J. Myanmar Acad. Arts Sci. 2018 **Vol. XVI. No. 5**

GRANULITE AND ITS *P-T* CONDITION OF THE MOUNT LOI-SAU AND ITS ENVIRONS, MOGOK TOWNSHIP, MANDALAY REGION AND MOMEIK TOWNSHIP, SHAN STATE (NORTH)

Wai Yan Lai Aung*

Abstract

A new unit composed of felsic and mafic granulitic rocks are exposed in the study area. Granulite (Latin granulum, "a little grain") is a name first introduced by petrographers. Such a rock is characterized by a mineral assemblage that was developed under high-grade metamorphic conditions. Granulites were observed around Mogok and Momeik area. The writer will try to draw some comparisons between felsic and mafic granulite of the study area with reference to the theoretical definitions by some authors and websites.

The study area is situated in the remote area between Mogok Township, Mandalay Region and Momeik Township, Shan State (North), on either side of Mogok-Momeik motor road. The study area, which is a segment of the Mogok Metamorphic Belt, is mainly composed of metamorphic rocks and granitic and syenitic intrusions. Taking the metamorphic rock units of the study area into consideration, granulite rock is fairly exposed and it is associated with both sillimanite-garnet-biotite gneiss and interbedded with marble and calc-silicate rocks. Granulite unit is intruded by syenitic and granitic rock. Granulite can be subdivided into two distinct units based on pyroxene percentage (< and > 30%); felsic granulite (<30%) (sapphirine-hypersthene-garnet-biotite granulite) and mafic granulite (>30%) (pyroxene granulite), respectively.

Petrochemically, sillimanite-garnet-biotite gneisses in the study area have reached granulite facies (730-810 ºC & 6.5-9.3 kbar), characterized by the mineral assemblages and petrochemical results from EPMA and XRF. The *P-T* condition of granulite rocks in the study area should probably be the same as and/ or greater than the *P-T* condition of the high-grade gneiss of the study area, according to the mineral assemblages: orthopyroxene + alkali feldspar + biotite + chlorite + plagioclase +garnet + quartz + rutile + sillimanite + sapphirine + opaque + hercynite + sillimanite + sericite + zircon + ilmenite of felsic granulite and mineral assemblages clinopyroxene + biotite + plagioclase (andesine) + alkali feldspar + quartz + perthite + orthopyroxene + sphene + opaque + chalcedony + antigorite of mafic granulite.

Key words: *felsic granulite, mafic granulite, sillimanite-garnet-biotite gneiss, EPMA, hercynite, sapphirine..*

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Introduction

The topic will deal with a new unit composed of felsic and mafic granulitic rock in the study area. Granulite (Latin granulum, "*a little grain*") is a name first introduced by petrographers. Such a rock is characterized by a mineral assemblage that was developed under high-grade metamorphic conditions. Granulite was first described in Bohemian Massif. As things stand, granulite rock was found around Mogok and Momeik area. The author drew some comparisons between felsic and mafic granulite of the study area with reference to the theoretical definitions by Weiss (1803), Michel Lévy (1874), Moorhouse (1959), Cogné (1961), Mehnert (1972), Winkler and Sen (1973), Alex Streckeisen (1975) and (*www.alexstrekeisen.it*), and some other authors and websites.

Location of the study area

The study area is situated in the remote area between Mogok Township, Mandalay Region and Momeik Township, Shan State (North), and located at about north of Mogok and south of Momeik, near the Mogok-Momeik highway. It lies between Latitudes 22° 56' 30" N - 23° 01' 00" N and Longitudes 96° 34' 30" E - 96° 41' 30" E. The study area is accessible by car from Mandalay, a city in Central Myanmar, which can be reached by air, rail, and road from Yangon, but the accessibility to the study area is limited due to some minor of insurgency. The location map is shown in (Fig. 1).

Practical naming of granulite in the study area

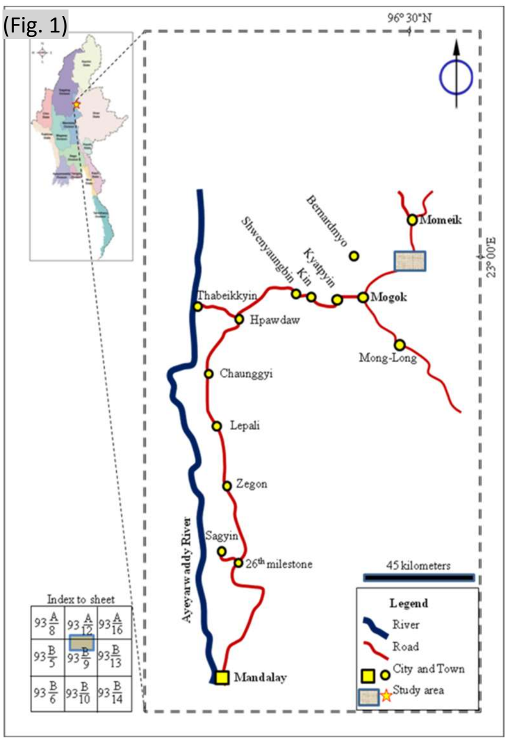
Granulite can be subdivided into two distinct units based on pyroxene percentage (< and > 30%); felsic granulite (<30%) (sapphirine-hypersthene-garnet-biotite granulite) and mafic granulite (>30%) (pyroxene granulite), respectively.

Mineral assemblages of granulite rocks in the study area are as follows:

Felsic granulite = orthopyroxene + alkali feldspar + biotite + plagioclase + chlorite + garnet + quartz + rutile + sapphirine + ilmenite + hercynite + sillimanite + zircon.

Mafic granulite = clinopyroxene + biotite + plagioclase + alkali feldspar + quartz + perthite + orthopyroxene + ilmenite + sphene + chalcedony + antigorite.

Mineral percentages of felsic and mafic granulites are shown in bar graphs (Fig. 2).



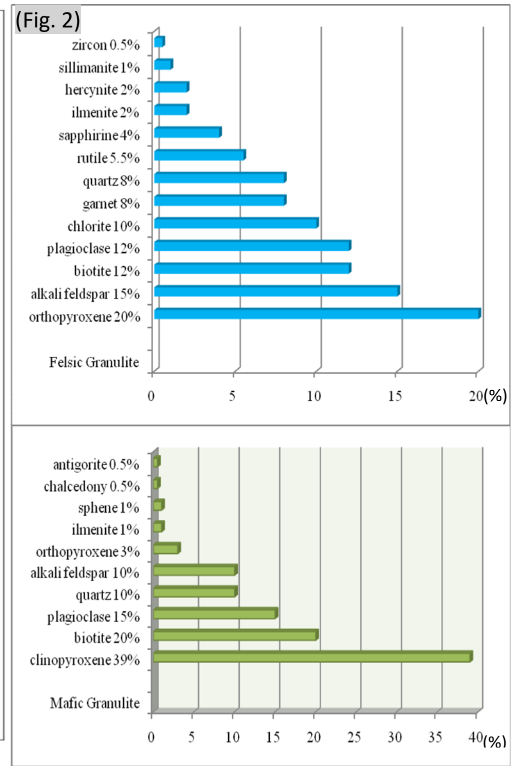


Figure1. Location map of the study area.

Figure 2. Mineral percentages bar graph of felsic granulite (sample no. 8B) and mafic granulite (sample no. 44) of the study area.

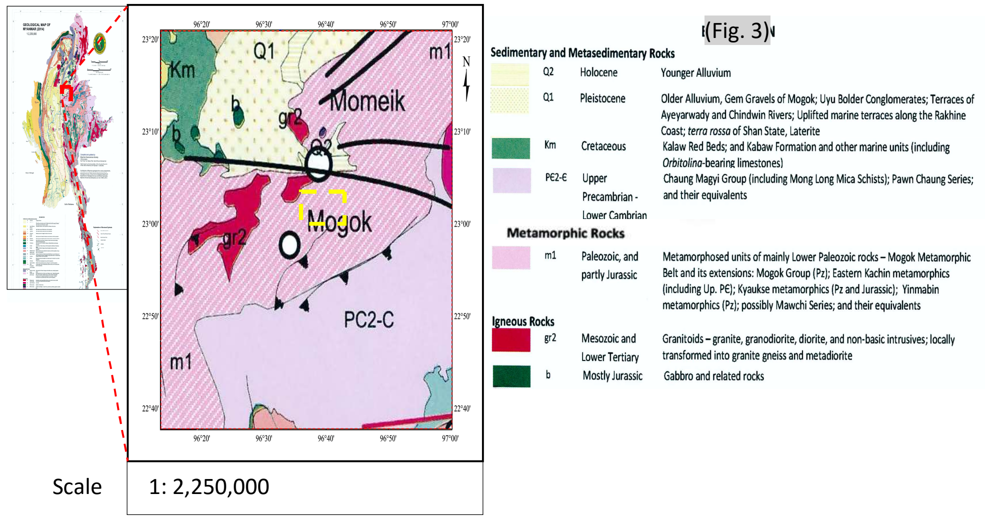


Figure 3. Regional geological map of the study area and its environs (After Geological Map of Myanmar Geosciences Society, 2014).

Geologic Setting

The study area, Mount Loi-Sau is situated in the northern part of Mogok Metamorphic Belt (MMB) of Searle & Ba Than Haq (1964). It is relatively narrow, elongated, sigmoidal belt which is generally oriented north-south, adjacent to the N-S trending Sagaing Fault in the west and Shan Scrap Fault in the east (Bertrand, 1999). The geology of Mogok area is very complex, and characterized by steeply dipping, deformed, medium to high grade metamorphic rocks consisting mainly of mica schist, marbles, calc-silicate rocks, gneisses and quartzites, which are often intruded by many granitic and syenitic intrusive rocks. Regional geological map of the study are is shown in (Fig. 3) (Myanmar Geosciences Soceity, 2014).

Rocks in the investigated area are categorized into medium- to- high-grade metamorphic rock units (Late Oligocene) and younger igneous intrusions (Early Cretaceous to Middle Miocene). The metamorphic rocks covered about 90% of the whole area which is principally underlain by sillimanite-garnet-biotite±ilmenite gneiss, garnet-biotite gneiss, spinel-diopside-forsterite-phlogopite marble, white marble and calc-silicate rocks.

Moreover, two types of granulite, namely felsic and mafic granulites are also recently contributed from the study area (Wai Yan Lai Aung, 2016) (Fig. 4).

General geology of granulite in the study area

Taking the metamorphic rock units of the study area into consideration, granulite rock is only fairly exposed and it is associated with sillimanite-garnet-biotite gneiss. This unit is intruded by syenitic and granitic rock, which can be subdivided into felsic granulite (sapphirine-hypersthene-garnet-biotite granulite) and mafic granulite (pyroxene granulite).

Felsic granulite is discovered at the base of Mount Loi-Sau (Loc: Lat : 22º 58' 49.4" N, Lon : 96º 37' 52.2" E) and associated with sillimanite-garnet-biotite gneiss. They comprise garnetiferous rock with a strongly gneissose texture. They show NE-SW trend and west dipping at 48º (Fig. 5, A).

On the other hand, good exposure of mafic granulite is found beside Mogok-Momeik motorway that is intruded by syenitic rock which is partially foliated (Loc: Lat : 22º 58' 33.6" N, Lon : 96º 34' 17.0" E, Fig. 5, B). Mafic granulites are of massive and banded type. It is very similar to calc-silicate rock in appearance but mafic granulites are mainly composed of pyroxene, feldspar, quartz and biotite minerals. It can be called ~~as~~ pyroxene granulite. This granulite shows NNE-SSW trend and west dipping at 85º. At this outcrop, the enclaves of pyroxene granulite can be seen clearly in syenitic rock.

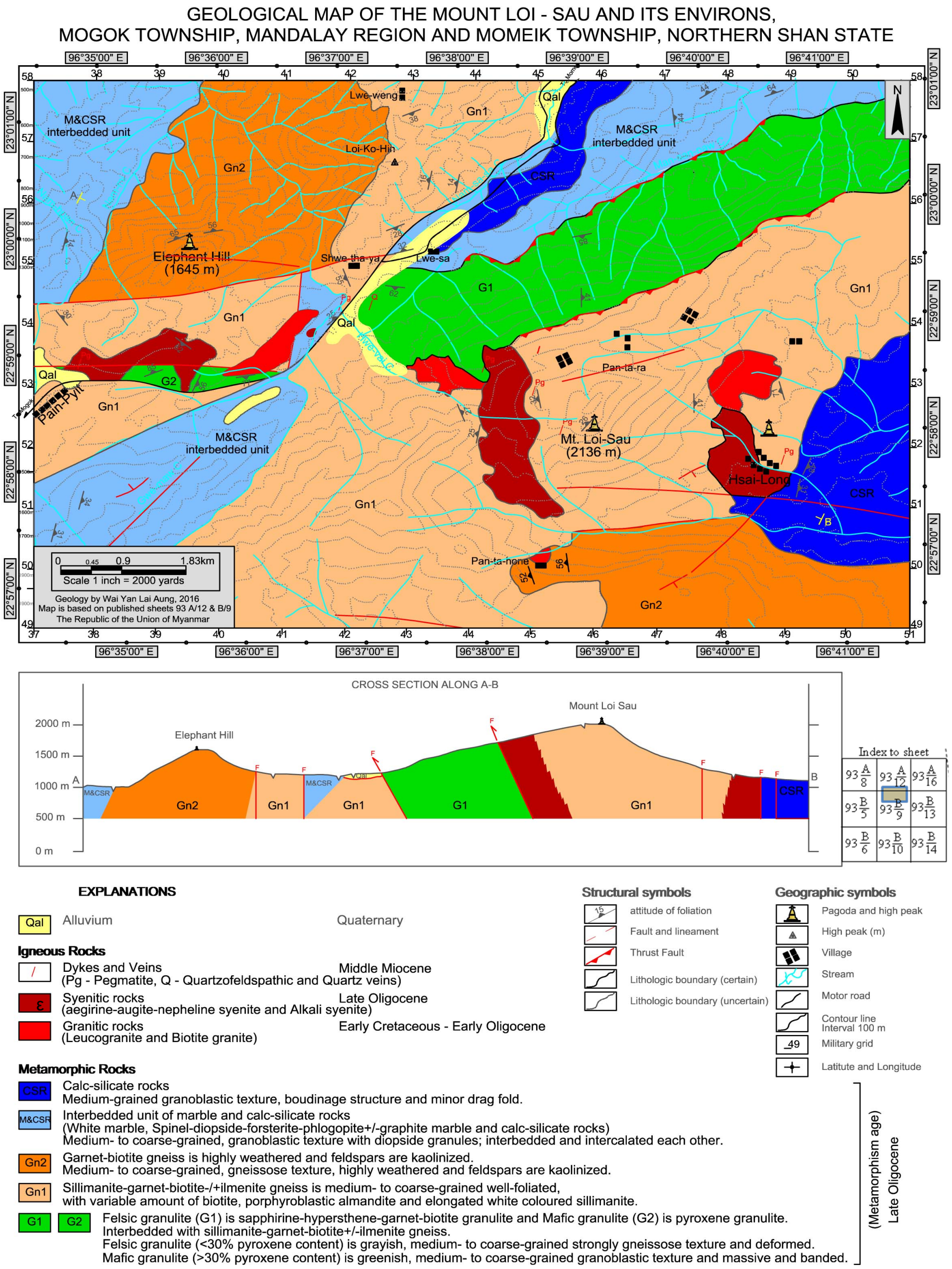


Figure 4. Geological map of the study area.

Figure 5.A Felsic granulite (Loc : Lat : 22º 58' 49.4" N, Lon : 96º 37' 52.2" E) (Looking 60º).

Figure 5.B Mafic granulite (Loc : Lat : 22º 58' 33.6" N, Lon : 96º 34' 17.0" E) (Looking 10º)

Confusions Between Felsic and Mafic Granulite in the Study Area

Felsic granulite (sapphirine-hypersthene-garnet-biotite granulite)

Megascopically, felsic granulite is medium- to coarse-grained with a strongly gneissose texture and well-jointed as it is always the case in nature. In hand specimen, quartz, feldspar, biotite, garnet, pyroxene are easily identifiable with the naked eye. In hand specimen, mostly pyroxene, quartz, feldspar and biotite show separate bands as mineralogical banding. Fresh surface of felsic granulite is whitish grey and weathered surface is reddish grey. Garnet is 0.4 cm to 1 cm in diameter while feldspars are sometimes up to 1 cm (Fig. 6, A).

Mafic granulite (pyroxene granulite)

Megascopically, pyroxene granulite is medium- to coarse-grained, of banded and massive type in nature. Most biotites are weathered and segregated as separated layers with the pyroxene + quartz + feldspar assemblages. Its fresh surface is greenish and weathered surface is dark green. Pyroxene is up to 1 cm in diameter (Fig. 6, B).

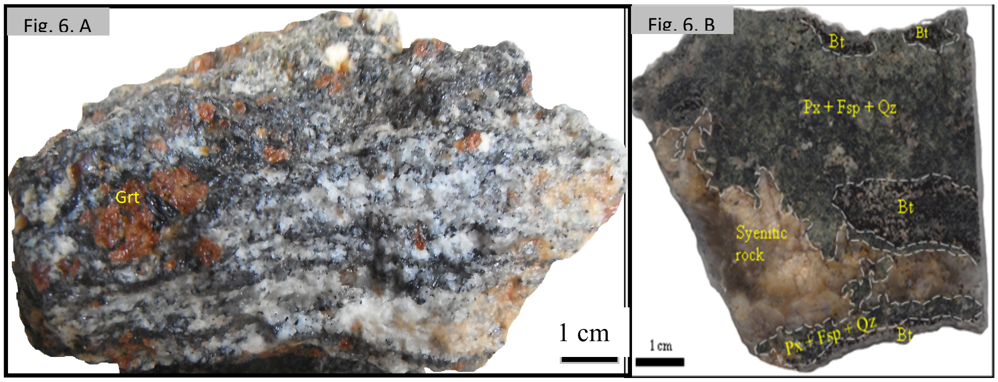


Figure 6. A Macroscopic view of felsic granulite
(Loc : Lat : 22º 58' 49.4" N, Lon : 96º 37' 52.2" E) (sample no. 8B).
Figure 6. B Macroscopic views of mafic granulite rocks' polished surfaces
(Loc : Lat : 22º 58' 33.6" N, Lon : 96º 34' 17.0" E) (sample no. 44)

Felsic granulite (<30% pyroxene content) is strongly deformed, grayish and can be confused with gneiss unit.	Mafic granulite (>30% pyroxene content) is massive and banded, greenish and can be confused with calc-silicate rocks.

Microscopic Description and Interpretation of Granulite

Felsic granulite (sapphirine-hypersthene-garnet-biotite granulite)

Microscopically, it is medium- to coarse-grained with a strongly foliated gneissose texture. It is mainly composed of orthopyroxene, plagioclase, alkali feldspar, garnet, biotite, chlorite, and quartz. Rutile, sapphirine, hercynite, sillimanite, sericite, ilmenite and zircon are accessory minerals (Fig. 7, A). Hypersthenes occur as pale red subhedral crystals and show greenish to pale reddish paleochroic colour under PPL, showing high relief, parallel extinction and first order pale red interference colour between crossed nicols. Hypersthene is associated with biotite, and sometimes with garnet, sapphirine and hercynite. Most plagioclases are cracked. They are found as anhedral to subhedral grains, surrounded by rim myrmekite and albite to andesine in range. Saussuritization is also common along the twin plane. K-feldspars are coarse-grained and in anhedral to subhedral forms. They are more or less kaolinized. Myrmekitic inclusion is present in perthitic orthoclase. Quartz is medium- to coarse-grained in groundmass and naturally shaped into a ribbon-like structure and also present in garnet as inclusion. Biotite crystals are strongly pleochroic varying from light yellow to reddish brown. Some orthopyroxene and biotite crystals indicate preferential orientations by the position of some prismatic crystals. Most biotites are altered to chlorite and associated with rutiles. Rutiles in felsic granulite occur as small acicular black crystals. They are always associated with biotite and chlorite, and also found as inclusion in biotite and chlorite. Anhedral garnets are found with quartz and biotite inclusions and chloritization occurs along garnet cracks. Subhedral to rounded garnet without inclusion may probably be magmatic garnet within the granitic melt formed due to the dehydration melting of biotite according to the reaction: Biotite + Sillimanite + Plagioclase + Quartz = Garnet + K-feldspar + Melt. Hercynites, iron alumina spinels, are found as equant grains. They show high relief, olive green under plane polarized light and isotropic between cross nicol. Sapphirines occur as disseminated grains or aggregates and body colour is bluish green and it gives weak pleochroism. In the study area, they are associated with pyroxene, spinel, garnet and quartz. This may be formed where rims of idiomorphic sapphirine have developed over spinel. The presence of spinel relics in sapphirine are shown in symplectic intergrowths of the two minerals (Fig. 7, B). Its development can be explained by the simple reaction: Spinel+Silica = Sapphirine (Deer, Howie & Zussman, 1992). Sillimanite is present in perthitic orthoclase and found as medium-grained slender prismatic crystals. Reaction rim around sillimanite shows a corona-like texture in felsic granulite rock (Fig. 7, C). Ilmenites occur in elongated forms. They are present in chlorite as foliated opaque minerals. Zircons are also enclosed in orthopyroxene mineral as inclusions.

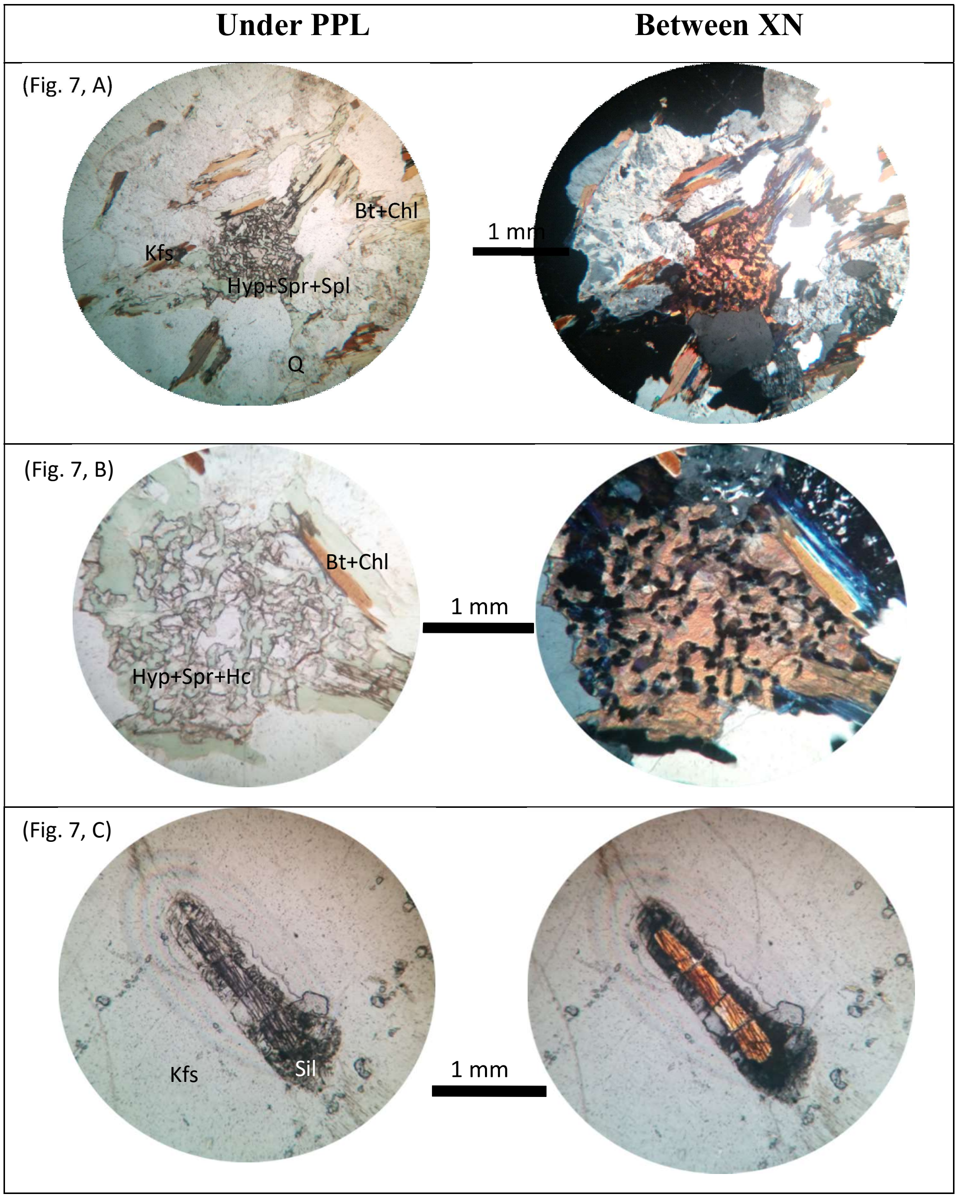


Figure 7.A Mineral assemblages of hypersthene, spinel, sapphirine (spr), biotite, orthoclase and quartz in felsic granulite.

Figure 7. B Symplectic intergrowth of sapphirine developed over spinel in felsic granulite.

Figure 7.C Reaction rim or corona-like texture around sillimanite in felsic granulite.

Mafic granulite (pyroxene granulite)

Microscopically, it is medium- to coarse-grained and shows a granular and polygonal texture (Fig. 8, A). It is mainly composed of pyroxene, plagioclase and biotite while the minor components are alkali feldspar and quartz. Orthopyroxene, sphene, chalcedonic silica, antigorite and ilmenite are accessory minerals. Clinopyroxene (diopside) are noted for their second order bright interference colours and oblique extinction (38° - 42°). Plagioclases are marked by polysynthetic twins. With Michel Levy's method applied, they show calcic plagioclase (andesine and above). Along the fracture or cracks of plagioclase, alterations are dominant and they may be relatively related to the calcium. Untwined feldspars are sodic and potassic feldspars. Alterations and rim myrmekitic texture occur along the boundary of the feldspars. Biotite occurs as tabular grains and shows strong pleochroism varying from light yellow to reddish brown with accumulated group. It is altered to chlorite. Many quartz grains are enclosed in porphyroblasts of plagioclase with poikiloblastic nature. Quartz can also be seen as an initial stage of exsolution texture. Some of the microscopic sequential alterations indicate the process of metasomatism. Later phases of silicification, filled up with chalcedonic silica (cryptocrystalline silica) into vesicles and then followed by saussuritization within intergranular grains. They are sequential processes. However, there is still a question about the origin of biotite between vesicles that are original grains. There are still some evidence~~s~~ of metasomatism process. Former pyroxene are completely recrystallized and replaced by hydrated minerals as antigorite (serpentine). Orthopyroxene is also replaced by alkali feldspar that is surrounded by clinopyroxene and sphene (Fig. 8, B). Rotated orthopyroxene porphyroblasts (helicitic or snowball texture) can be seen (Fig. 8, C). Foliation planes serve as layers of quartz in this orthopyroxene porphyroblast. It is noteworthy that the quartz layers in the orthopyroxene crystal are curved, indicating that the orthopyroxene grows during the rotation process. The relatively straight layers in the core of the orthopyroxene crystal, however, indicate that most of the rotation occurred during the growth of the outer part of the crystal. Some minerals also show replacement structure that is replaced by quartz in clinopyroxene minerals. Minerals of mafic granulite have fractures and alterations along cracks. The fact that this deformation is caused by dynamic metamorphism should be taken into consideration.

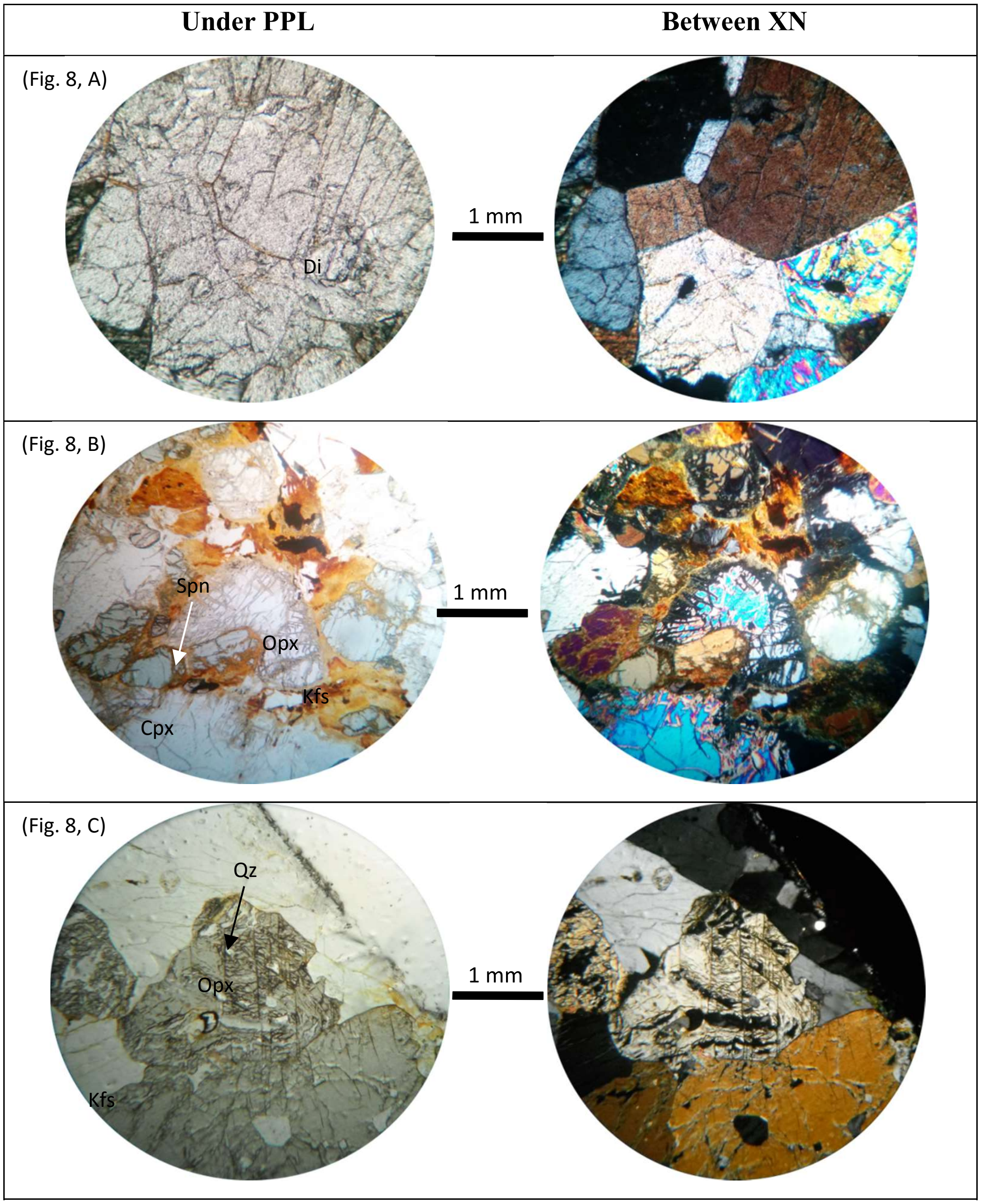


Figure 8. A Polygonal texture with pyroxene crystals in mafic granulite.

Figure 8. B Replacement of alkali feldspar in orthopyroxene in mafic granulite.

Figure 8. C Quartz inclusion in orthopyroxene (Opx) in mafic granulite.

Metamorphic Facies and Grade

Granulite is the type rock of the granulite facies although not all rocks in the granulite facies will be granulites. Only metamorphic rocks with mineral assemblages diagnostic of that facies, of the regional hypersthene zone, should be called "Granulites" (Winkler, 1979). Representative facies diagrams of the study area are presented based on mineral assemblages of petrographic studies by AKF Diagram (Fig. 9).

Significant phenomena of cordierite and/ or garnet in granulite facies

The study area may probably be the upper part of the granulite facies by the presence of almandine and lack of cordierite.

In the presence of quartz and sillimanite, the association and coexistence of almandine-rich garnet and cordierite is a significant phenomenon (Hensen & Green, 1971; Currie, 1971). The pair cordierite + almandine are restricted to a specific *P-T* range in high-grade metamorphism and the regional hypersthenes zone (granulite facies), verified in (Fig. 10, A & B).

(Fig. 10, A) show that *P-T* diagram of coexisting Crd + Alm + Sil + Qz for various FeO/(MgO+FeO) ratios of the bulk composition. If the ratio is increased then the stability field of garnet is reduced and that of cordierite extends towards higher pressure.

(Fig. 10, B) show that *P-X* diagram, reproduced at 700ºC, of coexisting cordierite and garnet, in the presence of ilmenite and quartz. Below the lower curve only cordierite is stable, above the upper curve only garnet is stable. In between the two curves cordierite and garnet coexist, together with sillimanite and quartz. The tie lines join compositions of coexisting cordierite and garnet at different pressures and constant temperature.

Pressure divisions for the granulite facies can be based on the presence of cordierite or almandine, although the absolute conditions affecting the appearance of these minerals include temperature. Cordierite indicates relatively low pressures, cordierite with almandine indicates intermediate pressures, and almandine without cordierite indicates high pressures. The reaction: Fe-Mg cordierite = Fe-Mg almandine+sillimanite+quartz+H_2O (Hyndman, 1985).

Cordierite could appear at 800 to 850ºC and at pressures no higher than about 4 kb. In the presence of almandine, pressure for Mg-cordierite is at 800ºC to would be greater than 7.5 kb. Partial melting of assemblages containing cordierite+ garnet + K-feldspar + sillimanite + biotite + plagioclase + quartz should occur near 700ºC (Holdaway & Lee, 1977). In the formation of the granulite facies, *P-T* estimates range from 700 to 980ºC at about 4 to 10 kb for cordierite-bearing areas and from 700 to 1050ºC at about 8 to 14 kb for cordierite-free areas.

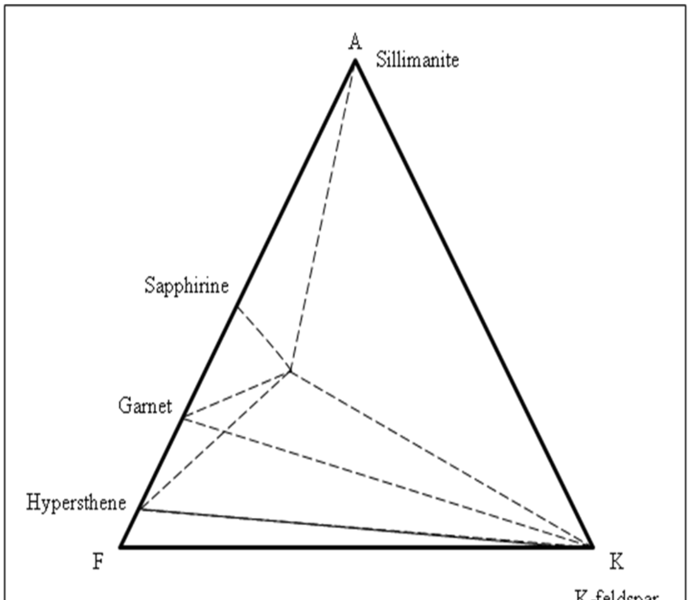


Fig. 9

Figure. 4.15 Representative facies diagram of granulite recognized in the Mount Loi-Sau and its environs, AKF diagram of granulite facies (After Hyndman, 1985).

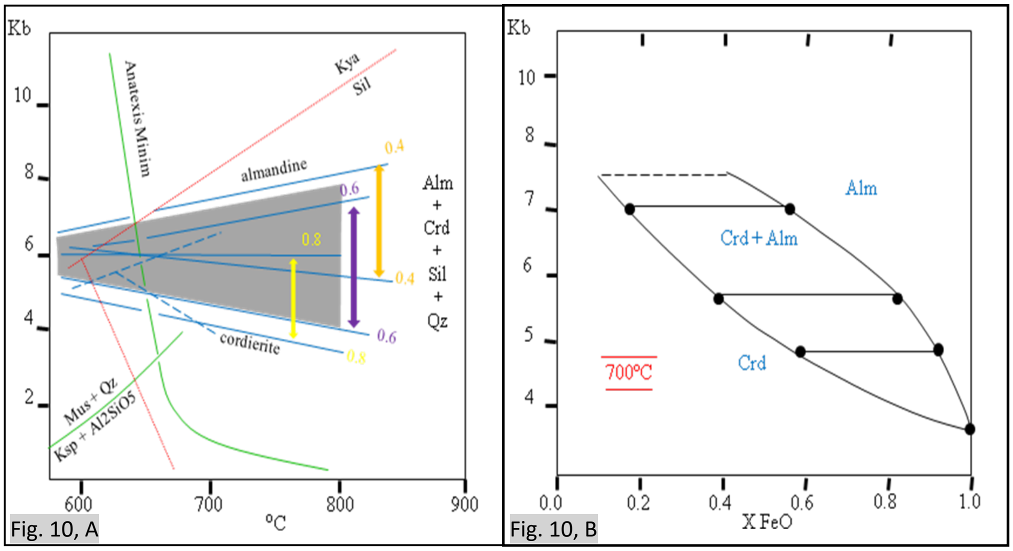


Figure. 4.16 (A) *P-T* diagram of coexisting Crd + Alm + Sil + Qz for various FeO/(MgO+FeO) ratios of the bulk composition. If the ratio is increased then the stability field of garnet is reduced and that of cordierite extends towards higher pressure. (Hensen & Green, 1971).

(B) *P-X* diagram of coexisting cordierite and garnet (in the presence of ilmanite and quartz) at 700ºC (Currie, 1971).

Significant phenomena of hypersthene in granulite facies

Hypersthene is the most diagnostic mineral in high-grade regional metamorphic rocks, granulites. In the regional hypersthene zone, hypersthene may also form in pelitic and semipelitic rocks due to the partial decomposition of biotite according to the reaction:

Biotite + Quartz = Hyperthene + Almandine + K feldspar (Winkler, 1979). Orthopyroxene takes place at about 700ºC to 900 ºC (Winkler, 1979). The assemblage hypersthene + sillimanite + quartz is the high pressure and stabilized at about 10 kb (Newton, 1972).

Significant phenomena of sapphirine in granulite facies

The formation of sapphirine is confined largely to high-grade metamorphic terrains belonging to the granulite facies. The presence of spinel relics in sapphirine is shown in symplectic intergrowths of the two minerals (Fig. 7, B), records changing conditions of temperature and pressure. In some occurrences the rims of idiomorphic sapphirine have developed over spinel. Its development can be explained by the simple reaction:

$$2MgAl_2O_4 \quad + \quad SiO_2 \quad \rightarrow \quad Mg_2Al_2(Al_2Si)O_{10}$$

$$\text{Spinel} \quad + \quad \text{Silica} \quad \rightarrow \quad \text{Sapphirine}$$

(Deer, Howie & Zussman, 1992). Sapphirine is formed at very high temperature zone and the stability field of sapphirine is at 600°-1500° C & at least 7 kbar (Seifert, 1974).

The assemblage sapphirine + quartz found in some high pressure granulite terrains indicates that water pressure was very much lower than total pressure. The association of sapphirine + quartz indicates pressures greater than about 8 kb. It is the same significance to the paragenesis hypersthene + sillimanite + quartz (Newton, 1972).

Possible physicochemical conditions of metamorphism

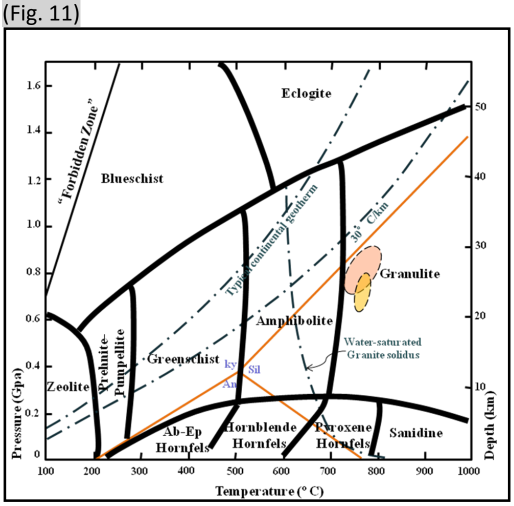
The rare paragenesis is found in the study area; hypersthene + sillimanite + quartz and sapphirine + quartz and it is the rare occurrence of paragenesis (Hensen & Green, 1973). These assemblages are related by the reaction and indicate at high temperatures (and high pressures):

Hypersthene + Sillimanite → Sapphirine + quartz

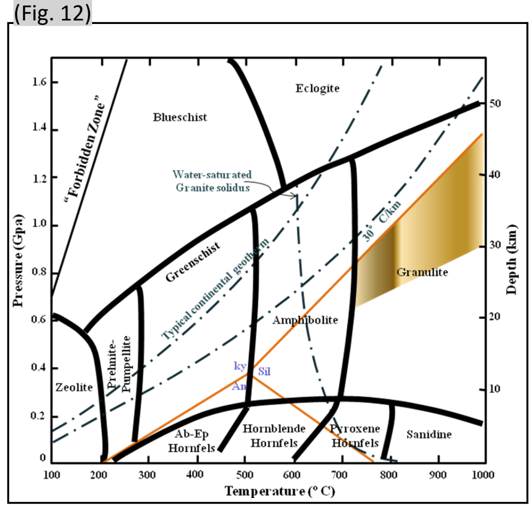
Petrochemically, sillimanite-garnet-biotite gneisses in the study area have reached granulite facies (730-810 ºC & 6.5-9.3 kbar), characterized by the mineral assemblages and petrochemical results from EPMA and XRF (Wai Yan Lai Aung, 2016) (Fig. 11). The *P-T* condition of granulite rocks in the study area should probably be the same as and/ or greater than the *P-T* condition of the high-grade gneiss of the study area, according to the mineral assemblages orthopyroxene + alkali feldspar + biotite + chlorite + plagioclase +garnet + quartz + rutile + sillimanite + sapphirine + opaque + hercynite + sillimanite + sericite + zircon + ilmenite of felsic granulite and mineral assemblages clinopyroxene + biotite + plagioclase (andesine) + alkali feldspar + quartz + perthite + orthopyroxene + sphene + opaque + chalcedony + antigorite of mafic granulite.

A possible physicochemical condition of metamorphism is shown in (Fig. 12), (after Winter, 2013). *P-T* condition of the granulitic rocks of the study area estimated in golden gradient.

(Fig. 11)



(Fig. 12)



	Sample 1A	At 6.5 to 9.3 kb, between 740 and 810ºC.
	Sample 1B	At 6.2 to 8 kb, Between 750 and 790ºC.

Figure 11. Temperature-Pressure diagram showing the stability field of sillimanite-garnet- biotite gneiss (sample 1A & 1B) from the study area (Wai Yan Lai Aung, 2016), estimated in coloured circles with the aid of electron microprobe analysis (EMPA).

Figure 12. Temperature-Pressure diagram showing the stability field of granulitic rock of the study area (After Winter, 2013), estimated in golden gradient with the aid of mineral assemblages and creative thinking.

Acknowledgements

This is a part of PhD Dissertation of the author and laboratory analyses of this study were financially supported by the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland and University of Yangon (UY). The author wishes to acknowledge gratefully Prof. Dr Day Wa Aung, Head of the Department of Geology, University of Yangon, for his kind permission to undertake this research, providing valuable advice and encouragement. I am deeply grateful to Prof. Dr Christoph A. Heinrich, Prof. Dr Lucie Tajčmanová, Department of Earth Sciences, Institute of Geochemistry and Petrology, ETH Zurich, Prof. Hla Kyi, Part-time Professor, Applied Geology Department, Prof. Thein Win, Pro-Rector (Retd.), West Yangon University are also acknowledged for their practical guidance and for this keen interest taken in the preparation of this research. The author is also much indebted to Dr Thet Tin Nyunt, Professor, University of Yangon and Dr Htay Win, Professor (Retd.), East Yangon University for their taking great pains to finish some vital part of this research. The author's heartfelt thanks are extended to some important persons who proposed the interesting remote area, and who accompany and follow the author to the insurgent area, only half expecting the area to be secure within the author's field trips; U Aung Kyaw Htoon, Part-time Lecturer, Dagon University, U Tin Tun, Former Associate Professor, University of Yangon, Dr Thet Tin Nyunt, Dr Kyaw Khaing Win, Mg Lwin Moe Aung and Mg Han. The author thanks to the personal concerned of local authorities and people from the study area for their kindness, hospitality, security and care during the author's stay.

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