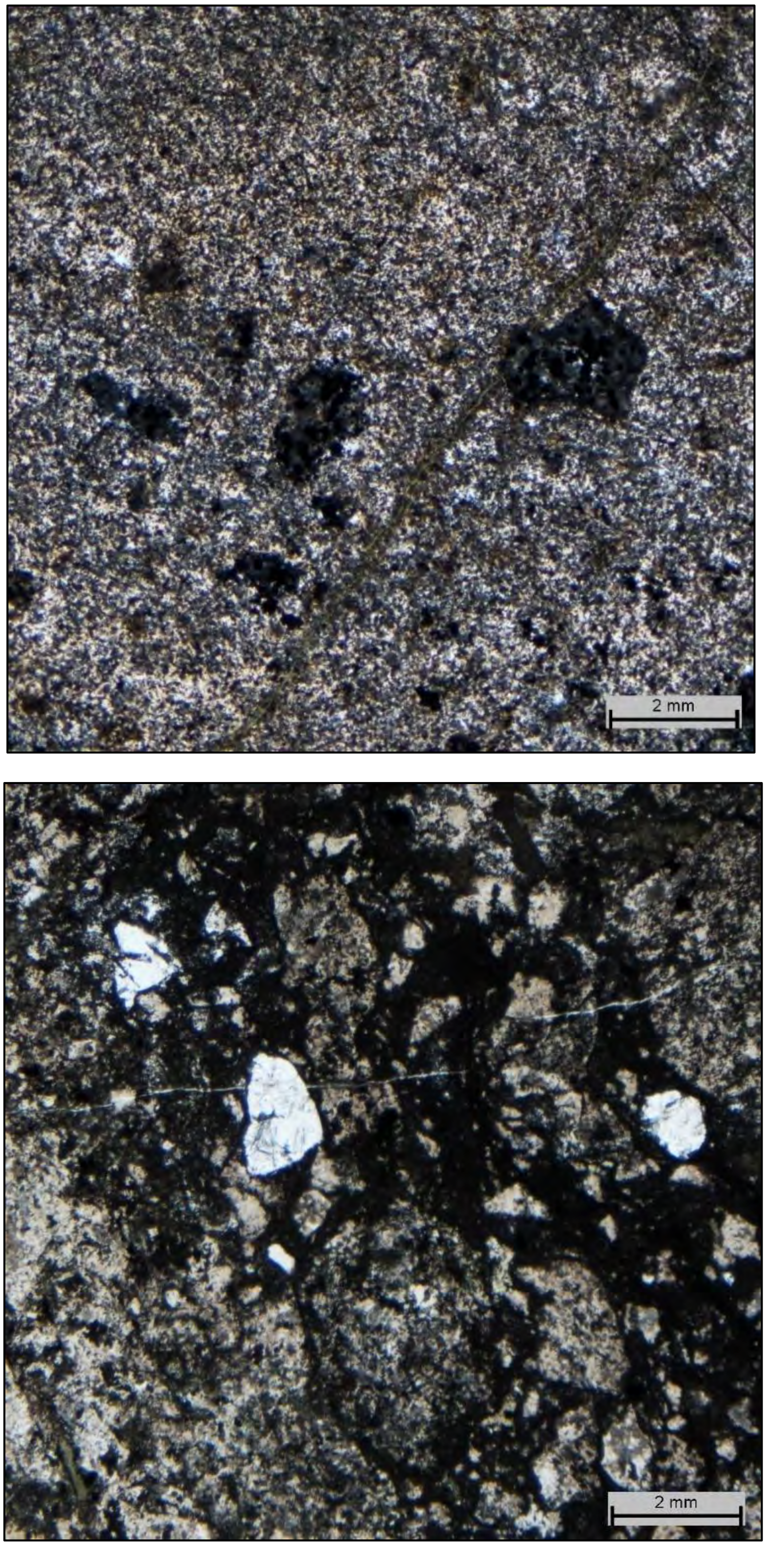


Figure 3.9 Photomicrographs of andesitic sandstone are showing microcrystalline quartz, calcite and pyroxene. (Upper: PPL, Lower: XPL; sample number: KL12)

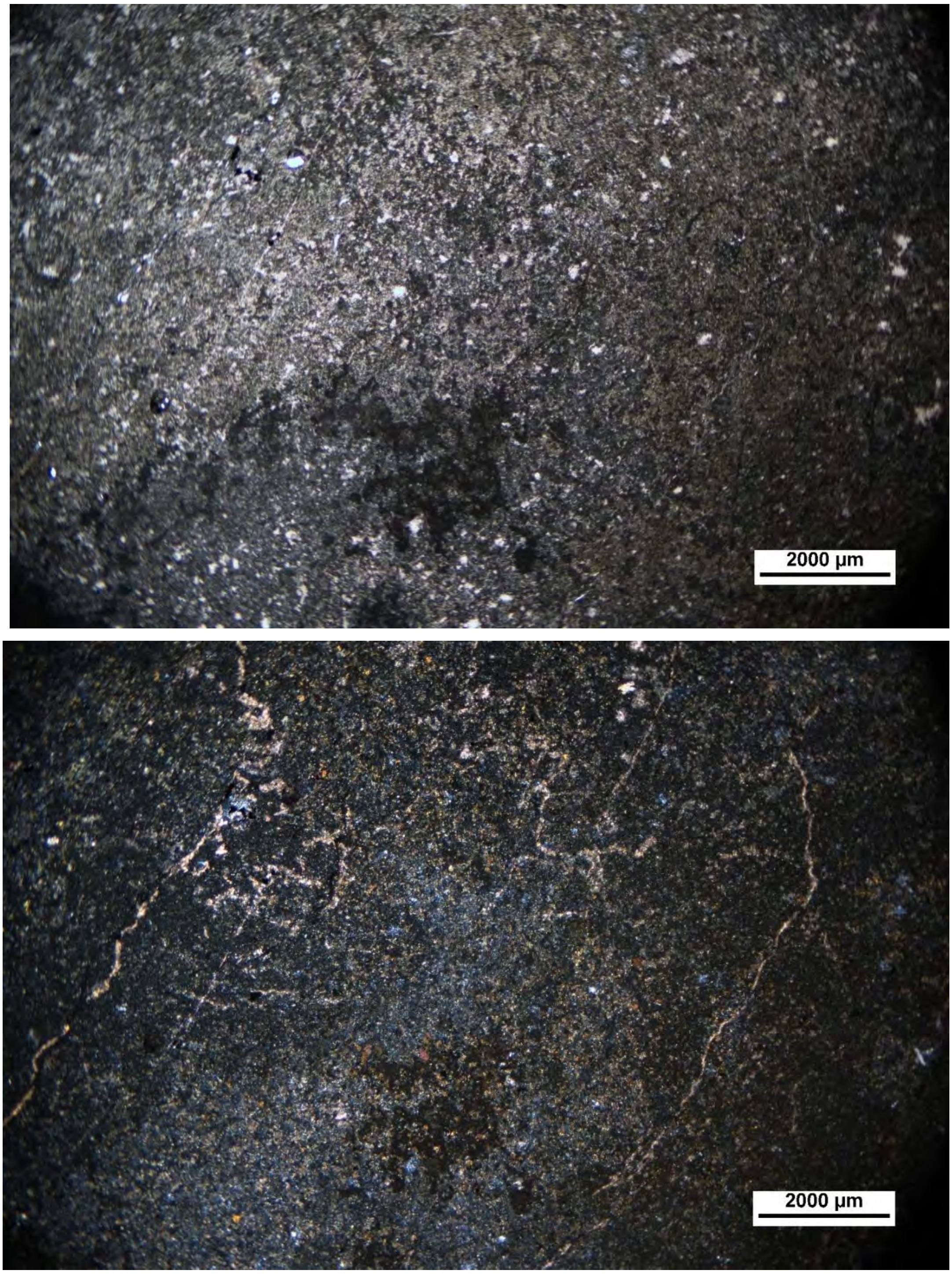


Figure 3.10 Photomicrographs of andesitic sandstone are showing cryptocrystalline quartz, calcite and pyroxene. It also shows small fractures in NE-SW trending. (Upper: PPL, Lower: XPL; sample number: SN10)

3.2 Skarn Alteration

Skarn at Khao Lek was formed by metasomatism alteration of marble and volcanic rocks. The skarn at mine section in Khao Lek occurs on flanks of magnetite dike as contact aureoles discontinuously, only in outcrop view but in microscopic view the skarn zone is continuous, in NW-SE trending and dipping conformable with country rocks. Skarn zone is variable in size ranging from 1 to 10 meters wide. Skarn is medium- to coarse-grained rock with granoblastic, grano-porphyroblastic and poikiloblastic textures. It showed as massive bodies in carbonate rocks and as veinlets in volcanic rock which can be observed only under polarizing-microscope. Alteration can be divided into 2 types; prograde, higher temperature, and retrograde alterations, lower temperature.

3.2.1 Prograde Alteration

Prograde skarn is usually consisted of garnet and clinopyroxene as essential minerals. The accessory minerals are calcite, epidote, tremolite-actinolite, quartz, albite, biotite and chlorite. Rocks in this unit can be separated into garnet skarn, garnet-clinopyroxene skarn, clinopyroxene skarn and skarn marble.

a. Garnet skarn

Garnet skarn can be more divided by basing on colors of garnet. It mainly consisted of garnet more than 90% as essential mineral. There are some calcite, chlorite and epidote as accessory. Rock commonly formed granoblastic and grano-porphyroblastic textures. These rocks commonly occurred nearby the ore zone and adjacent with pyroxene skarn or volcanic rocks. Garnet skarn was extended about 3 to 10 meters.

Red garnet skarn is the most common type that we found in the area. Hand specimen, SN08, is coarse-grained and pinkish red in color. Its slab is very brittle and highly fractured. It mainly consisted of garnet more than 90% in composition. In thin section, it is coarse-grained and subhedral to euhedral shape with granoblastic texture. Garnet crystals were highly irregular cracked and high relief. The crystals mostly are isotropic grain and showed some oscillatory zoning. Another 10% mainly is calcite that was overprinted by garnet and epidote. Epidote was found in some point that replaced on calcite and garnet. It is yellowish green and fine-grained clustering together.

Yellowish green garnet skarn occurred closed with ore zone in middle part of quarry face. Its hand specimen is coarse-grained and yellowish green in color. It is containing subhedral garnet crystal in the sample, KL05, with size about 0.5 to 1 centimeters. It mainly composed of garnet with granoblastic textures in thin section. All garnet crystals are isotropic grains and rarely to show zoning. Accessory minerals are clinopyroxene, chlorite, biotite and calcite which are 5- 10% in rock composition. Calcite occurred as poikiloblast containing clinopyroxene as idioblast on its crystal. Moreover, clinopyroxene, chlorite and biotite commonly concentrated along garnet margin or overprinted on garnet.

Brownish garnet skarn occurred in between ore zone and andesite on the western side of mine. Its hand sample, KL07 and KL09, is fine- to medium-grained and greenish to reddish brown color. It is harder and stronger than others garnet skarn. Its composition is garnet 80 to 85%, calcite 5-7%, clinopyroxene 5 to 10%, quartz 5%, albite 5%, chlorite about 1 to 5% with grano-porphyroblastic texture. Garnet crystals mostly are anisotropic grains showing zoned margin. Garnet grain was mostly replaced by albite, quartz, clinopyroxene but still showed relict grain boundary. it also showed partial corona texture and reaction rim. Calcite commonly occurred as poikiloblast containing tiny subhedral clinopyroxene and garnet as inclusion, idioblast. Quartz commonly occurred as fibrous and fine-grained granoblast in relict garnet.

b. Garnet-Clinopyroxene Skarn

The rock is yellow to dark green in color. It is medium- to fine-grained with 0.1 to 0.5 centimeters. The rock composed of garnet 40%, clinopyroxene 40%, calcite 5-10%, epidote 10%, chlorite, tremolite-actinolite and quartz 5% with grano-porphyroblastic texture. Garnet is yellowish green color in hand sample and zoned in thin section. It is subhedral to euhedral shape and usually replaced by microcrystalline quartz, clinopyroxene and epidote. Clinopyroxene is fine-grained black crystals in hand sample and fine- to medium-grained subhedral in thin section. It usually altered to epidote which can be seen clearly in hand specimen (figure 3.15). Calcite occurred as poikiloblast with medium- to coarse-grained anhedral. It contains fine- to medium-grained inclusion of epidote and acicular tremolite-actinolite. Because garnet and clinopyroxene occurred as essential minerals in this rock, so we can call this rock as “Garnet-Clinopyroxene Skarn”.

c. Pyroxene Skarn

Pyroxene skarn is less extended than garnet skarn. It was found as dike continuous from garnet skarn or meta-volcanic rock. It also occurred as veinlets in meta-andesite. Host rock of this skarn is both volcanic and carbonate rocks. Thickness of this zone is not over than 4 or 5 meters which is narrow relatively with others zone. This skarn showed granoblastic and grano-porphyroblastic textures. Rocks in this zone can be further divided as volcanic pyroxene skarn, carbonate pyroxene skarn, based on its host rocks.

Carbonate Pyroxene Skarn

From hand sample, the rock is dark green in color and fine-grained in size. Its slab showed small black spots and yellowish green zone of pyroxene and epidote, respectively. It composed of clinopyroxene 65-70%, epidote 15-20%, calcite 10% and garnet 5%, and tremolite-actinolite, chlorite, quartz 2-5%. Clinopyroxene is medium- to coarse-grained, euhedral to subhedral crystal and occurred as poikiloblast. It commonly was replaced or overprinted by epidote and chlorite. Tremolite-actinolite formed as fine-grained acicular crystals. Garnet is usually medium- to coarse-grained, euhedral to subhedral shape. It commonly was replaced by microcrystalline quartz and epidote and also showed sector zoning. For epidote, it commonly filled in cracks associated with chlorite. The retrograde assemblage in this rock commonly formed as fine-grained crystals showing strong green pleochoism. Calcite occurred as poikiloblasts and anhedral shape.

Volcanic Pyroxene Skarn

Pyroxene skarn in meta-volcanic rock occurred as clinopyroxene veinlet. The veinlet consisted of medium- to coarse-grained, anhedral to subhedral shape of clinopyroxene, tremolite-actinolite and chlorite. It contains clinopyroxene 60%, orthopyroxene 20% tremolite-actinolite 25% and chlorite 5%. Veinlet has width 0.5 to 1 millimeters and length 1.5 to 2 centimeters, for instance, in microscopic measurement. Clinopyroxene is commonly altered to tremolite-actinolite and chlorite.

d. Skarn Marble

Marble that was found in Khao Lek area can be divided into 2 categories based on dominated mineral in marble.

Garnet Marble

Garnet marble occurred adjacent with ore zone in middle to eastern part of the area. This rock showed grano-porphyroblastic texture which has dark green dodecahedral garnet as phenoblast and coarse-grained calcite as groundmass. The phenoblast garnet is very coarse-grained with 1 to 2 centimeters in size (indicated its occurrence at very proximal skarn). Calcite is also medium- to coarse-grained with 0.1 to 0.5 centimeters. In thin section, garnet occurred as grano-poikiloblast containing calcite and clinopyroxene as idioblast. This rock is containing calcite 80-85%, garnet 10%, clinopyroxene 5% and chlorite about 1-5%.

Diopsidic Marble

It developed just on eastern side of quarry face which adjacent with garnet-clinopyroxene skarn. It has moderate to dark green in color which is effect from diopsidic pyroxene in the rock. In thin section, we found that it has subhedral to anhedral calcite interlocking with fine-grained anhedral diopside. Diopsidic marble has finer-grained calcite than in garnet marble.

3.2.2 Retrograde Alteration

Retrograde skarn was extensively found in Khao Lek area. It usually overprinted or replace on others skarn. Mineral assemblage in this skarn mainly composed of epidote-chlorite-calcite. In clinopyroxene skarn, pyroxene commonly was replaced by epidote-chlorite and also some biotite. Epidote commonly occurred as fine-grained cluster associated with chlorite that formed as fine-grained fibrous. Moreover, in pyroxene veinlets, pyroxene mostly was altered to tremolite-actinolite. In garnet skarn, many garnet were selectively altered. Selective alteration of garnet caused sector zoning and higher birefringence at rim of crystal. They were commonly replaced by calcite-epidote and some quartz and albite. Calcite is often occasionally associated with garnet.

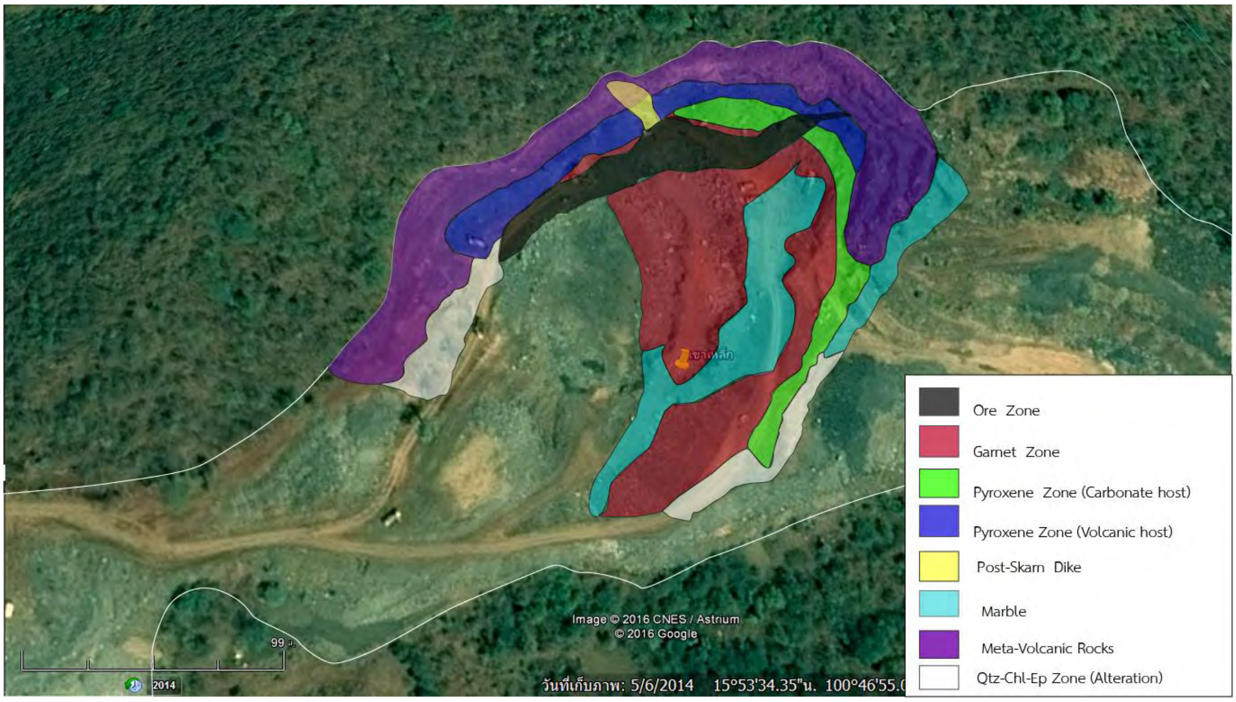


Figure 3.11 Simplified geology of Khao Lek deposit showing skarn alteration zonation.

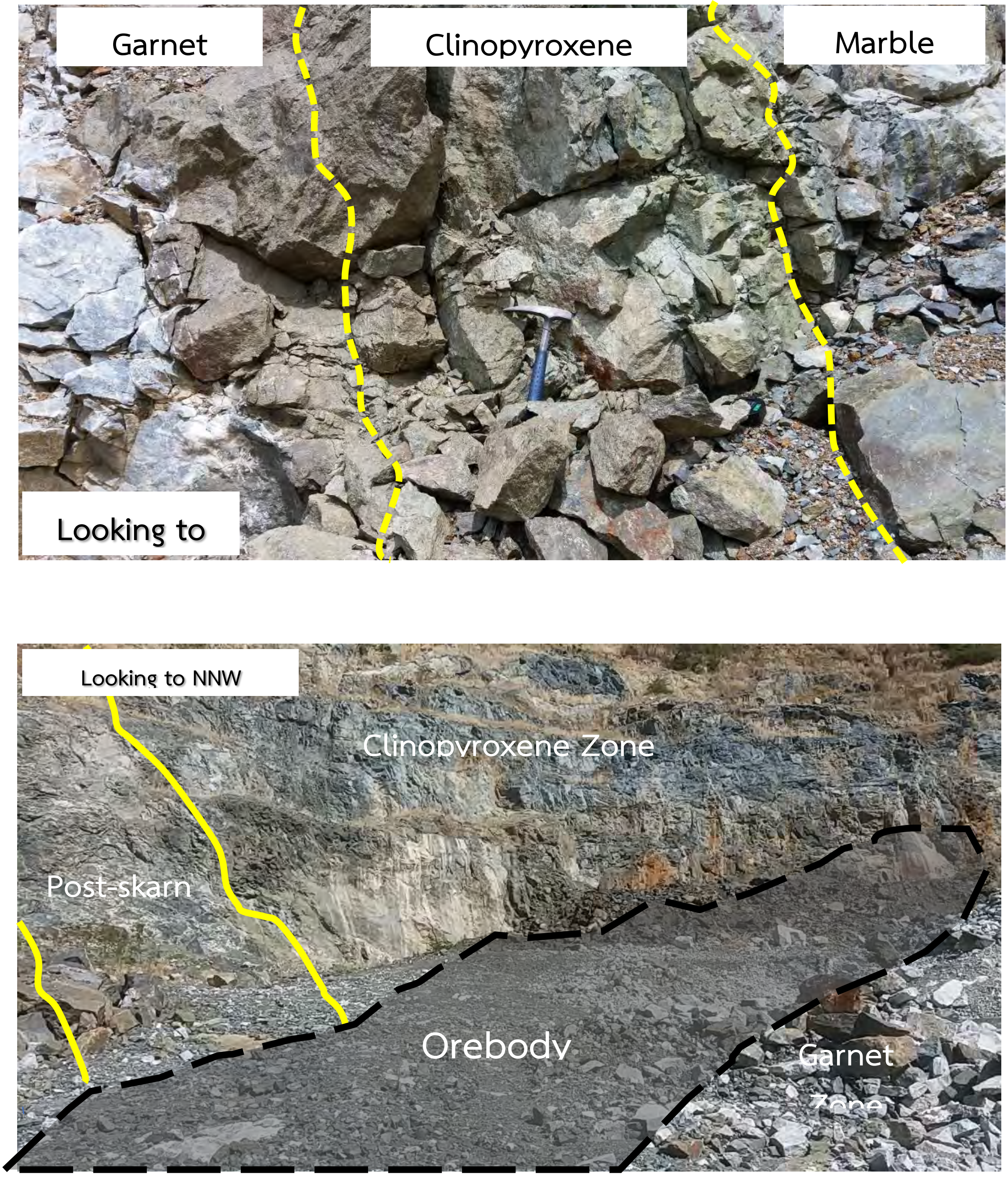


Figure 3.12 Outcrop of skarn which showing contact of each zone at quarry section.

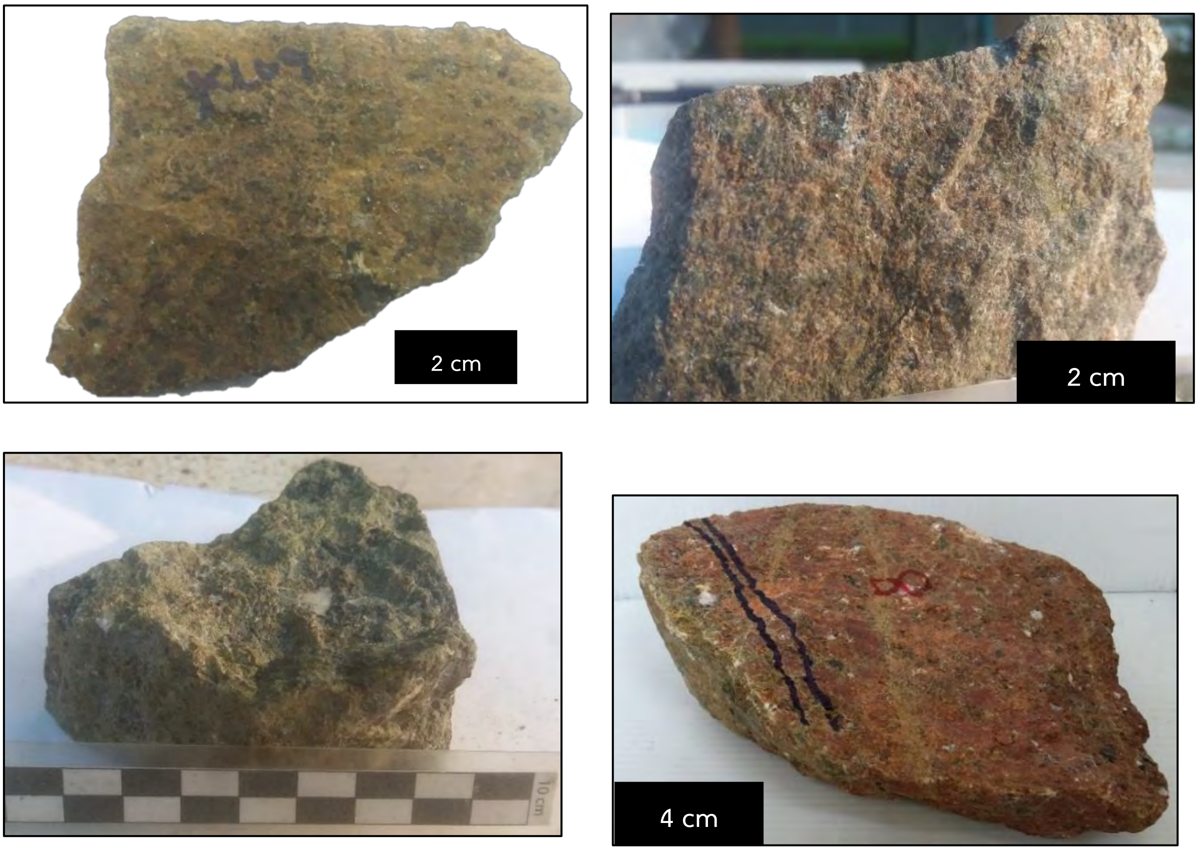


Figure 3.13 Hand specimen of garnet skarn that found in Khao Lek area. They show vary color of garnet which maybe reflect to it composition, dark color should have high Fe contents. [a & b: brownish garnet, c: yellowish green garnet, d: red garnet]

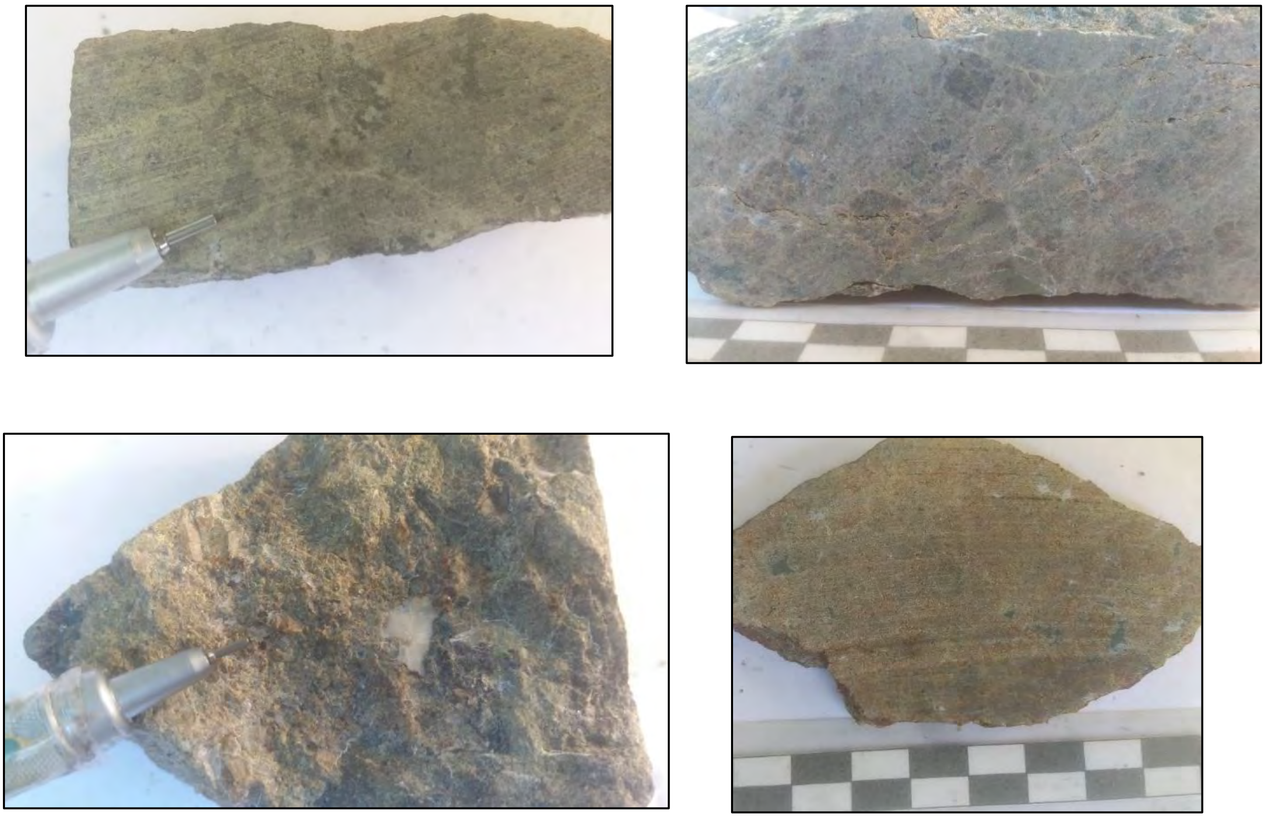


Figure 3.14 Closer view in rock slabs and hand specimen. Slabs are showing many phenoblasts. In hand sample KL05, it shows many coarse-grained yellowish green garnets. These samples also showed clearly replacement of calcite.

Figure 3.15 Sample of garnet-clinopyroxene skarn. Upper photo shows contact of garnet-clinopyroxene skarn and diopsidic marble. Lower photo is rock slab showing clearly replacement of epidote at rim of pyroxene grain. (sample number: KL01b to c)

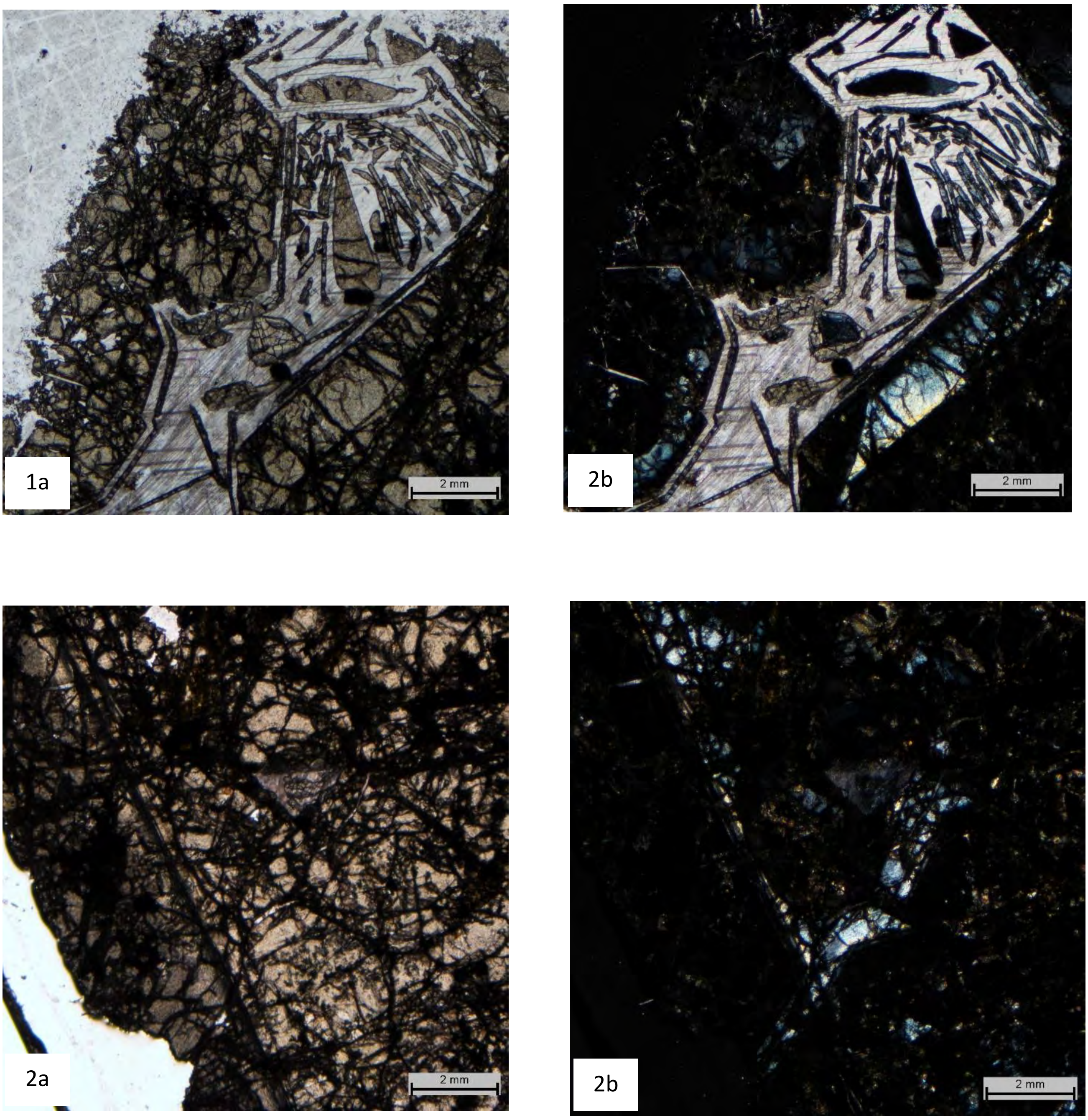


Figure 3.16 Photomicrograph of yellowish green garnet skarn [upper photos] showed isotropic core and birefringence rim of garnet which overprinted in anhedral calcite. Lower photos showed highly cracked isotropic grain of garnet. (a: PPL, b: XPL, sample number: KL05)

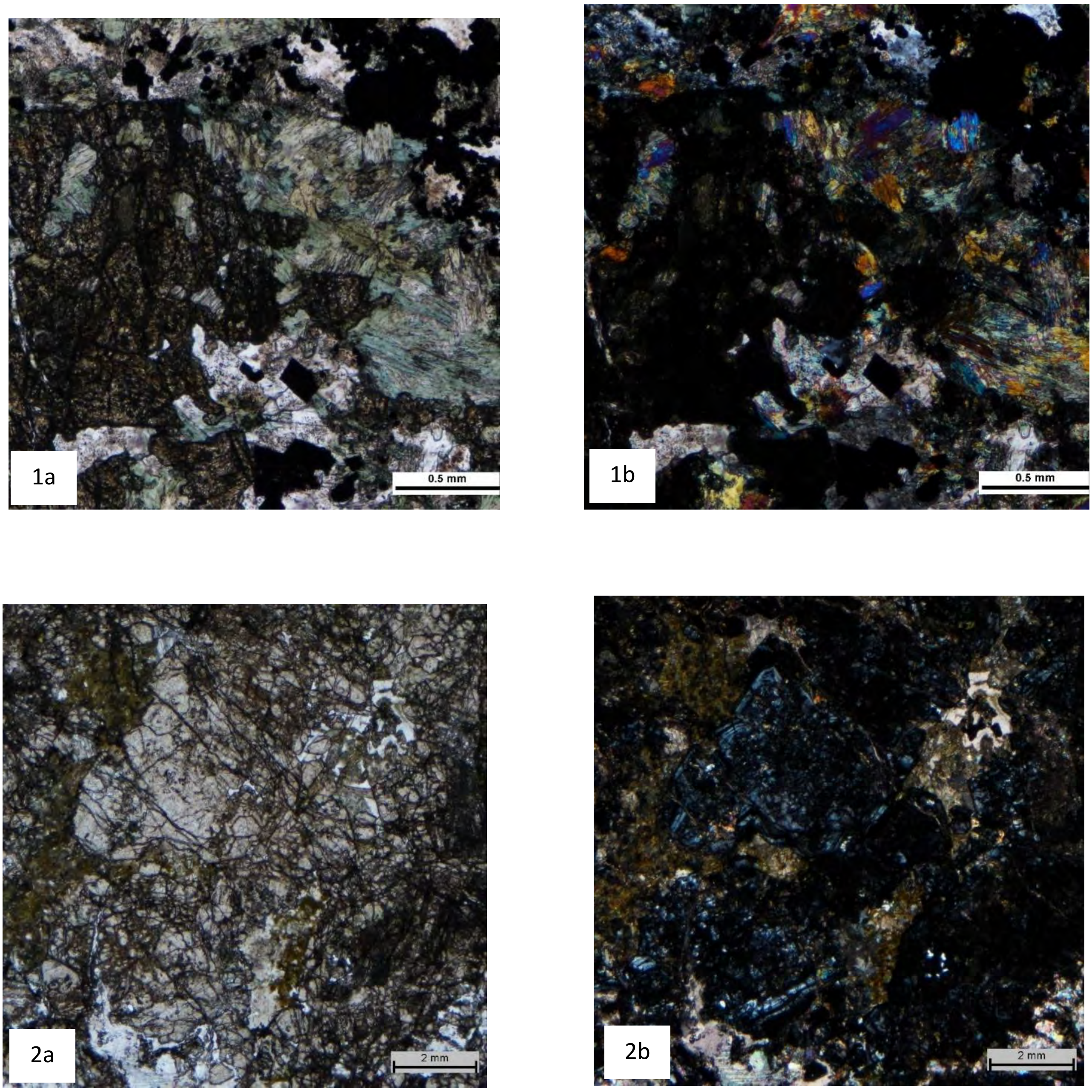


Figure 3.17 Photomicrograph of garnet-clinopyroxene skarn [Upper] showed garnet intergrowth with clinopyroxene at contact of skarn and marble. Lower photos showed anisotropic grain of garnet which some was replaced by epidote-chlorite. (a: PPL, b: XPL, sample number: KL01C)

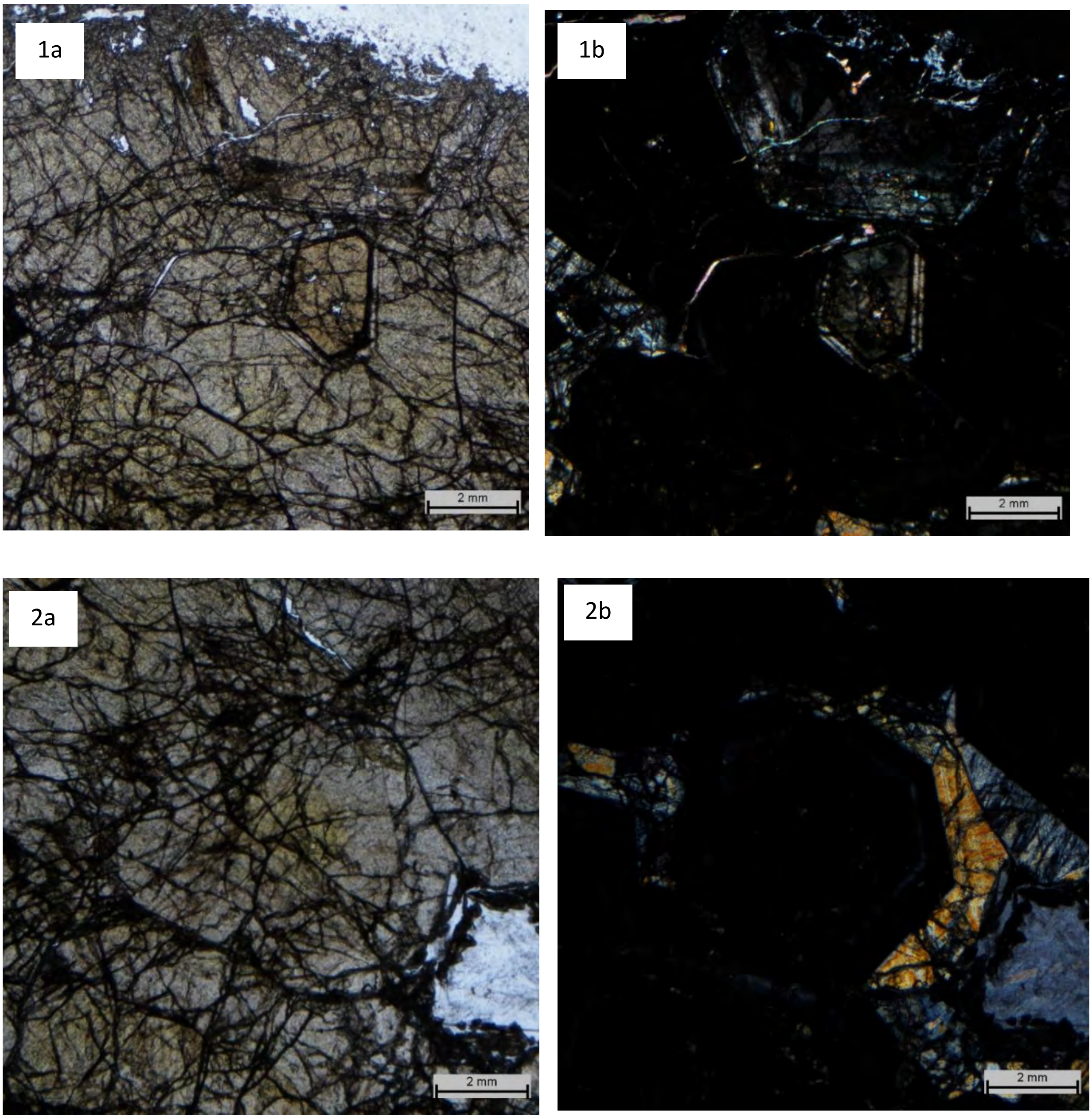


Figure 3.18 Photomicrograph of brown garnet skarn showed oscillatory zoning of garnet which some was replaced by clinopyroxene.
(a: PPL, b: XPL, sample number: KL09)

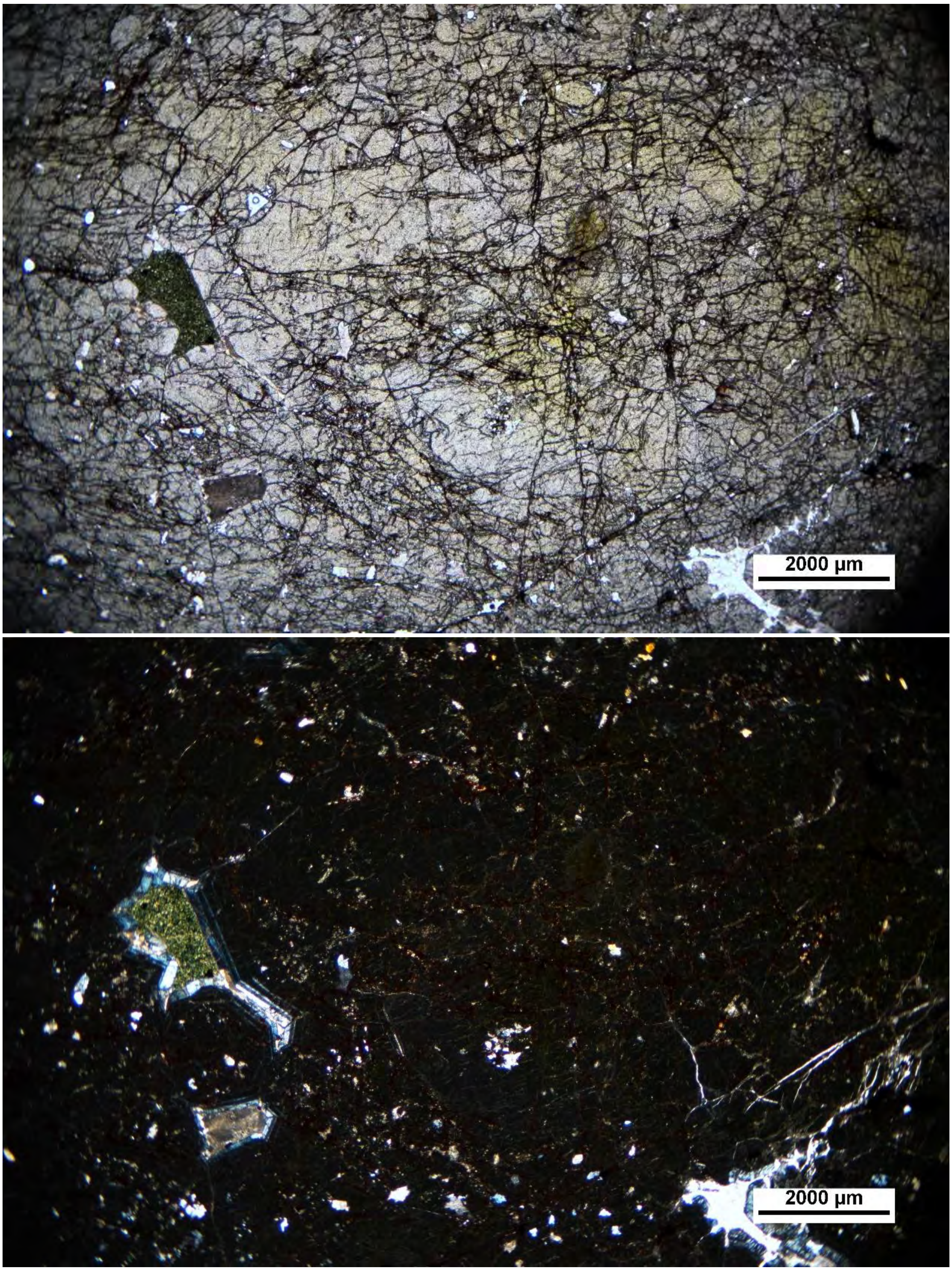


Figure 3.19 Photomicrograph of red garnet skarn is showing zoned garnet and abundant with isotropic grains. Garnet is highly cracked but not separated into individual grains. Moreover, there was some replacement of epidote in between grain boundary of garnet. (Upper: PPL, Lower: XPL; sample number SN08)

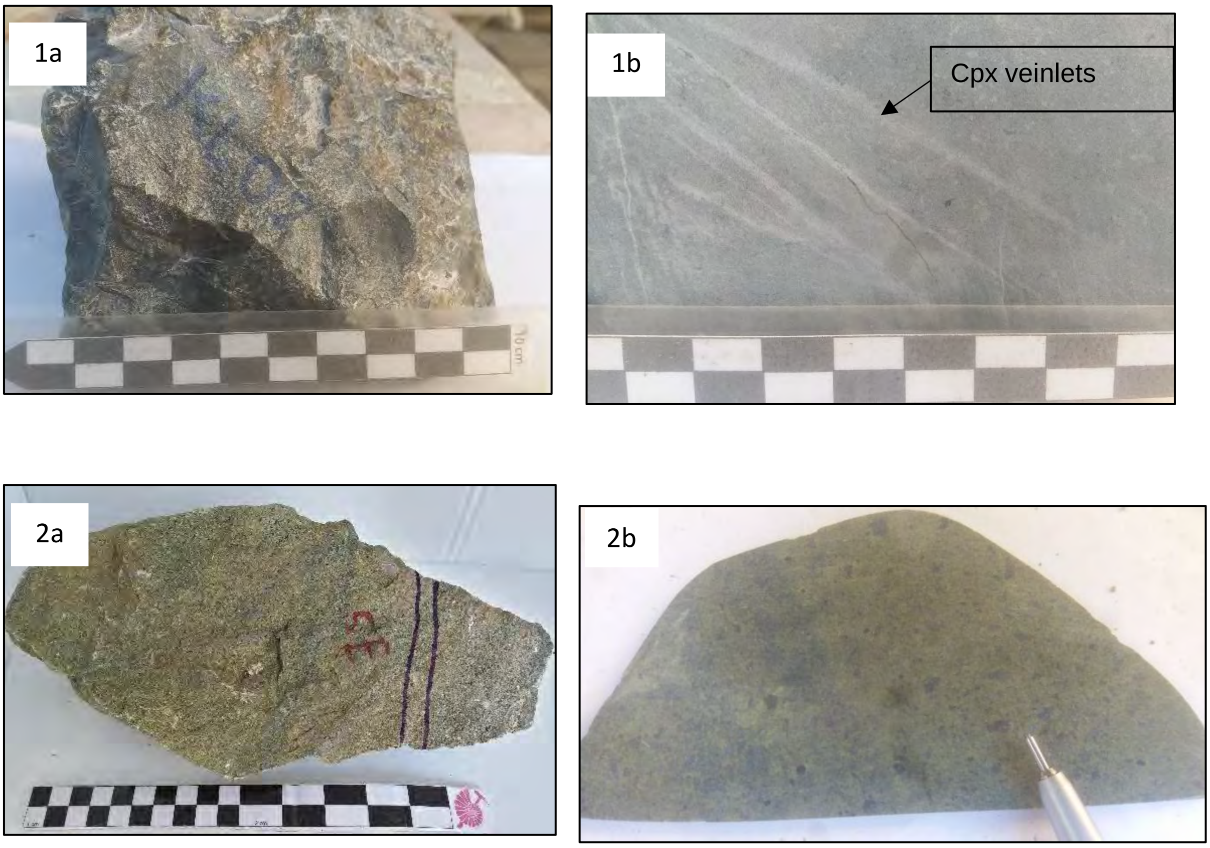


Figure 3.20 Samples of clinopyroxene skarn

Upper photos are samples of volcanic pyroxene skarn which show aphanitic texture and dark green to grey color in hand specimen. Its slab shows white veinlets (sample number: KL02). Lower photos are samples of epidote-clinopyroxene skarn which is one of carbonate clinopyroxene skarn. In hand specimen show green color which came from containing epidote, chlorite and pyroxene in its composition. Rock slab also show green color and show many small phenoblasts of pyroxene (sample number: SN05).

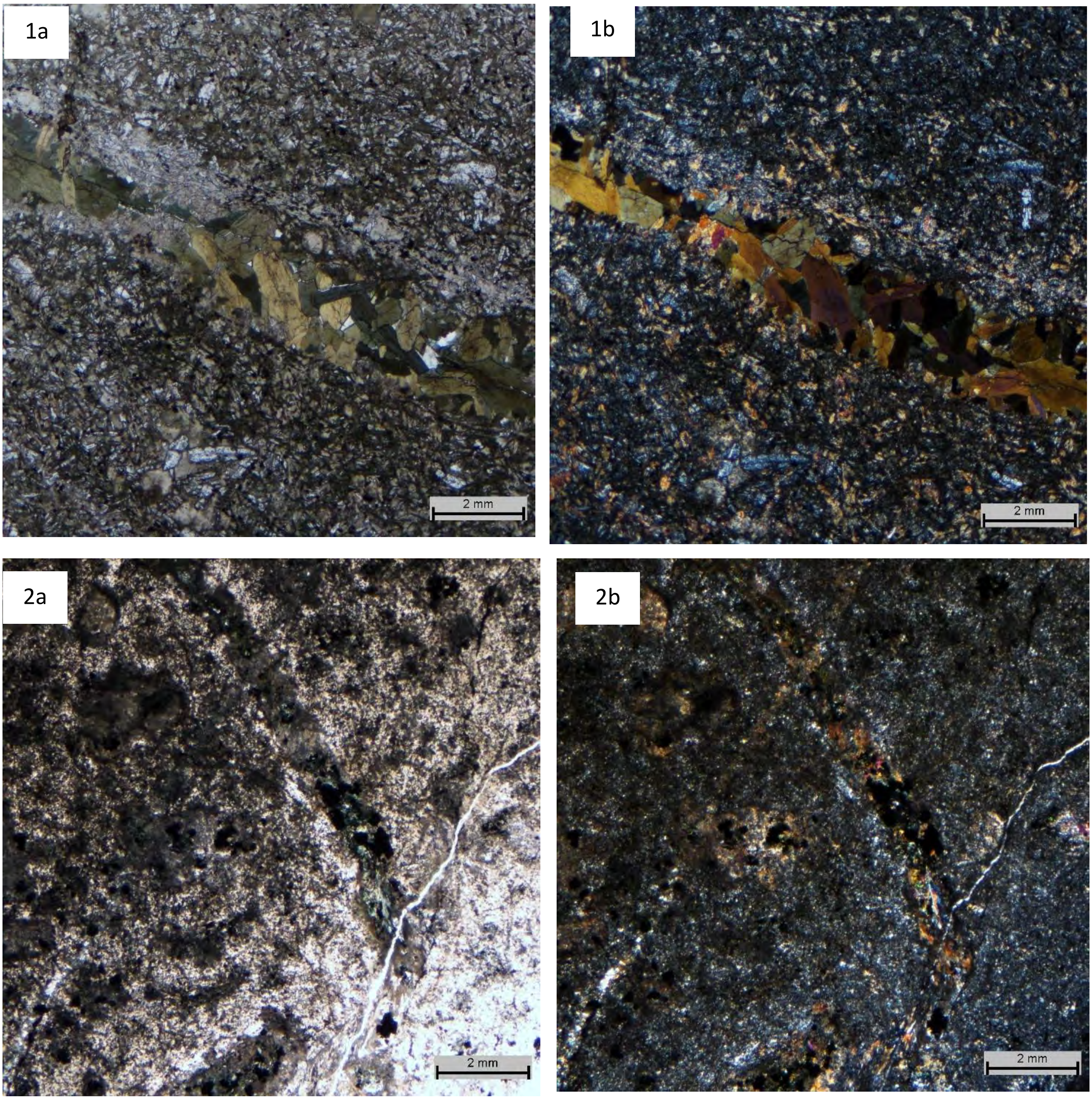


Figure 3.21 Photomicrograph of volcanic pyroxene skarn is showing pyroxene veinlet cut through meta-volcanic rocks. Veinlets are usually narrow and not extensive. Pyroxene in these veins are common altered into lower temperature minerals in retrograde skarn assemblage. (a: PPL, b: XPL; sample number Upper: KL02, Lower KL12)

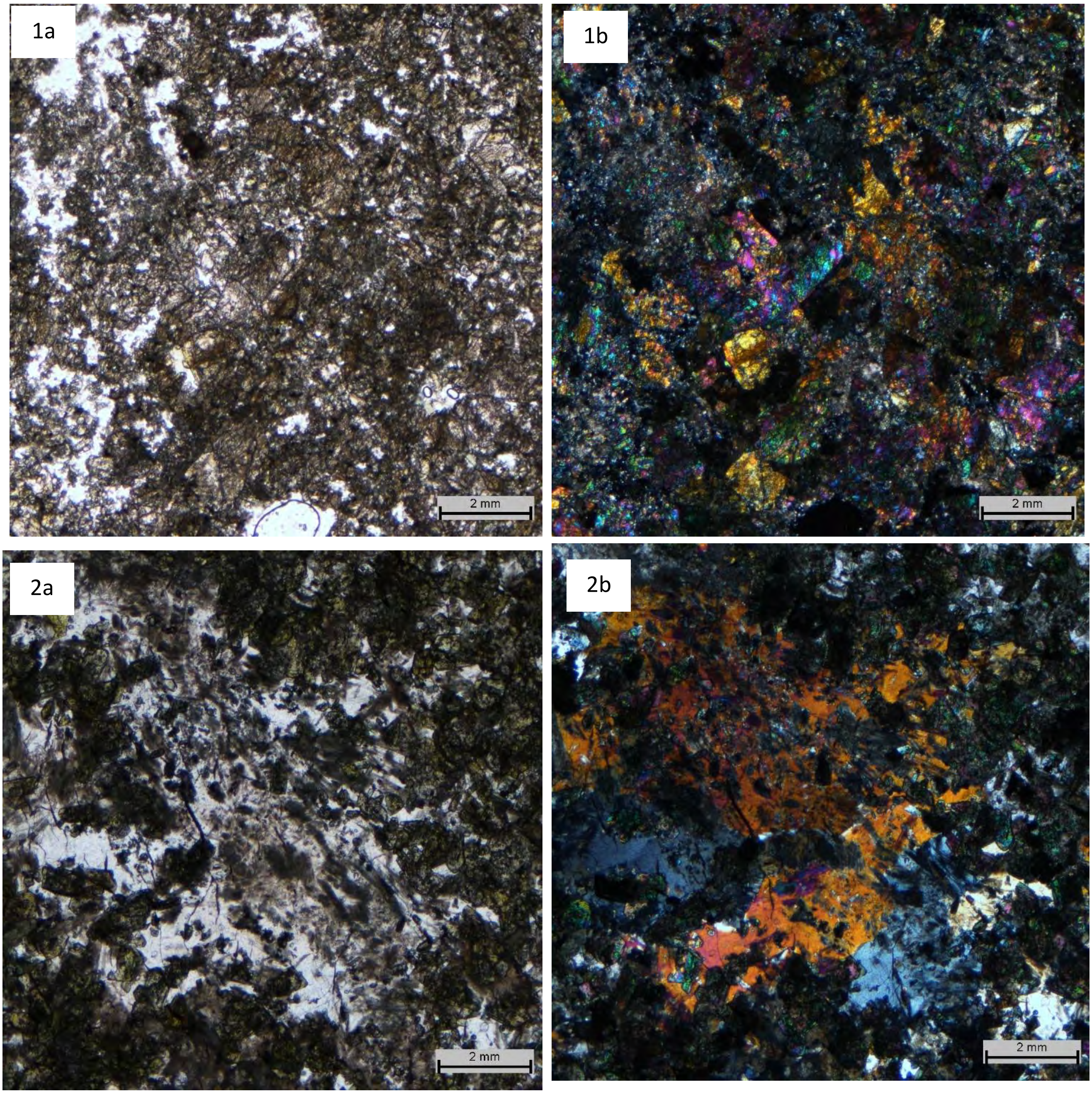


Figure 3.22 Photomicrograph of carbonate pyroxene skarn is showing medium- to coarse-grained diopside. Diopside is euhedral shape and showing prismatic crystal. Clinopyroxene is occasionally showing corroded grains.
(a: PPL, b: XPL; sample number Upper: KL03, Lower SN05)

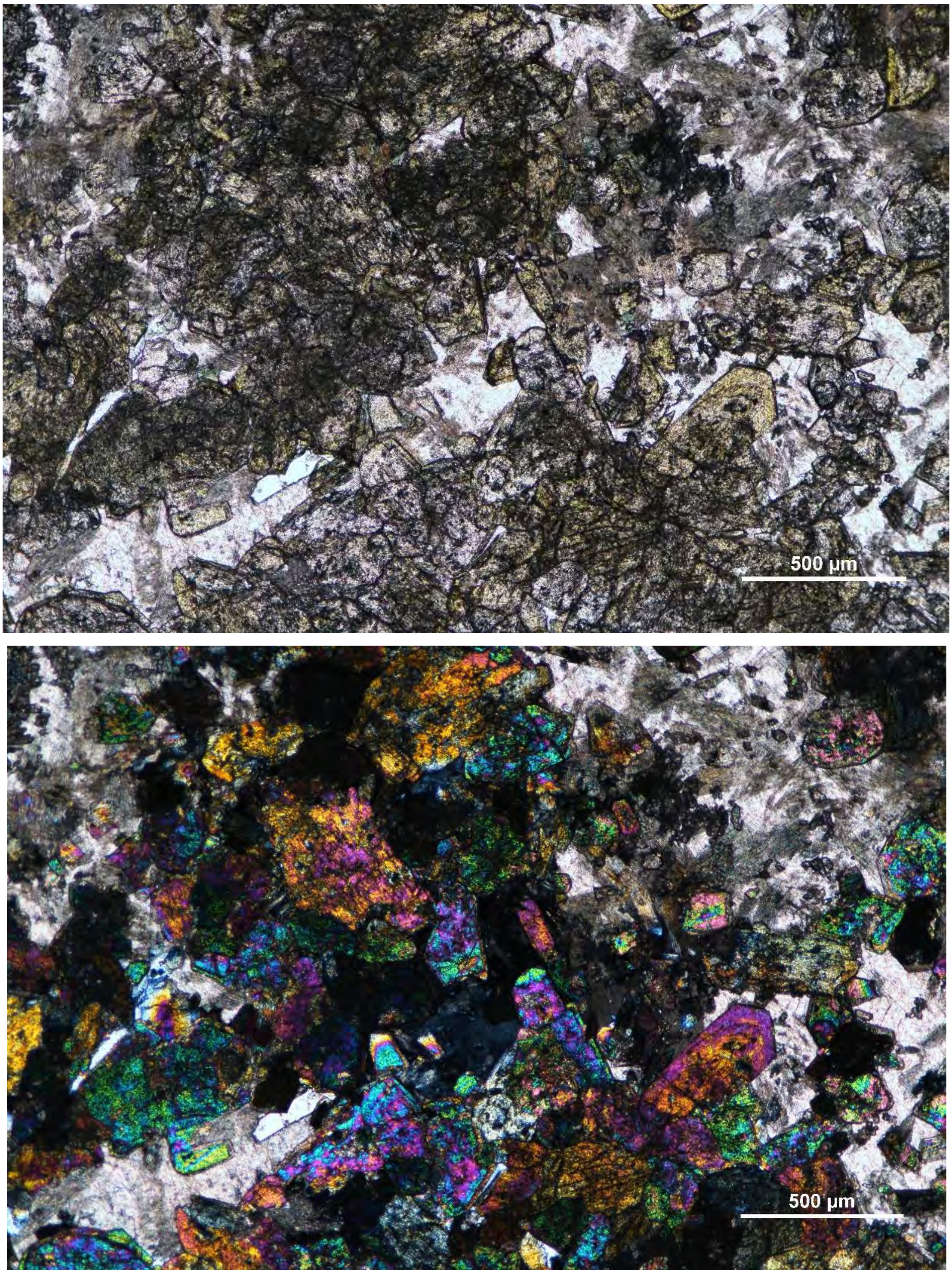


Figure 3.23 Closing up of epidote-clinopyroxene skarn under polarizing microscope. This photomicrograph shows high birefringence of diopside, euhedral prismatic and stubby shape. Most of diopside was replaced by epidote-chlorite-quartz that caused yellowish green color under PPL. (Upper: PPL, Lower: XPL; sample number SN05)

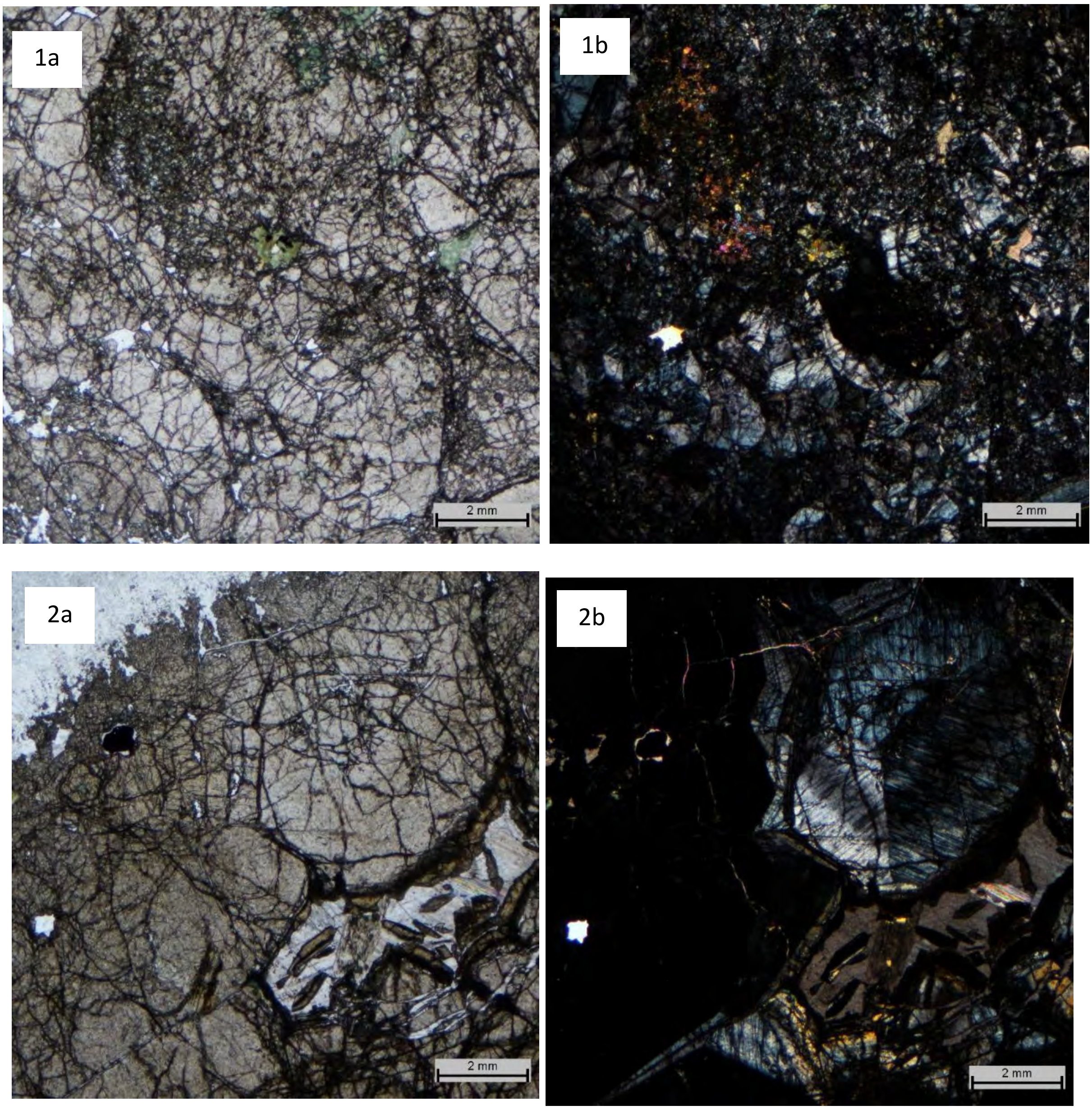


Figure 3.24 Photomicrograph of garnet skarn showed alteration features in garnet grains. Garnet was replaced by albite-quartz and chlorite-epidote-pyroxene. Alteration caused garnet increasing amount of anisotropic grains and also caused many crack in crystals.

(a: PPL, b: XPL, sample number: Upper; KL07, Lower; KL09)

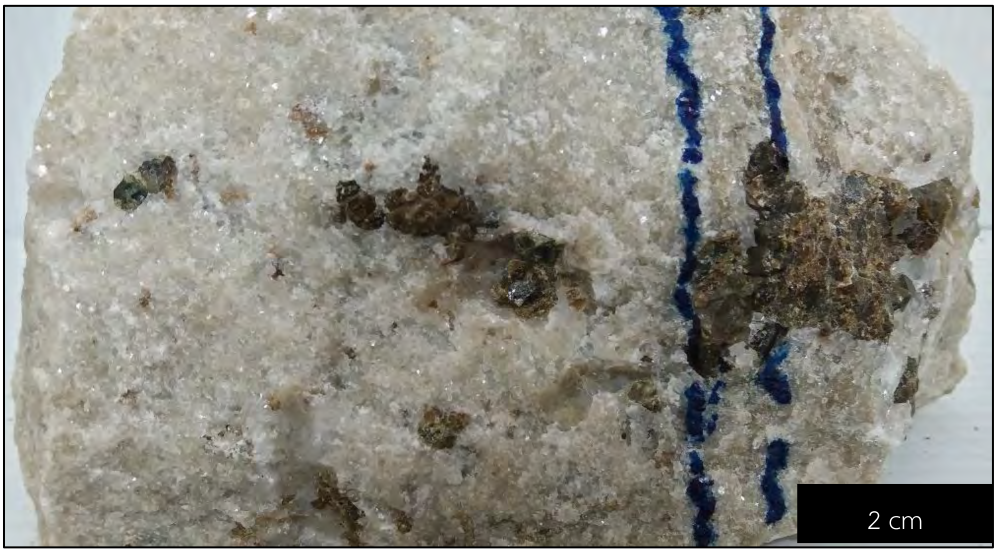


Figure 3.25 Hand specimen [upper photo] and slab [lower photo] garnet marble is showing large dark green garnet phenoblasts and coarse-grained of calcite. (sample number: SN09)

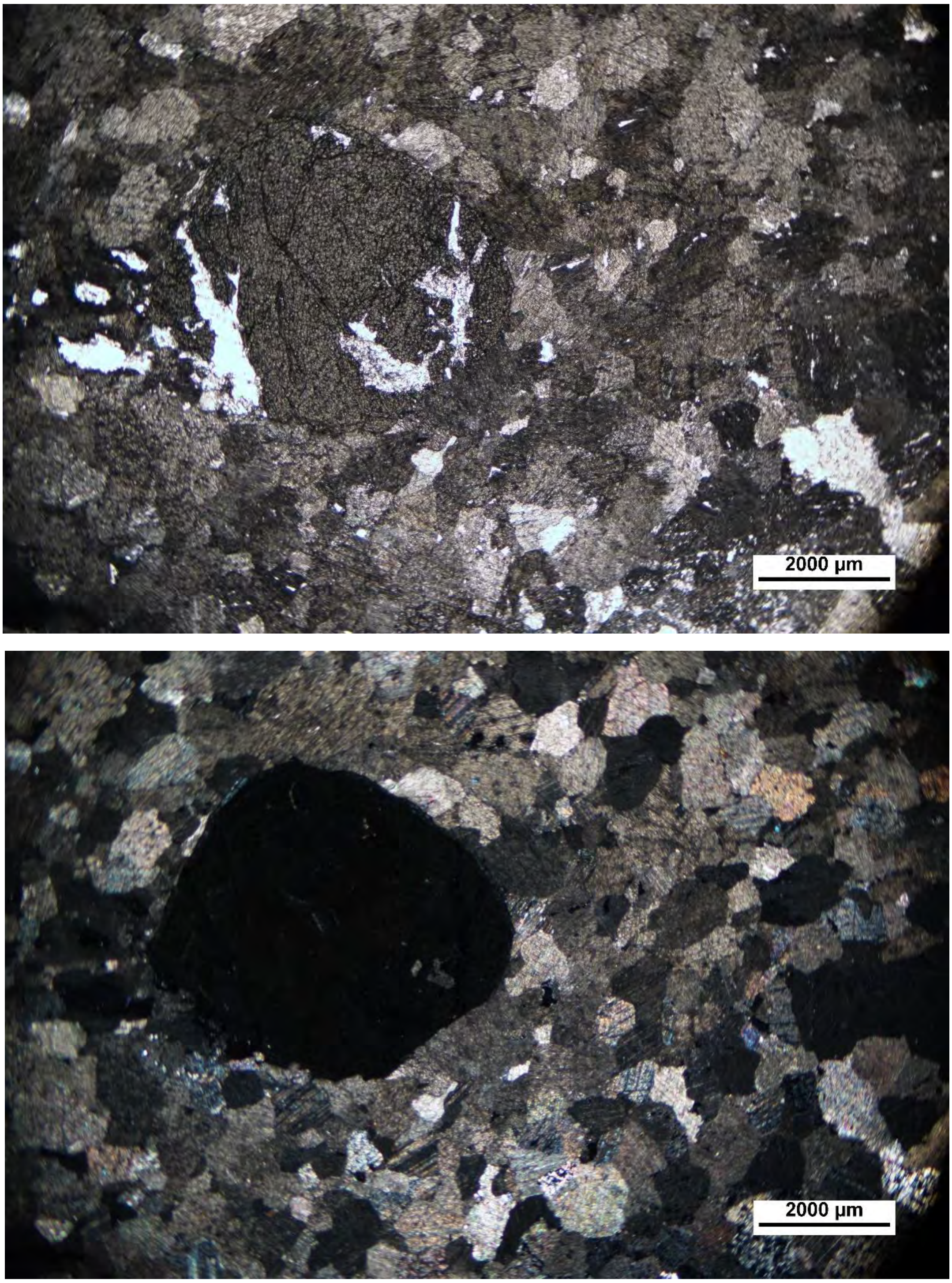


Figure 3.26 Photomicrograph of garnet marble is showing garnet phenoblast surrounded by calcite groundmass. Garnet is euhedral coarse-grained and isotropic. If you notice in plane polarized light photo, you will see some replacement of calcite in garnet. moreover, there are few pyroxene intergrowth with garnet grain.
(Upper: PPL, Lower: XPL; sample number: SN09)

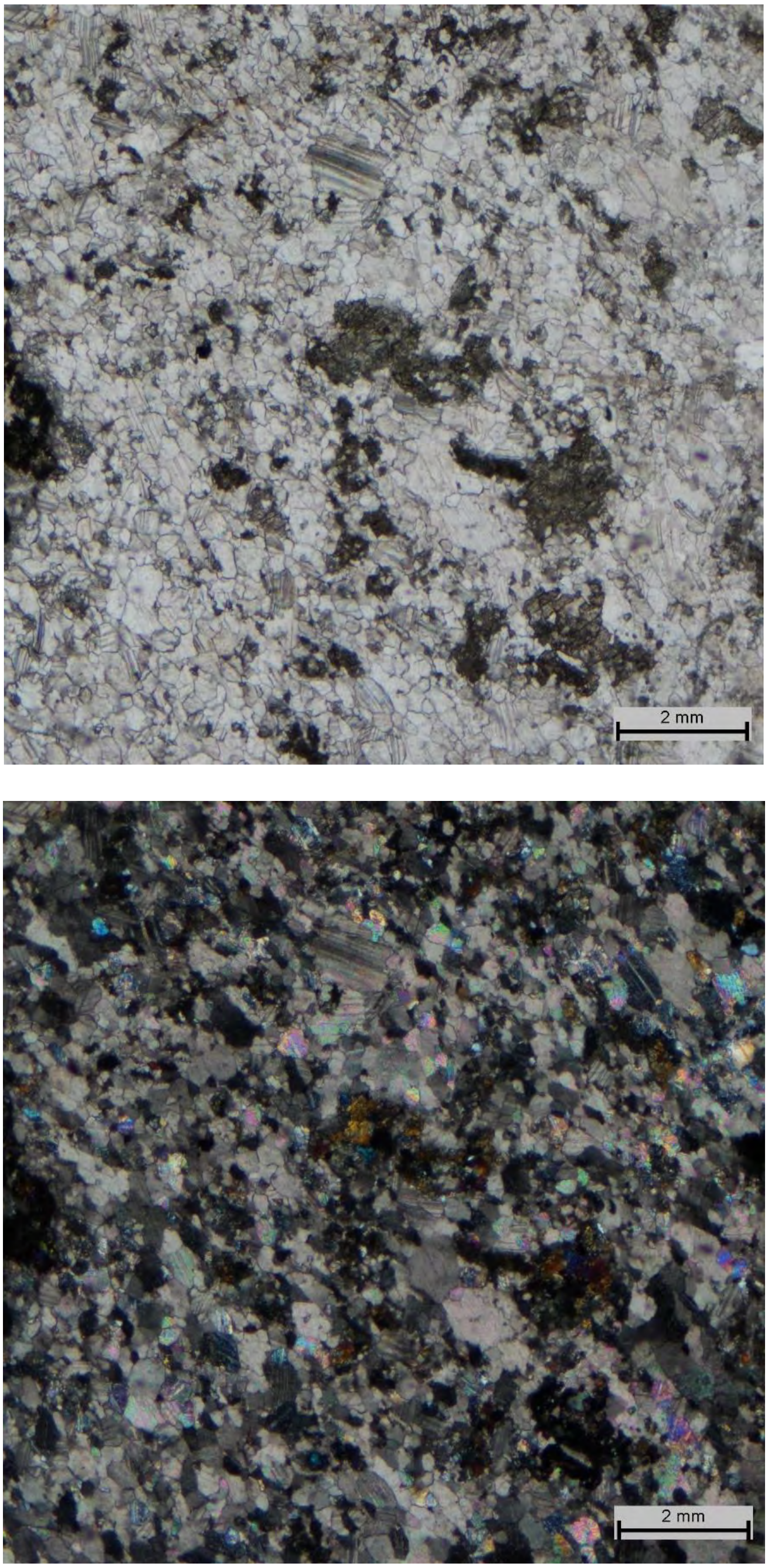


Figure 3.27 Photomicrograph of diopside marble is showing anhedral diopside intergrowth with calcite. Diopside is fine- to medium-grained and showing high birefringence. (Upper: PPL, Lower: XPL; sample number: KL01a)

CHAPTER 4
DISCUSSIONS

4.1 Zonation of Skarn

In Khao Lek area, mineral zonation of exoskarn can be divided into 2 main zones: garnet and clinopyroxene zones. In each zone also has composition variation which can be further divided into subzones. Extension of main zone is varying. It ranges from a few millimeters to 10 meters. This chapter is about classification exoskarn based on dominant minerals in each zone. Zonal arrangement of skarn at Khao Lek will be described below with some dominant petrographical features in each zone (Figure 4.1).

4.1.1 Garnet zone

Rocks in this zone composed of skarn and marble. It usually formed nearby magnetite dike. They commonly showed granoblastic texture. In proximal zone, closed to ore zone, most of garnets are anisotropic grains and showing oscillatory and sector zoning. This zoning reflects to fluctuation of fluid composition during prograde skarn formation. Those garnets should be Ca-Fe-rich garnet but may not be 100% andradite. They were commonly replaced by albite-quartz-epidote assemblage. Garnets were observed as medium- to coarse-grained granular aggregate and also cracked into crystal fragments varying in sizes.

Further away from magnetite dike, rocks mostly composed of isotropic garnet. There were a few alternating zoned grains. The crystals were also fractured but not shattered to pieces. They commonly altered to epidote-chlorite-calcite assemblage. From those features, it can be interpreted that later generations of fluid infiltration may not come through this zone. So, composition of fluid was not fluctuated, crystallizing to more homogeneous garnets consequently. In garnet marble, garnets were formed as phenoblasts in grano-porphyroblastic texture. Garnets are totally isotropic grain and showing euhedral shape. Garnet in marble usually was eroded which maybe occurred during retrograde alteration. These rocks, distal garnet skarn and garnet marble, have resemble features. So, we can group rocks into the same subzone.

From those information, we found that garnet in different position would show different features including alteration assemblages. This zone can be further divided in to 2 subzones: *Anisotropic garnet* and *Isotropic garnet* subzones, proximal and distal area respectively.

4.1.2 Clinopyroxene Zone

Clinopyroxene skarn can be classified 2 categories based on host rocks. Carbonate clinopyroxene zone contains clinopyroxene, epidote and calcite as essential minerals and chlorite, garnet, quartz as accessory. It usually altered to epidote-chlorite-calcite assemblage. While in volcanic clinopyroxene zone, skarn occurred as veinlets and mostly consisted of pyroxene and commonly altered to tremolite-actinolite-albite assemblage.

<u>Carbonate Clinopyroxene Zone</u>

In proximal zone, closed to garnet zone, clinopyroxenes in this skarn mostly are hedenbergite. It is common showing medium- to coarse-grained elongate crystals and has anhedral to subhedral shape. Hedenbergite is usually overprinted or replaced by epidote-chlorite-calcite. In distal zone, clinopyroxene will contain more diopside which may be due to effect of host rock composition or Mg-enrichment during metasomatism. Diopside often show stubby and granular aggregate which commonly was replaced by epidote. This skarn was commonly altered to epidote-chlorite-amphibole assemblage with occasional biotite. In diopsidic marble, diopside is fine-grained and anhedral shape intergrowth with calcite.

<u>Volcanic Clinopyroxene Zone</u>

For volcanic pyroxene skarn consists of granular aggregate of clinopyroxene and some prismatic orthopyroxene. They often altered to tremolite-actinolite-albite assemblage and some epidote-chlorite. Skarn in this zone is mostly formed as vein in meta-volcanic rocks.

In field observation, contact of garnet and clinopyroxene zone is sharply. But in thin section, we found that they also have gradation in composition. At the contact, skarn contains clinopyroxene as well as garnet content. We called this rock as garnet-clinopyroxene skarn. Garnet is yellowish green color and showing sector zoning. It is subhedral to euhedral shape and usually replaced by microcrystalline quartz, clinopyroxene and epidote. Clinopyroxene is fine-grained black crystals in hand sample and fine- to medium-grained subhedral in thin section, and usually altered to epidote.

As iron skarn deposit in the Turgai belt, northwestern Kazakhstan, the skarn was hosted by carbonate and volcanic rocks of the Carboniferous and related to mafic to felsic intrusive rocks. From previous studies of Hawkins et al. (2015), skarn and magnetite deposits are usually developed in carbonate host, but also, lesser extension and development in volcanic host rocks. So, from compare with another work, we can conclude that types of host affected to skarn zonation and extension.

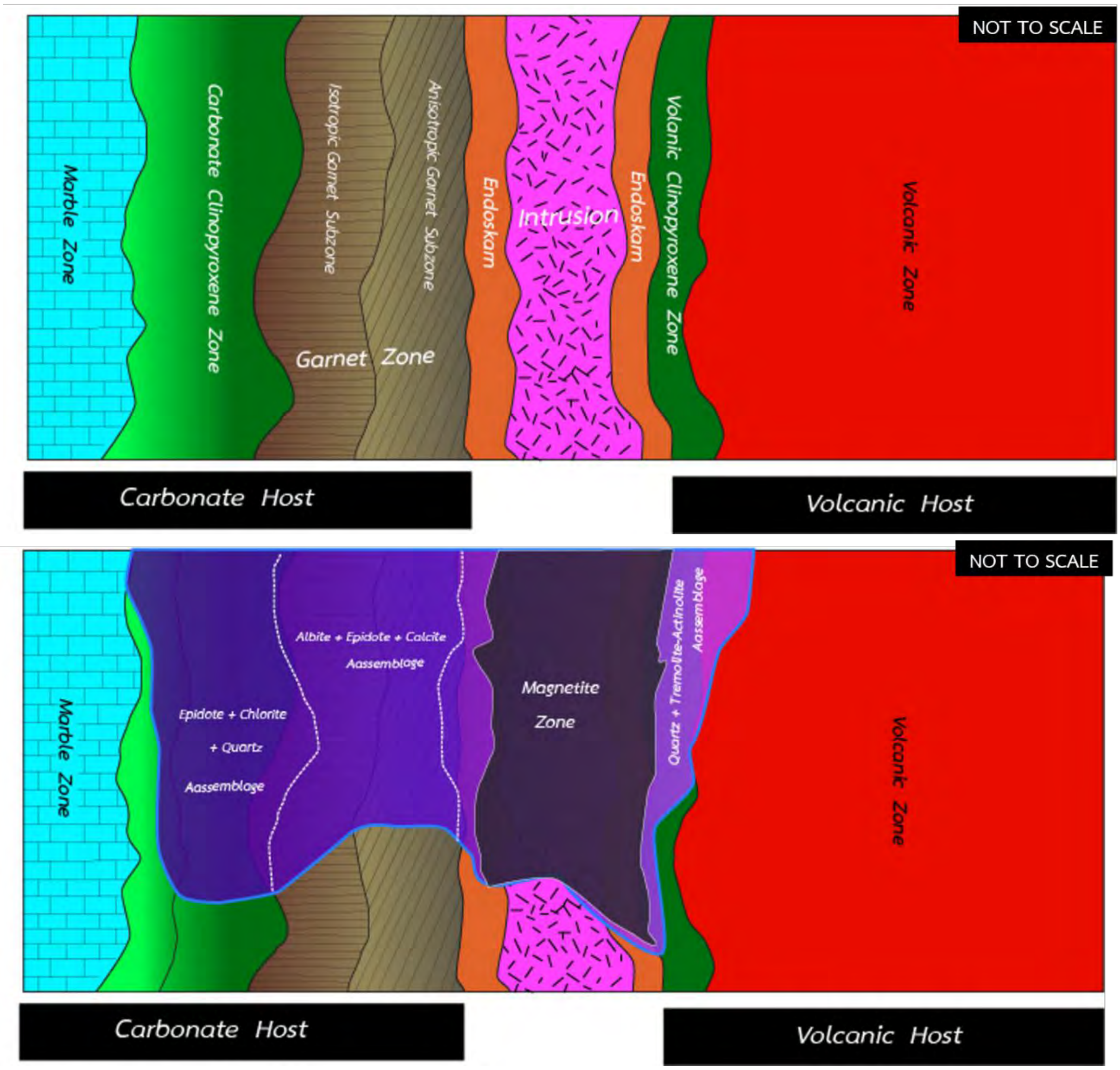


Figure 4.1 Simple models of skarn zonation in difference host rocks
a.) Prograde skarn zonation and zonal extension in difference host rocks.
b.) Retrograde skarn replacement which occurred as 3 main assemblages depended on each prograde skarn composition.

4.2 Khao Lek Iron Skarn Evolution

From previous work by Nakornsri (1977) and Khositanont (2008), carbonate rock in the area is Tak Fa Formation and Permian in age. Volcanic rocks in area are in Loei-Phetchabun volcanic belt and mainly are Permo-Triassic in age. From field and petrographic studies, we gained information about mineral assemblages and distribution of skarn at Khao Lek area. So, we can interpret the evolution of rock in study area.

In the Permian, there was carbonate deposits in Khao Kwang Platform which covered Khao Lek area and then they exposed to surface showing as mountain. The carbonate mountain was eroded and formed karst topography over time by surficial process. In the Permo-Triassic, there was lava flows in this area which caused volcanic rock discontinuously overlain on eroded carbonate unit (Figure 4.3).

Magma intruded to country rocks in the Triassic. It had thermally metamorphosed the wall rocks which are Permian carbonate rock of Tak Fa Formation and Permo-Triassic volcanic rock. When contact metamorphism and metasomatism took place, it caused development of prograde skarn assemblages replacing in host rocks. After that, external fluid had come to involve and developed retrograde skarn assemblages. In late stage of retrograde alteration, there was volcanic dike and hydrothermal breccia cross-cut through skarn. Finally, when system was cooling down, magnetite mineralization would occur and overprint on the skarn

From above, iron skarn formation in this area can be separated into 3 main stage; Isochemical metamorphism stage, metasomatism stage and retrograde alteration stage. Mineralization occurred during middle to late stage of retrograde alteration.

4.2.1 Isochemical Metamorphism Stage

It began with magma had intruded to carbonate and volcanic country rocks. They had respond to heat of magma as changing their textures and mineral phases. From previous petrochemistry studies, they found that plutonic rocks in Loei-Phetchabun fold belt, including at Khao Lek, has felsic to intermediate composition classified as granodiorite and diorite (Figure 4.2.; Kromkhun K. et al., 2013). Limestone had been recrystallized to marble. This stage might be taken place shortly after igneous emplacement and not significant ion exchanging between host rocks and igneous intrusion. Heat in this stage will cause metamorphic reaction, devolatilization, and gave some exchanging volatile phases such as; H_2O and CO_2 between carbonate and intrusion.

4.2.2 Metasomatism and Prograde Alteration Stage

During late stage of crystallization, magmatic fluid will be expulsed from intrusion and flowing through wall rocks. Infiltration of magmatic hydrothermal fluids produced endoskarn and small clinopyroxene exoskarn envelope. Early conduits would be blocked by former minerals. So, it caused new channels opening and resulting in other prograde envelopes. Continued fluid infiltration would cause progressive expansion of exoskarn envelope and develop proximal garnet exoskarn. Over time fluid composition would be fluctuated due to chemical properties of elements and metasomatic reaction in the fluids.

Characteristic of this stage is the formation of anhydrous calcsilicate mineral such as garnet and clinopyroxene. This stage began when fluid had been expulsed and come to involve in the system usually after isochemical metamorphism stage. Thermal metamorphism caused metasomatic process by released volatile materials, iron and silica rich fluids of magma as a result appeared skarns.

During metasomatism, fluid was containing Fe, Al Si and alkali elements which was added from the intrusion while CO_2 and H_2O would be lost. For Ca and Mg, they could be added or lost. The infiltration of magmatic fluid would form high-temperature skarn which contained largely anhydrous calcsilicate minerals, such as Ca-Fe-Al garnet (grossular-andradite), calcic clinopyroxene (hedenbergite-diopside) in metasomatized marble. Fluid would travel with dissolved elements through porosity of wall rocks. During fluid was flowing, it occurred chemical reaction and consequently formed those anhydrous minerals.

Clinopyroxene is essential mineral in prograde skarn assemblage. It was form during early to late stages of prograde alteration. Early alteration should mostly form clinopyroxenes as hedenbergite more than diopside but these hedenbergite usually altered to garnet or others minerals as in equation 6 and 7. When temperature changed, the cation enrichment sequence of clinopyroxene will occur due to changing thermal stabilities of the endmembers diopside, hedenbergite and johannsenite (Burt D.M., 1977). Fluids passing through clinopyroxene are usually depleted first in Mg that caused Fe enrichment and formed as hedenbergite. Next, closer to marble, fluids would be depleted in Fe and enriched in Mg formed diopside consequently. Finally, there was only Mn remaining in fluids. So, they should be forming johannsenite nearly marble unit but we did not observe them in our samples.

Changing temperature and fluid compositions were not only causing solid-solution but also causing mineral compatibilities and stabilities change such as; at hedenbergite-marble contact, these minerals will react together and become unstable like that showed in reaction (3). This reaction can explain that why we found some garnet zone attached with marble zone. (Figure 4.8)

$2CaCO_3$ + $4CaFeSi_2O_6$ + O_2 ----> $2Ca_3Fe_2Si_3O_{12}$ + $2SiO_2$ + $2CO_2$

(3)

Calcite Hedenbergite Andradite Quartz

And diopside might be formed like this:

$(Ca, Mg)CO_3$ + $2SiO_2$ ----> $CaMgSi_2O_6$ + $2CO_2$ (Intayot S. 2000)

(5)

Dolomite Quartz Diopside

$9CaFeSi_2O_6$ + $2O_2$ ----> $3Ca_3Fe_2Si_3O_{12}$ + $9SiO_2$ + Fe_3O_4

(6)

Hedenbergite Andradite Quartz Magnetite

$3CaFeSi_2O_6$ + S_2 ----> $Ca_3Fe_2Si_3O_{12}$ + $3SiO_2$ + FeS_2

(7)

Hedenbergite Andradite Quartz Pyrite

Garnet was abundant and important mineral in this stage. At the contact of intrusive out to host rocks, this chemical reaction would be occurred in fluid:

$3CaCO_3$ + Fe_2O_3 + SiO_2 ----> $Ca_3Fe_2Si_3O_{12}$ + $3CO_2$ (Deer et al.,1982)

(1)

Calcite Hematite Quartz Andradite

As you saw in above reaction, andradite concentration was resulting increasing fluid pressure (X_{CO2} pressure and f_{O2}) that caused cracking in host rock. And then amount of Fe_2O3 will be decreased due to fluid pressure decreasing**.** Then solid-solution of grossular-andradite can be formed as we showed in following reaction:

$3CaCO_3$ + Fe_2O_3 (Al_2O_3) + $3SiO_2$ ----> $Ca_3(Fe, Al)_2Si_3O_{12}$ + $3CO_2$ (Best, 1982)

(2) Calcite Quartz Grandite

Some garnet in Khao Lek skarn also shows complex, euhedral, oscillatory growth zoning, reflecting a history of garnet growth in a fluid. From petrographic study, we found that garnet in proximal skarn tended to be zoned/anisotropic rather than in distal skarn.

From our data, we think that hydrothermal fluid should be expulsed more than one time. So, when it was traveling through former garnet zone which generally consisted of isotropic grains of garnet. The fluid would alter those garnet crystals and make composition fluctuation at crystal rim, caused zoning in garnet consequently. While in distal zone, no new fluid moved through garnet so it can preserve the originally isotropic features.

Retrograde Alteration Stage

It was affected from meteoric circulated into the skarn system. The meteoric water would be heated and evolving to hydrothermal solution. The solution would be traveling through skarn and altered minerals in prograde skarn assemblages into lower temperature mineral assemblages which mainly consisted of epidote, chlorite, quartz, biotite and tremolite-actinolite. Moreover, the late stage fluid of retrograde skarn would be causing iron mineralization fully overprinted on intrusive body and endoskarn. So that why we found ore zone attached to garnet skarn and did not see any plutonic dike or endoskarn in the mine.

During retrograde skarn formation, the hydrothermal fluids, H_2O-rich fluid, will come through skarn and change the existed minerals. Changing in fluid pressure will lead to chemical disequilibrium and cause shape of garnet rims that are growing from this fluid irregular. This changing is also causing many fractures in garnet crystals. Moreover, fluids also reacted with former mineral assemblage to formed replacement of minerals according to reaction (8);

$$Ca(Mg, Fe)Si_2O_6 + 3CO_2 + H_2O \dashrightarrow Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2 + 3CaCO_3 + SiO_2 \quad (8)$$

Diopside-Hedenbergite Tremolite-Actinolite Calcite Quartz

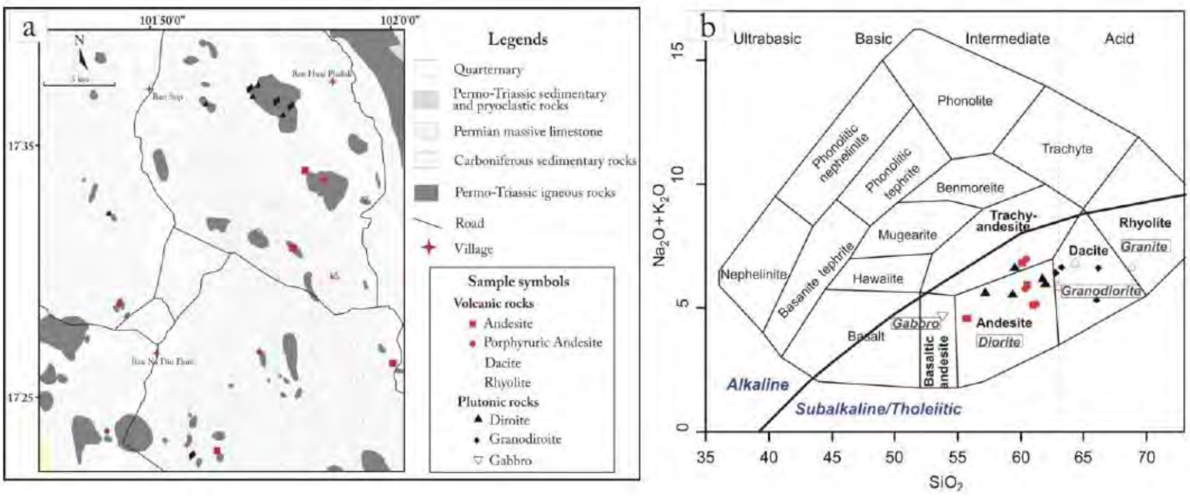


Figure 4.2 Total-alkali-silica diagrams of plutonic rocks in Loei belt;
a.) Geologic map and sample locations;
b.) Classification and composition of Loei igneous rock.
(Kronkhun K. et al., 2013)

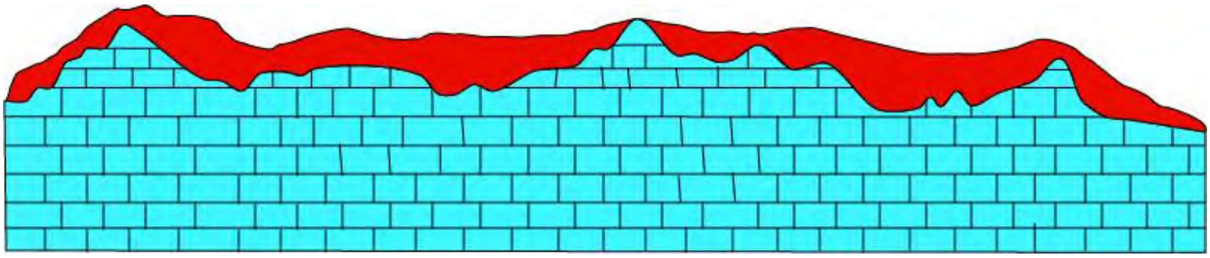


Figure 4.3 Simple model shows host rocks deposit before magma intrusion.

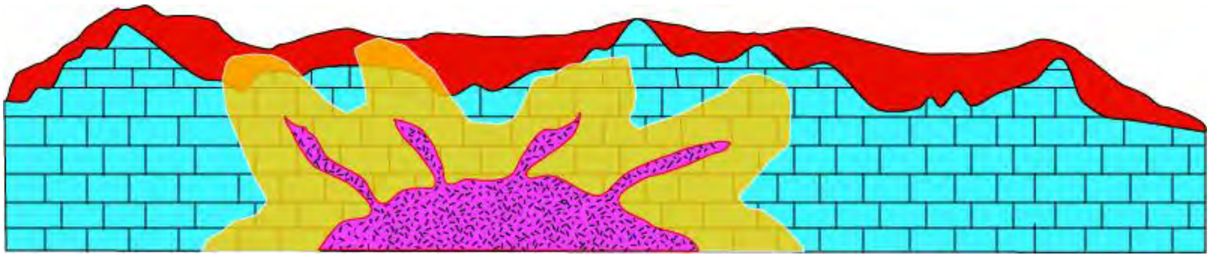


Figure 4.4 Simple model of isochemical metamorphism occurred in large scale caused calcsilicate and marble formation in the area.

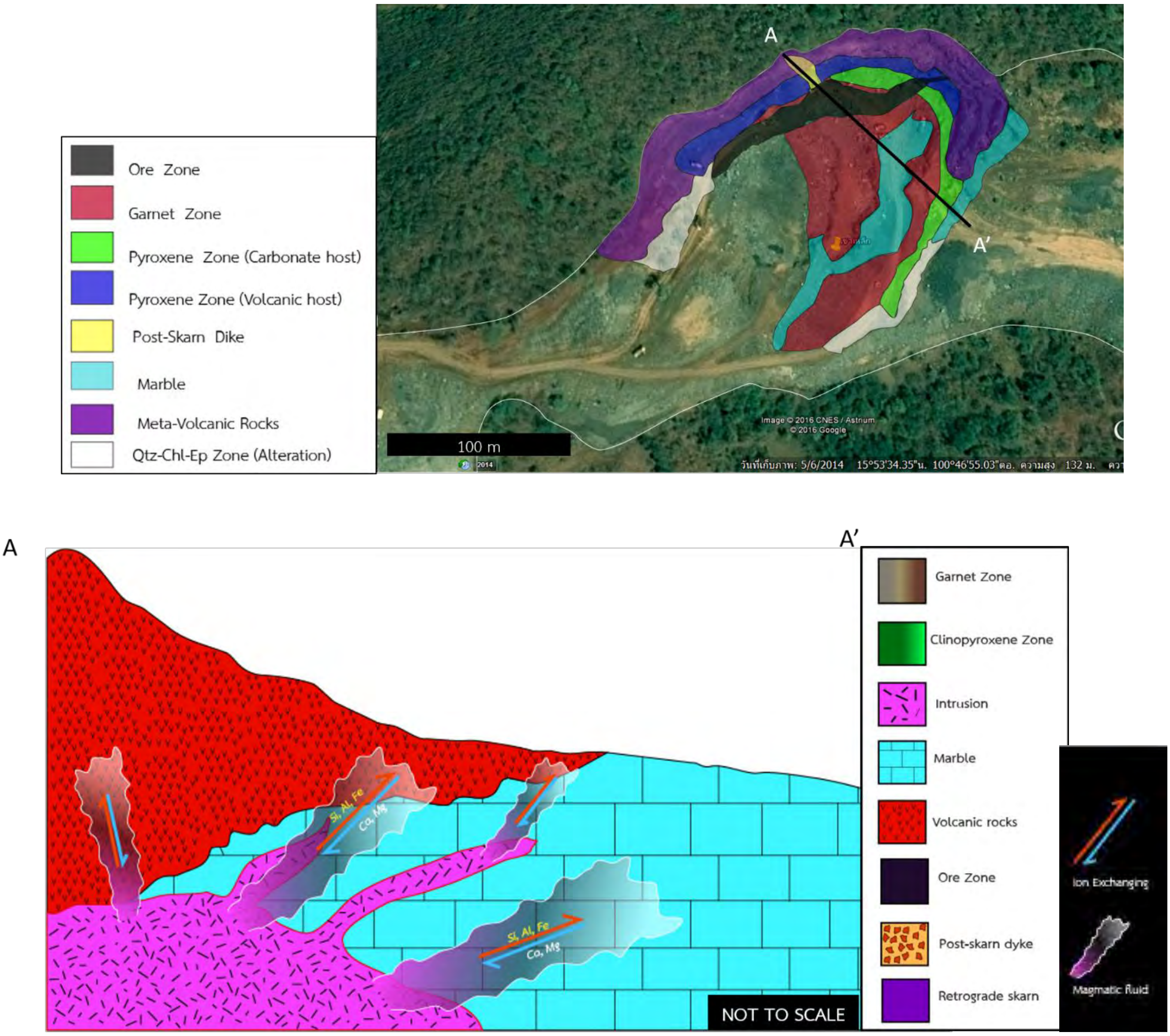


Figure 4.5 Comparison of model and position in mining area.
In upper photo, line of cross section that show all units of skarn alteration. Lower photo shows late stage of crystallization causing magmatic fluid expulsed and ion exchanging in fluid between 2 rocks that we called metasomatism.

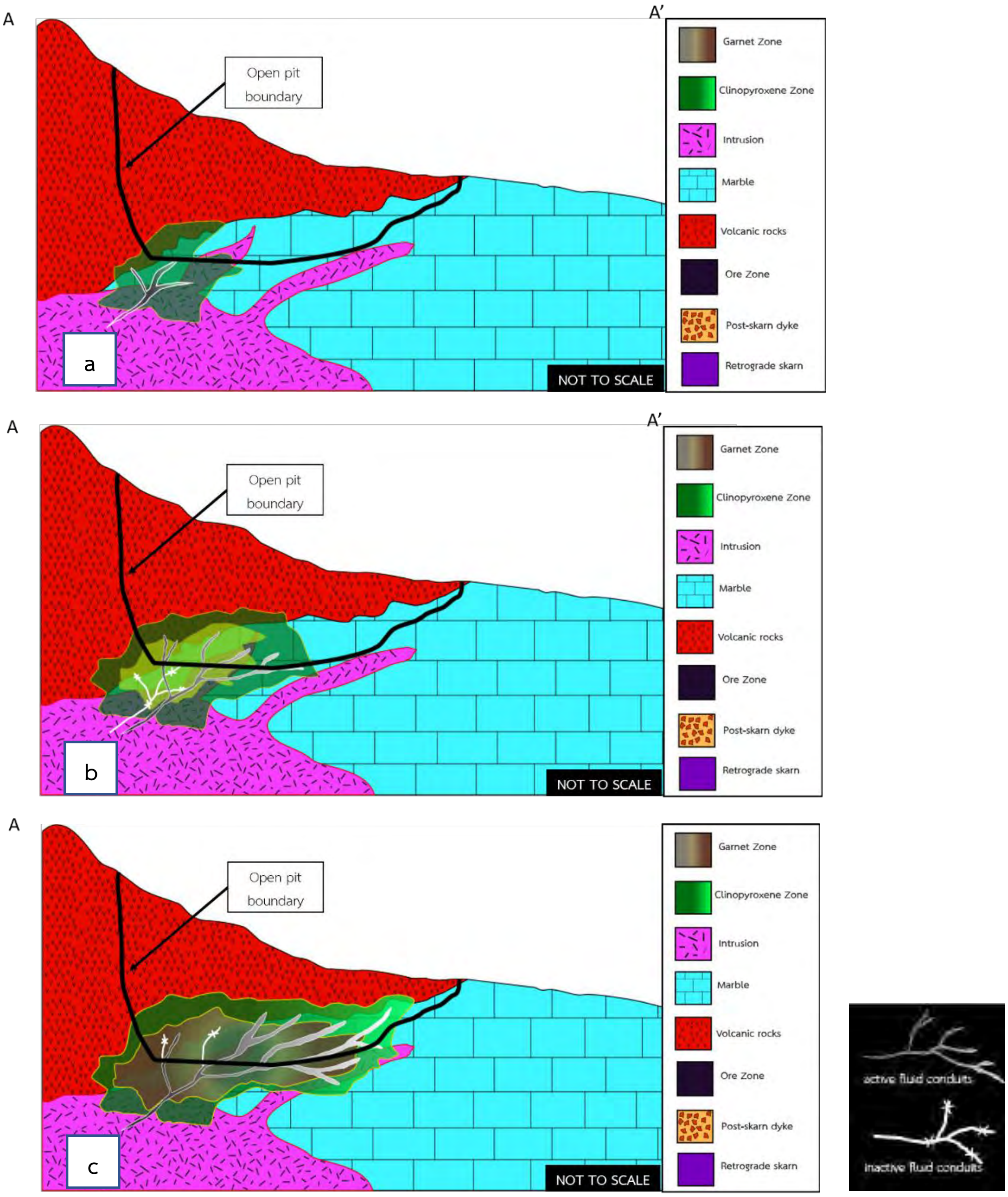


Figure 4.6 Models of prograde skarn alteration stage

a.) Fluid infiltration to produce endoskarn & small prograde exoskarn envelope

b.) Earlier conduits were blocked, resulting in new channel opening and development of garnet skarn.

c.) Continued fluid infiltration caused progressive expansion and composition variation of exoskarn

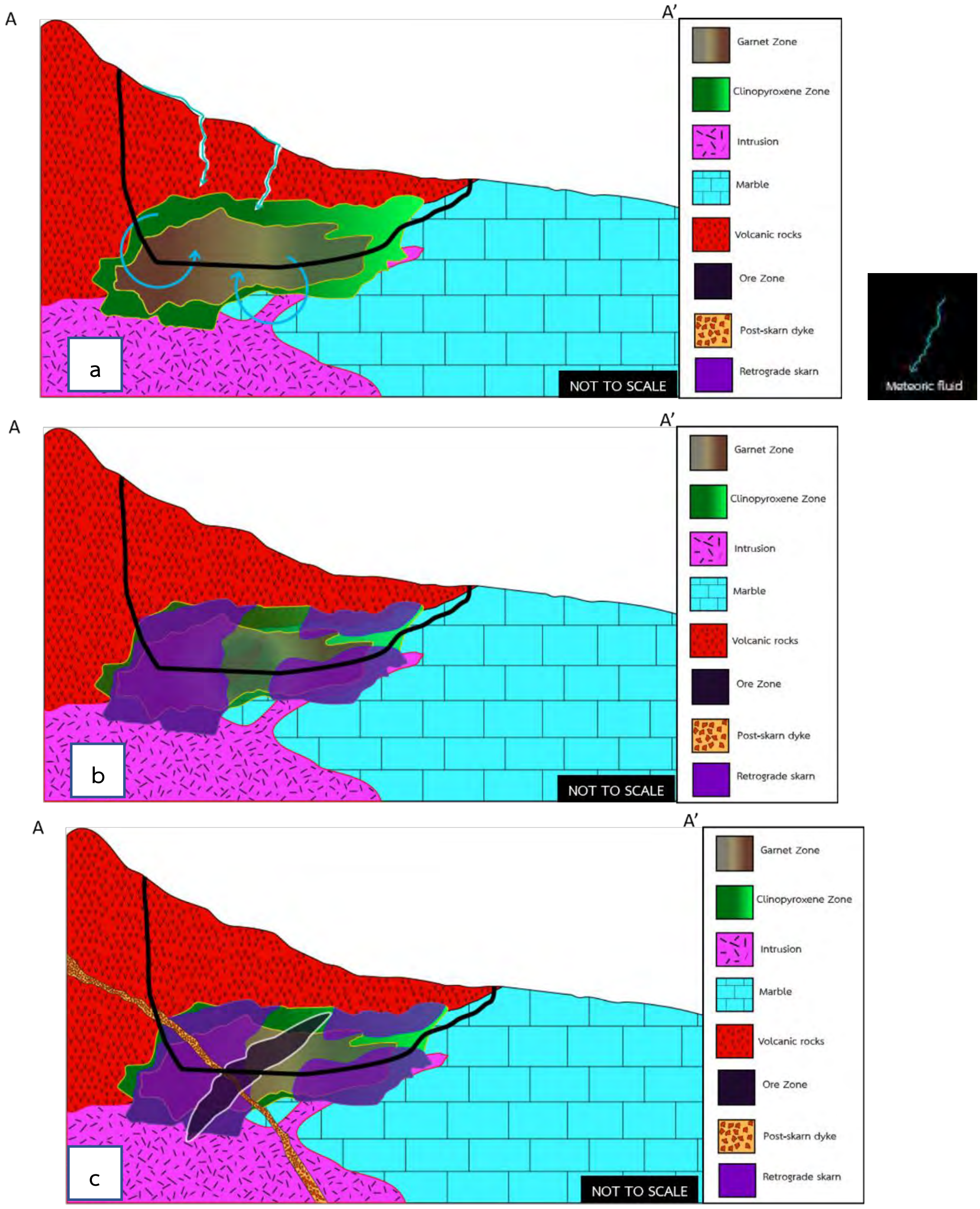


Figure 4.7 Models of retrograde skarn alteration stage

a.) Meteoric fluid circulated into skarn and caused system cooling down.

b.) Meteoric hydrothermal fluid would induce H_2O and O_2 caused hydrous minerals formation in retrograde skarn.

c.) When the hydrothermal system was cooling down, metal-rich fluids would migrate into exoskarn and redeposit to form orebody.

Figure 4.8 Contact of garnet and marble zone in outcrop scale.

CHAPTER 5
CONCLUSION

- Khao Lek skarn is classified as calcic skarn and iron skarn deposit. Host of skarn composes of andesitic sandstone and marble. Skarn zonation arranges from garnet zone, garnet-pyroxene zone, epidote-clinopyroxene zone to marble or unaltered volcanic rock. Magnetite formed as massive body closed to garnet zone. Ore body occurred as overprinting on endoskarn and intrusive body.

- Types of host affect to skarn extension. Because andesitic rocks contain less calcic components than in limestone, and their compositions are also different from intrusive not enough to cause ion exchanging as a wide area. So, skarn formed as veinlets in volcanic host and extended less than in carbonate host which skarn replaced whole outcrops.

- Proximity of skarn also affect to petrographic features of garnet crystals. In proximal garnet zone which closed to intrusive body, garnet crystals mostly show first order interference colors under cross polar and also have many zoned grains. Those features indicated to anisotropic grains. Whereas in more distal garnet zone which is far away from ore zone and closed to clinopyroxene or marble zones, garnet crystals mostly are isotropic grains and containing a few zoned grains. All of these can be concluded that hydrothermal fluid was expulsed many times from intrusive. So, it was traveling through former garnet zone which generally consisted of isotropic grains of garnet. The fluid would alter those garnet crystals and make composition fluctuation at crystal rim, caused zoning in garnet consequently. While in distal zone, no new fluid moved through garnet. So it can preserve the originally isotropic features.

- Skarn evolution at Khao Lek area is similar to general skarn formation which have three main stages: isochemical metamorphism, metasomatism and prograde skarn alteration, retrograde alteration and mineralization. Due to skarn was found as only in Khao Lek area, so magma that caused iron skarn deposit in the area should come as small intrusive body and cause metasomatism in local scale.

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