## Petrological and geochemical contribution to the origin of jadeitite and associated rocks of the Tawmaw Area, Kachin State, Myanmar

von

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Institut für Mineralogie und Kristallchemie der Universität Stuttgart

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#### Summary

Jade is the trade term for the jewellers but mineralogically two types of jade exist: jadeite (pyroxene end-member  $NaAlSi_2O_6$ ); and Ca-amphibole (end-member  $Ca_2Mg_5Si_8O_{10}(OH)_2$ ),

nephrite. Jadeite jade (petrological term: jadeitite) is rarer and also more valuable than nephrite jade. Jadeitite is found only in a few countries including Myanmar, Japan and Guatemala where corresponding deposits are associated with major strike slip faults and highpressure tectonic zones and always associated with serpentinites and high-pressure rocks.

The recent geotectonic evolution of Myanmar is related to the India-Asia collision. In the central part of Myanmar the N-S trending Central Burma Basin is located which is filled with Eocene to Plio-Quaternary sediments. The sedimentary association is related to a fore-arc basin which resulted from northeastward-directed subduction of the Bengal oceanic crust beneath Myanmar.

The study area, the Tawmaw area, is located in the northern part of the Central Burma Basin at the western part of the Sagaing strike-slip fault zone around 15 km northwest of the city of Pharkant. This area is part of the so-called "jade mines area" or "jade belt" which extends over ca. 2600 km<sup>2</sup>. Glaucophane schist is the most common rock which is exposed together with epidote schist in the eastern part of the Tawmaw area where serpentinized peridotite-dunite and jadeite-bearing rocks also occur. Garnet-mica schists also occur in tectonic contact with the serpentinized peridotite-dunite in the western part of the Tawmaw area. A larger elongated ultramafic body of late Cretaceous to early Eocene (dismembered) ophiolite unit occur in the central part.

Jadeitite is found as vein-like or lens-shape bodies in the serpentinized peridotite-dunite body. In this jadeitite-bearing unit it is possible to distinguish between two main zones. The Outer Zone, occurring at the border of ultramafic rocks, is made up of thin layers chlorite, actinolite schists and amphibole felses (so-called wall rocks), which can, however, also lack. Jadeite and kosmochlor are also included in the amphibole felses together with chromite. The Central Zone is composed of the vein-like or massive lenses of jadeitite but can also contain albitite. The petrological study revealed that the supply of chromium in jadeite is from chromite of the former (and still adjacent) peridotite. This can be clearly seen in maw-sit-sit and amphibole felses where kosmochlor formed from destabilized chromite keeping the size of the original chromite grain. Thus, chromium is immobile in contrast to strongly mobile Na. Moreover, it means that sperpentinite and not the country rocks surrounding serpentinite was replaced by the wall-rocks.

In the (nearly) pure jadeitite, vesuvianite, identified by RAMAN-spectroscopy, was found for the first time in one sample only. Vesuvianite normally occurs in low-pressure environments such as contact aureoles, rodingite/metarodingite, and skarns. This study shows that this phase can also appear in a high-pressure environment. The mineral assemblage of vesuvianite + end-member jadeite does not show any indication for non-equilibrium. The composition of this vesuvianite is characterized by up to 1.5 wt.% Na<sub>2</sub>O that is higher than for vesuvianite described from elsewhere. A major mechanism to incorporate Na into vesuvianite is the charge-balanced substitution Ca + Al = Na + Ti.

A detailed petrological investigation of mica schists and blueschists in the immediate vicinity of the serpentinite was undertaken to understand the formation of jadeitite and jadeite-albite rocks in the Tawmaw area. P-T conditions of garnet- and glaucophane-bearing mica schists were calculated using the computer program PTGIBBS (Brandelik and Massonne, 2004) for the thermodynamic calculation of mineral equilibria. In addition, P-T pseudosections, considering the corresponding chemical bulk rock compositions, were calculated with the computer program package PERPLE\_X (Connolly, 2005). The obtained results indicate that the P-T condition of metamorphic stage I (e.g. related to the core of garnet in mica schists) were 470-540° C and 16-19 kbar. During stage III (rim composition of garnet, phengite rim) conditions of 5.5-8.5 kbar and 570-630°C were reached. The P-T condition of stage II are intermediate between those of stages I and III. The P-T conditions estimated for glaucophane schists are similar to those of the garnet mica schist. For the core of the garnet, 470-490°C, 18-20 kbar are derived, and the P-T condition of rim compositions of garnet from the glaucophane schist result in 560-620°C, 7-12 kbar.

The here derived P-T evolution of the glaucophane schist and garnet mica schist is different to previous interpretions of other authors (Shi et al. 2003, 2001, Goffé et al. 2000). Monazite in garnet mica schists were analysed with the electron microprobe also for their U, Th, and Pb contents. 43 analyses yielded an age range between <15 and 120 Ma.

#### Zusammenfassung

Jade als Handelsname für eine Gruppe von Schmucksteine benutzt. Dabei handelt es sich mineralogisch um Jadeit (Pyroxen-Endglied NaAlSi<sub>2</sub>O<sub>6</sub>) oder Ca-Amphibol (Endglied Ca<sub>2</sub>Mg<sub>5</sub>Si<sub>8</sub>O<sub>10</sub>(OH)<sub>2</sub>) (Nephrit). Jadeit-Jade, der petrologisch als Jadeitit bezeichnet wird, ist seltener und auch wertvoller als Nephrit-Jade, vor allem aufgrund seiner auffälligen Farbe und größeren Widerstandsfähigkeit sowie der einfacheren Möglichkeit zur Steinbearbeitung bei der Herstellung von Gegenständen und Ornamenten. Jadeitit-Vorkommen gibt es nur in wenigen Ländern, wie Myanmar, Japan und Guatemala, und diese sind dort ökonomisch von großer Bedeutung. Geologisch sind Jade-Vorkommen an Seitenverschiebungen, Serpentinite und hochdruckmetamorphe Gesteine gebunden.

Die rezente geotektonische Entwicklung von Myanmar steht in enger Beziehung zur Kollision zwischen Indien und Asien. Im zentralen Teil von Myanmar befindet sich das sedimentäre, zentrale Burma-Becken, einem fore-arc Becken, welches sich im Zusammenhang mit einer nordöstlich gerichteten Subduktion von bengalischer Ozeankruste unter Myanmar gebildet hat. Das Arbeitsgebiet ist das Tawmaw-Gebiet im nördlichen Bereich des zentralen Burma-Beckens, westlich der Sagaing-Seitenverschiebung und etwa 15 km nördlich der Stadt Pharkant. Dieses Gebiet gehört zum Jade-Bergbau-Gebiet (oder Jade-Gürtel) in Myanmar. Im östlichen Tawmaw-Gebiet treten Glaukophan-Schiefer zusammen mit serpentinisierten Peridotiten und Jadeit-führenden Gesteinen auf. Neben diesen Gesteinen treten im westlichen Tawmaw-Gebiet auch Granat-Glimmerschiefer auf, die in tektonischem Kontakt mit den serpentinisierten Peridotiten stehen.

Im Bereich der Jadeitite können eine innere und eine äußere Zone unterschieden werden. Die äußere Zone, die im Kontakt zu den Ultrabasiten auftritt, ist durch dünne Lagen von Chloritund Aktinolith-Schiefern oder Amphibol-Felse (sogenannte Wall-Rocks) gekennzeichnet. Auch Jadeit und Kosmochlor kommen zusammen mit Chromit in diesen Gesteinen vor. Die innere Zone enthält die genannten linsenförmigen oder gangähnlichen Jadeitit-Körper. Daneben kommen hier auch Albitite vor. Die petrologische Untersuchung ergab, dass das Chrom im Jadeit aus dem ehemaligen (und noch angrenzenden) Peridotit stammt. Dies ist deutlich in "Maw-sit-sit" und Amphibol-Fels sichtbar, in dem Kosmochlor sich aus abgebautem Chromit bildete, der noch die Größe des ehemaligen Chromit-Korns wiedergibt. Chrom ist daher immobil im Gegensatz zum stark mobilen Na. Dies bedeutet weiterhin, dass der Serpentinit selbst und nicht die umgebenden Gesteine durch die "wall-rocks" ersetzt wurden.

In einem (nahezu) reinen Jadeitit wurde zum ersten Mal Vesuvian in nur einer Probe efunden und mittels Raman-Spektroskopie identifiziert. Dieses Vorkommen ist deshalb emerkenswert, da Vesuvian üblicherweise im Niedrigdruckmilieu vorkommt, etwa in Kontaktaureolen, in Rodingiten und Skarnen. Hier konnte erstmals gezeigt werden, dass diese Phase auch in Hochdruckgesteinen auftritt. Die Paragenese von Vesuvian + reinem Jadeit zeigt keine strukturellen Anzeichen für ein chemisches Ungleichgewicht. Der Vesuvianit ist durch bis zu 1.5 Gew.-% Na<sub>2</sub>O gekennzeichnet, welcher höher ist als bislang von Vesuvian bekannt. Na wird in den Vesuvian durch die Substitutionen Ca + Al = Na + Ti und Ca + (Mg+Fe<sup>2+</sup>+Mn) = Na + Al eingebaut.

Glimmerschiefer und Blauschiefer in unmittelbarer Umgebung des Serpentinits wurden petrologisch und mikrochemisch untersucht. Dies ist für das Verständnis der Bildung von Jadeit und Jadeit-Albit-Gesteinen im Tawmaw Gebiet von Bedeutung, die selber kaum für eine detaillierte P-T-Bestimmung geeignet sind. Die P-T Bedingungen für jedes Stadium wurden durch thermodynamische Berechnungen (PTGIBBS von Brandelik & Massonne, 2004, und PERPLE X von Connolly, 2005) von Zusammensetzungen koexistierender Minerale ermittelt, um einen P-T Pfad für diese Gesteine zu bestimmen. Die Ergebnisse zeigen, dass die P-T Bedingungen für das Metamorphosestadium I (z.B. für die Bildung des Granat-Kerns in den Glimmerschiefern) bei 470-540° C und 16-19 kbar lagen. Während des Stadiums III (Randzusammensetzungen von Granat und Phengit) wurden 5.5-8.5 kbar und 570-630°C erreicht. Die P-T Bedingungen von Stadium II liegen zwischen denen der Stadien I und III. Die P-T Bedingungen der Glaukophan-Schiefer entsprechen in etwa denen der Granat-Glimmerschiefer. Als Bildungsbedingungen für den Granat-Kern in den Glaukophan-Schiefern wurden 470-490°C und 18-20 kbar abgeleitet, für die Granat-Randzusammensetzungen 560-620°C, 7-12 kbar. Die hier abgeleiteten PT-Pfade der Glaukophan-Schiefer und Granat-Glimmerschiefer gerben deutlich höhere Drücke als bsiherige Arbeite (Shi et al. 2003, 2001; Goffé et al. 2000). Monazite aus Granat-Glimmerschiefern auf U, wurden ihre Th und Pb-Gehalte hin mit der Elektronenstrahlmikrosonde untersucht. 43 Analysen ergaben eine Alterspanne zwischen <15 und 120 Ma.

#### CHAPTER I Introduction to Part I

#### **I. Introduction**

One of the world's largest and best quality jade deposit is exposed in the Pharkant-Tawmaw Jade belt (also written Hparkant or Hpakan and Tawhmaw). This deposit is located between latitudes 25° and 26° N and longitudes 96° 12' and 96° 25' E in the Myitkyina District, Northern Myanmar (Fig. 1.1). The occurrence of this jade deposit is related to the collision of the plates India and Asia. The Sagaing fault is a major N-S trending dextral strike-slip fault (Fig.1.1) resulting from late movements of these colliding plates. This active tectonic feature of Myanmar, extending more than 900 km, cuts through the Tertiary sedimentary units of the Central Burma Basin. Along this fault, which was active since the Eocene, serpentinites including jadeitite jade bodies where brought to the surface. In addition, various low to medium-grade metamorphic rocks are exposed (Fig. 1.2) in the neighbourhood of the jade deposits. The appearance of these lower crustal rocks and observed structural features gave rise to the assumption that lower crust was exhumed in a transpressional regime older than 10 million years (Rangin *et al.* 2002).

Jadeitite and associated garnet- and phengite-bearing blueschists exposed in the Tawmaw area could be a result a subduction and subsequent exhumation of geological units in the Tawmaw area because minerals such as glaucophane and phengite are a hint at high-pressure metamorphism. To support or reject this hypothesis thermobarometric estimates were carried out applying garnet-phengite geothermobarometers. The present study also presents the petrography of jadeitite and associated rocks from the Tawmaw area. These rocks were formed by the collision of India-Asia plate during the Mesozoic and late Cretaceous period - (e.g., Mitchell, 1993). Major outcrops in the Pharkant-Tawmaw area, also called Jade mine belt, occur over an area of about 1200 km<sup>2</sup> (Chhibber, 1934). This belt is running nearly in N-S direction which parallel to the Sagaing strike-slip fault and is formed by the result of the underthrusting of the India Plate by the Burma Plate, beginning approximately 50 Ma ago (Ni *et al.* 1989; Satyabala 1998; Larson *et al.* 1999). This belt is bounded in the east by right lateral Sagaing strike slip fault and Indo-Burman Ranges in the west.

The present study area is situated at the western margin of the boundary of the Sagaing Fault zone. The regional geology of this area is shown in Figure 1.2. Ultramafic rocks such as serpentinized peridotite and amphibole felses (Shi *et al.* 2003), and metamorphic rocks such as garnet-mica schist of crustal origin and sedimentary rocks ranging in age from Cretaceous to Quaternary are exposed in the Pharkant-Tawmaw area. The best exposures in the Tawmaw



Fig. 1.1: Simplified tectonic map of Myanmar (after Bender, 1983; Mitchell *et al.*, 2006 and Socquet et al., 2002). Black quadrangle shows positions of the area of Fig. 1.2.



Fig. 1.2: Geological map of the Pharkant-Tawmaw Area, Kachin State, Myanmar (modified after Chhibber, 1934 and Tun, 1997). Black quadrangle indicates Study area. area are at the primary jadeite working sites. The ultramafic rocks are part of the ophiolite belt east of the Indian Plate (Ni *et al.* 1989).

The jade mines belt includes complex schists, jadeitite, albite-jadeite rock, albitite and metamorphosed serpentinized peridotite (Chhibber, 1934). The complex crystalline schists involve ordinary garnet-mica schists, but also unusually composed epidote schists, glaucophane schists and epidote-glaucophane schists (Fig.2, SE of Tawmaw, 25° 40' 44.3"N and 96° 18' 04.6" E). The occurrence of high-pressure metamorphic rocks in the Tawmaw area has not yet been studied in detail due to the dense vegetation, poor accessibility and limited permission for the field trip for a decade.

Previous studies of Pharkant-Tawmaw jade mine belt were carried out by Chhibber (1934), Mével and Kiénast (1986), Sorensen and Harlow (1999), Goffé *et al.* (2000) and Shi *et al.* (2001, 2005a, 2005b, 2006, 2008). The presented detailed petrological study will mainly spot light on the P-T evolution of glaucophane-bearing schist and jadeitite and albite-jadeite rocks in the Pharkant-Tawmaw belt. Moreover this study can provide useful constraints for the tectonic processes of India-Asia collision in the past.

The occurrence of jadeite and glaucophane bearing schist in the belt is recognized as the world's best quality jadeite source. However, the relationships of high-pressure glaucophane bearing schist and jadeitite and albite-jadeite rocks are still unclear. This study will contribute to the understanding of the relationships of HP rocks and jadeitite deposits from the Pharkant-Tawmaw Jade Mine area.

#### **1.1. Location and area of study**

The study area lies in the Tawmaw area, Pharkant Township, Myitkyina District, Kachin State, Myanmar. The region Pharkant and surrounding Townships, which is about 1200 km<sup>2</sup> has been known as "jade-mines area" or "jade belt" for its wealth of World's famous jade. The study area lies between latitudes 25° 30' to 25° 45' N and longitudes 96° 10'to 96° 30' E, covered by one-inch topographic map-sheets nos. 92 C/2 and C/6. It is about 1050 km north of Yangon and about 112 km by road from Mogaung. Considerable sizes and amounts of jades have been quarried from both primary and placer deposits in the study area.

Detailed study area is located about 20 km northwest of Lonkhin and 35 km northwest of Pharkant which is in 92 C/2 and 92 C/6 one inch topographic maps of Myanmar. The SanKha stream in the east and the SanPhe stream in the west are the main tributaries that support the major supply of alluvial boulders to the Uru stream. In Tawmaw area, there are more than 4 primary worksites for jadeite mining namely Khine Kyin, Marangan, Sama, Htellonesein, ShweThanLwin, JadeLand and Jingphaw Academy.

#### **1.2.** Communication and Accessibility

This area can be accessed from Yangon to Mandalay by train or car and then from Mandalay via Mogaung and Lonkhin to Tawmaw by car. The accessibility during the rainy season is very difficult. Another way to this area is from Yangon to Myitkyina by plane and from Myitkyina to Mogaung-Lonkhin-Tawmaw by car.

Primary jade mines in the Tawmaw area are Marangan, Sama, Khinekyin, Jingphaw Academy and JadeLand located about 20 km northwest of Lonkhin. The Sama worksite is about 6 km south west of the Marangan worksite and about 1.6 km from Tawmaw. The Khinekyin worksite is near the Sama work site and they are contact in area. JadeLand and Jingphaw Academy mines are at the Tawmaw.

#### 1.3. Physiography and Drainage pattern

The relief of the study area is a highly dissected upland forming ranges and hills, which are related to the Chindwin-Irrawaddy watershed. The northern part of the area is higher than the southern part. The central part is mainly made up of about 600 meter high mountain ranges and covered with dense vegetation. The prime interest area, Tawmaw, is situated on a plateau of about 2211 meter above sea level. The eastern margin of the area is marked by the Uru river whereas the Chindwin river forms the western limit.

The Uru river valley is the major site for the deposition of the valuable Myanmar Jade. The Uru river is the major stream which flows from north to south direction in the eastern part until it reaches the Pharkant, and then changes its direction to the south-west and join into the Chindwin river below about 4.5 km of Homemalin.

Most of the streams in the area run along major fractures. The main tributaries of the Uru river are Sanphe chaung (stream in Myanmar) in the east and Sankha chaung in the west.

The study area is characterized by high rainfall. Thus, most of the outcrops are highly weathered except the excavated mine sites and those along the streams. The overburden soil is usually reddish-brown and may be few meters to tens of meters thick.

#### 1.4. Nature of the Rock Exposure

The major intrusive complex composed mainly of strongly serpentinized peridotite-dunite crops out in the western part of the study area. This complex shows an elongated oval shape in the map. The most abundant units in the study area are the mafic and pelitic schist units. These schist units are the host for the serpentinized peridotite-dunite complex but the contact to the ultramafics is obscure. The contact is probably tectonic and mostly covered by soil.

Small limestone units of Permo-Carboniferious age crop out at the eastern and south-eastern part of the Tawmaw area. The other units are made up of Tertiary sandstone and shale. Pleistocene to the recent Uru boulder conglomerate occurs in places. These rocks with variable thickness from few to several meters are important because they contain valuable secondary jade. In addition, these conglomerates also include various sizes serpentinized peridotite and schist.

#### **1.5. Previous Works**

The first geologist who investigated the geology of the jade mine area was Noetling (1892). This researcher published a preliminary report on the economic resources of amber and jade of Upper Burma and also on the occurrence of jadeite in Upper Burma on small scale map. Bauer (1895) described jadeite and other rocks collected by Noetling in the Tawmaw area. Bleeck (1908) visited the area and made an account on the occurrence of jade. Lacroix (1930) gave an analysis of a chromojadeite from Burma which contained 11 % of kosmochlor component. This author also described pleochroic amphiboles which he considered as chromiferous. Brown (1924) and Chhibber (1934) described the occurrence of jade in the northern Burma as *in situ* veins of albite-jadeite dykes and secondary deposits of detrital boulders along the Uru river. Gübelin's (1965) detailed examination of the Maw-sit-sit resulted in the knowledge that it is neither jadeite (jade) or chloromelanite, nor epidote, but definitely a fine-grained albite the colour of which is induced by a pigment mineral which has been determined to be a chrome-rich jadeite (chrome-jadeite). He suggested the name "jadealbite" for this particular jade of northern Burma, although the original native name Maw-sitsit is used at present. Soe Win (1966) described the application of geology to the mining of jade. Bauer (1969) made comparative studies of the chemical analyses of jadeite from Burma and chloromelanite from Morbihan (Brittany). Yang (1984) analyzed jade samples from Burma and found pyroxene with kosmochlor component ranging from 50 to 86 %. This author also described chromiferous amphiboles. (Thin, 1991) proposed the tectonic environment responsible for the formation of the Myanmar jadeite deposits as triple junction idea. Harlow and Olds (1987) and Mével and Kiénast (1986) studied some Burmese samples selected from Lacroix's rock collection containing Cr-rich sodic pyroxene with 82 % kosmochlor component and also analysed the amphiboles in order to determine the behaviour of chromium in these exceptional minerals. Mével and Kiénast (1986) studied the jadeitekosmochlor solid solution and chromian sodic amphiboles in jadeitites and associated rocks from the Tawmaw area. These authors proposed that Myanmar jadeites were related to particular chemical environment during a high-pressure low-temperature metamorphic event and produce unsual rocks rich in sodium and magnesium and Cr-rich silicates. Sodic pyroxene compositions confirm the occurrence of kosmochlor in terrestrial rocks because they show a wide range of solid solution between pure jadeite and 85% kosmochlor, but suggest the existence of a miscibility gap between Ko 25 and Ko 50 under corresponding metamorphic conditions. The sodic amphiboles, kataphorite, glaucophane and eckermannite contain up to 10 wt.% Cr<sub>2</sub>O<sub>3</sub>. These exceptional compositions were explained by the formation in a particular chemical environment resulting from metasomatic reaction between an albitite dyke containing chromite xenocrysts and the enclosing serpentinites during metamorphism (Mével and Kiénast, 1986). Htein and Naing (1994,1995) presented chemical compositions of jadeite, kosmochlor and associated minerals in jade from Myanmar. Sorensen and Harlow (1998, 1999) studied the origin of jadeitite-forming subduction-zone fluids based on the oxygen-isotope and trace-element evidences. Sorensen and Harlow (2001) studied the jadeitites of Nansibon with emphasis on the geochemistry of subduction zone fluids. Shi et al. (2001, 2003) studied the petrology of jadeite-bearing serpentinized peridotite, complex sodic and sodic-calcic amphibole association and its implications for the metasomatic processes in the jadeitite area of northwestern Myanmar. Shi et al. (2005a, 2005b) also investigated the methane-bearing fluid inclusions and kosmochlor and chromian jadeite aggregates from Myanmar jadeitite area. Yi et al. (2006) studied on the jadeitized omphacitite from Myanmar jadeite area. Shi et al. (2008) presented data on the geochemistry and zircon U-Pb age of Myanmar jadeitite by ion microprobe analyses.

#### 1.6. Methodology of the Study

#### Analytical procedures

Numerous rock thin-sections were prepared from selected rock samples taken in the field to study these rocks under the polarizing microscope for mineral content, optical characteristics of the constituent minerals, texture and identification of paragenesis. The compositions of minerals in selected samples were routinely analyzed at the Institut für Mineralogie und Kristallchemie, Universität Stuttgart, Germany, by using a Cameca SX100 electron microprobe with five wavelength-dispersive spectrometers to determine the concentration of Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn, Ni, Fe and Ba. The applied acceleration voltage and beam current were 15 kV and 15 nA, respectively. The beam diameter was generally about 6  $\mu$ m, but was reduced to 1  $\mu$ m to analyze small sized minerals despite possible problems in damaging specific minerals.

Counting time per element for full analyses were 20 s on peak and background each. The PaP correction procedure provided by Cameca was applied. Concentration maps for major

elements were prepared by step-wise movement (100 or 200 ms per step) of the thin section under the electron beam of the microprobe and subsequent computer aided evaluation and processing. The energy-dispersive system of the microprobe served as mean of identification of phases during the selection of spots for full analyses. Natural and synthetic silicates and oxides were used as standard for calibration.

ICP-MS analyses for rare-earth elements (REEs) were carried out on some representative samples at Universität Karlsruhe. For the preparation of REEs analyses, 50 mg of rock powder (<63  $\mu$ m) were put in the Teflon cup and then 4 ml of 40 % HF and 1 ml of 65 % HNO<sub>3</sub> (all acids are supra pure) were added. Subsequently, the cup was closed and put in an Ethos+Plus microwave furnace which was heated for 2 hours at 230°C. After cooling of the Teflon cup, the acids were removed from the solutions by means of vacuum and a cooling water system. 4 ml of demineralized water were added and then removed with the same procedure as above. Then 4 ml of 30 % HCl were added and removed again. After that, 4 ml of demineralized water were added into the solution and then removed again. Finally, the solution has nearly 1 ml which was diluted by 8 ml of 1 % HNO<sub>3</sub> and heated at 100°C for 30 mins. After that, this solution was filled up to 50 ml with 1 % of HNO<sub>3</sub>.

Identification on mineral analyses was made by the D8 Advance Röntgen-Diffraktometer with the Diffrac Plus 50 Software for identifying the mineral data. For this purpose, the rock samples were crushed down to  $< 63 \mu m$ .

The chemical compositions of the rocks were obtained by X-ray fluorescence spectrometry. A oportion of the rock sample was crushed and ground with a tungsten-carbide dish-and-puck-mill until the size reached < 63  $\mu$ m. A spectromelt A 12 flux powder was dried at 450°C for 3 hours and then cooled down in exsiccator (Dehydrator). Then the powder was dried in an oven for 12 hr at 105°C and then stored in exsiccator (Dehydrator). After that, 0.5 g of rock powder was mixed with 5 g of Spectromelt A12 and then heated it in the Platinum crucible at 1200°C for 13 mins and cooled down for 6 mins to obtain the glass disk. This disk was used for the analyses of major elements. The pellet for analysing the trace elements was prepared by the rock powder which have the size < 63  $\mu$ m. This powder was put in the oven at temperature about 50-60°C for one night to dry and then cooled down in the Exsiccator (Dehydrator). After that, 12 g of rock powder and 3 g of wax mixture were put into a container and then homogenized for about 45 mins. After that, these thoroughly mixed powders were pressed by using hand-pressed machine to obtain a flat cylindrical pellet with the pressure up to 200 kg/cm<sup>2</sup> (~ 0.2 kbar). The prepared glass disk were analyses were performed

with a WDS X-ray fluorescence (XRF) spectrometer PHILIPS PW 2400 equipped with the Super Q software at the Institut für Mineralogie und Kristallchemie, Universität Stuttgart.

 $H_2O$  and  $CO_2$  concentration were carried out with a LECO RC-412 multiphase carbon/water determinator at the Institut für Mineralogie und Kristallchemie, Universität Stuttgart. Rock powders (<63 µm) were dried in the oven at 50-60°C over a night. Then analysed rock powders were put into the quartz-glass crucible and analysed at 1000°C in oxidizing atmosphere for 5 minutes. The analyses were repeated for two times. The machine was calibrated with the following standards: oxalat for H<sub>2</sub>O and CaCO<sub>3</sub> for CO<sub>2</sub>.

#### 1.7. Purpose and Aims of the Study

The main purpose of the study is to describe the detailed petrography and petrology of the jadeitite and related rocks, to analyse the geochemical characteristics of the high-pressure metamorphism and associated jadeite mineralization and other geochemical processes occurred in the jadeite-bearing rock; and discuss the origin, mode of occurrence and tectonic significance of the jadeite and associated rocks based on their petrography, petrology, whole rock chemical analysis and geochronology.

#### CHAPTER

#### Π

#### II. Historical Background and Regional Geology

#### 2.1. Historical Background

Jadeite deposits occur only in a few countries such as Myanmar, Japan, and Guatemala where these deposits are associated with major faults, high pressure tectonic zones and also with other rock types such as glaucophane schist.

Jade is the trade term for the jewellers. There are two type of jade in the market, one is jadeite jade (pyroxene) and the other is nephrite jade (amphibole). Jadeite jade has better physical and optical appearance than nephrite jade and has been used for weapons in the earliest time like axes and a variety of ornamental materials. Jadeite jade is usually made up of aggregates of interlocking jadeite crystals of granular and fibrous grains. Therefore, jadeite jade shows slightly directional difference in hardness and forms a dimple surface effect on the polished surface. Due to its great toughness, it is better suited to make for curving and beautiful ornaments and utensils. Most of the jadeite jade is used as cabochons, ear-rings, bracelets, necklace, brooches and bangles.

Myanmar jades is characterised by purity of grains and color attracting the world wide jade lovers. So Myanmar is most important source of jadeite jade for hundreds of years and still one and only source of world's supply of best quality finest jade. The colour of Myanmar jade ranges from white, shades of green, lavender blue, violet, black and yellow. The latter is formed by the staining by iron oxide. The nature of jadeite is generally medium to fine-grained. Pure jadeite showing a white colour has about 98 % of jadeite component. Depending on their different color, texture, transparency, purity and grain size, jadeite jade can be classified into 3 varieties: (a) imperial jade, (b) commercial jade and (c) utility jade.

Jadeite with the best transparency (semi-transparent) and a colour of emerald green is called imperial jade. Commercial jade is the second quality jade having hues of green and violet or stripes of green and violet. Most of the commercial jade is used for making jewellery especially for bangles. The third quality is utility jade and which has neither green nor violet hues. This variety has variation in hues of colour such as white, yellow, blue, black and brown. It is the most common and available in big sizes.

#### 2.2. Geological Setting

The recent geotectonic evolution of Myanmar is related to the India-Asia collision which is responsible for the tectonic intercalation between accrectionary wedge complex, arc related basins and marine to continental metasedimentary sequences of the basement. There are 4 tectonic domains which make the geomorphic features of Myanmar (Fig.1.1). In the eastern part of Myanmar there are high mountain ranges called the Shan Plateau which is composed of Paleozoic and continental Mesozoic low grade meta-sedimentary and sedimentary rocks cut by Mesozoic calc-alkaline granites (Mitchell 1977; Mitchell et al. 2002; Morely 2004). The western part of the Shan Plateau is truncated by the Shan scarp fault which is a high lateral transpressive shear zone with reverse component (Bertrand & Rangin 2003). The Mogok Metamorphic Belt (Chhibber, 1934) is located at the western border of the Shan Plateau and is composed of mica schist, ruby-bearing marble, rare quartzite, orthogneiss and various types of foliated intrusive rocks. The sedimentary structures and stratigraphic informations correlate with the sedimentary rocks, which are Permian limestones. The intrusive rocks gave Upper Jurassic to Late Cretaceous radiometric ages (Searle & Haq 1964; Cobbing et al. 1992; Mitchell 2006). These rocks are highly foliated generally with EW trend and gentle dips towards the north or the south. On the foliation plane stretching lineations occur which are trending in NNW-SSE direction (Bertrand & Rangin 2003; Bertrand et al. 2001). There are two metamorphic events in these rocks with grade ranging from greenschist to granulite facies (Bender 1983; Mitchell 2006). The ages of metamorphic events, determined by K/Ar and Ar/Ar geochronology, range between Oligocene to Middle Miocene (32 and 16 Ma) (Bertrand et al. 1999, 2001; Betrand & Rangin 2003).

In the central part of Myanmar, the Central Burma Basin occurs which is filled with Eocene to Plio-Quaternary sediments. This basin is N-S trending and the deeper part reaches 15 km or more in thickness (Curray *et al.* 1979; Pivnik *et al.* 1998). The latter portion is located in the western part of the basin. This sedimentary association is interpreted to be similar to a forearc basin in regard of the northeastward subduction of the Bengal oceanic crust beneath Myanmar (Swe 1981; Bertrand & Rangin 2003).

The Indo-Burman Ranges is located between the Eastern Himalayan Syntaxis and the northern termination of the Sunda Trench. This range is mainly composed of Cenozoic rocks and is interpreted as an accretionary wedge, resulting from the eastward subduction of the Bengal's oceanic crust (Socquet *et al.* 2002). This range can be subdivided into two parts: an eastern narrow strip composed of metamorphic rocks, ophiolites, Triassic schists and Late Cretaceous sediments which occurs the internal zone of the range and a large western belt of Cenozoic sediments that form the present accrectionary wedge (Socquet *et al.* 2002).

Metamorphic rocks from the eastern strip of this range include metapelites, metagreywacke and basic rocks. These rocks are affected by ductile deformation and it is possible to recognize two main foliations. These are imprinted by NNW-SSE stretching lineation and a top-to-the-southeast shear indicating ductile deformation. Phengite, epidote and blue amphibole (Mg-riebeckites and crossites) indicate a greenschist to blueschist transistion of peak metamorphic conditions (Socquet *et al.* 2002). There are three major phases affecting on this range: the first phase ophiolite thrust over the Mesozoic metamorphic wedge in Late Cretaceous-Eocene times, the second extensive ductile crustal thinning with the metamorphism along the Shan Scarp region since Eocene and the third Pliocene compressive phase that formed the present accretion wedge. Therefore, the evolution of this range shows similarities to the construction of the Himalayas and because of its location away from the frontal convergence of India and Asia may have preserved rocks of a high-pressure facies (Socquet *et al.* 2002).

There are two different Neogene deformation regimes in Myanmar. The first one is NNE-SSW –trending extensional regime marked by ductile stretching and associated ENE-WSW brittle normal faults characterizing the Mogok Metamorphic Belt. The second regime shows compressive deformation, which occurred from Middle or Upper Miocene times to the Present. The corresponding structures were cross-cut by brittle right-lateral faults, such as the NW-SE Shan scarp fault zone and the N-S Sagaing fault (Bertrand & Rangin 2002). A large shear transform-fault belt has been forming along the eastern margin of the India Plate and large scale subduction probably started since the Late Cretaceous. The collision of India Plate with the Eurasian plate probably begun about 50 Ma ago and initiated the anticlockwise rotation during this time (Molnar and Tapponier, 1984; Patriat and Achache 1984: Powell *et al.* 1985).

The study area is located in the northern part of Central Burma Basin around 30 km North West of Pharkant city. Geological mapping of the area show the dominance of crystalline rocks with relation to the sedimentary association of the basin. The western and central part of the area is dominated by the intercalation of pelitic schist, mafic and subordinate magnesian schist. In the central part of the area, intercalated with the crystalline schist, occurs an elongate body of ultramafic rock which is trending NNE-SSW direction. The eastern part of the study area is composed of the sedimentary units from the Central Burma Basin with small occurrences of Cretaceous limestone especially in the southern part. All the previous associations are covered in the central and southern part of the area by Pleistocene Uru Boulder Conglomerate.

The occurrence of these blocks of crystalline rocks in the Central Burma Basin is related to the second deformation regime, where the transpressional deformation is responsible for uplift of deep rocks through the shear zones.

By the previous studies, it is possible to correlate the studied crystalline rocks with the association described in the Indo-Burman Ranges.

The Pharkant-Tawmaw jadeitite bodies occur as discontinuous veins in the northern part of eastern subduction belt of India Plate (Burma sub-plate). The Tawmaw area generally composed of crystalline schists unit of continental origin, serpentinized peridotite of oceanic source and Tertiary sedimentary units. Minor granite intruded into the crystalline schist. Also minor andesitic intrusions are found at the north-eastern part into the Tertiary sandstone unit. The glaucophane-bearing schist occurs in the eastern part and south-eastern part. Most of the units are highly weathered and covered with dense vegetation. The relationship and contact of these units are tectonic.

#### **2.3.** Distribution and Description of Rock Units

There are 5 major associations in the study area, complex crystalline schist, serpentinized peridotite-dunite, Tertiary sandstones, Uru boulder conglomerate and alluvium (Fig. 1.2). The complex schist is the most abundant unit which mainly occurs at the western, eastern and southern part of the area and forming 60 % of the entire area. This unit is composed of two different associations: mafic and metapelitic schist. The second most abundant unit is serpentinized peridotite-dunite which mainly cropped out at the central and northeastern part of the area. This is the most important unit for the present study because of the occurrence of jadeititee as vein-like bodies in the serpentinized ultramafic rocks. It makes about 20-25 % of the entire area. Most of these units are covered by thick overburden soils. Primary vein-like bodies of jadeitite are mainly found at Tawmaw and also at the Natmaw. The mineralization of jadeite is possibly related with the Tawmaw fault which is roughly running about NNE-SSW. Jadeitite, albite-jadeite rocks, albitite, chlorite schist, actinolite schist and amphibole felses are found within the serpentinized peridotite-dunite. Jadeitite occur as vein-like bodies with about 15 meter in length, 6 meter in width and 9 meter in depth (thickness) at Natmaw area and about 2 x 3 x 3 meter at JadeLand worksite and sometimes 1 to 2 meter in width (Fig. 2.1 a-b, 2.2 a-b, 2.3 a-b). This vein has tabular shape and different types of rocks like irregular layers are associated. It is possible to recognise two main zones. At the border near to the surrounding ultramafic rocks, thin layers of different type of mafic to ultramafic schist, like chlorite schist, actinolite schist and amphibole felses (Fig. 2.4). The central zone is composed by massive lenses, sometimes with boudinage feature, of jadeitite, albite-jadeite rocks and albitite. The Uru boulder conglomerate unit is found near the vicinity of Lonkin,



b

Fig. 2.1 a-b: Contact nature of jadeitite, albitite, amphibole felses and serpentinized peridotite: a. Albitite at the left contact with amphibole felses and serpentinized peridotite at the right side. b. Contact of albitite and albite-jadeite rocks at the right side and amphibole felses near the piller and serpentinized peridotite at the left side. The rock that the author standing is jadeitite. Natmaw,Jade dragon, Looking 218°.



b

Fig. 2.2: a. Outcrop nature of albitite within the serpentinized peridotite, which is surrounded by chlorite schist and swelling feature at the base of the photo where the jadeitite is occur, b. zone of jadeitite which is surrounded by albite-jadeite unit and albite, chlorite schist and outermost unit serpentinized peridotite. Tawmaw, JadeLand.



b

Fig. 2.3: a-b. a. Encrusting nature of jadeitite surrounded by thin albitite zone which in then surrounded by amphibole felses within the serpentinized peridotite, b. Outcrop nature of jadeitite in the central part, centre top have green jadeitite, and right side have albitite intermingled with amphibole felses. Natmaw, Jade dragon, Looking 140° & 110°.



Fig. 2.4: Generalized sketch showing the nature of jadeitite body in Tawmaw area where the innermost core of jadeitite is surrounded by gradational composition of albite-jadeite rock and albitite, which is also surrounded by amphibole felses (sometimes this unit is missing and sometimes directly contact with jadeitite unit), which in then surrounded by actinolite schist, and chlorite schist within the ultramafic body. Sankha and south of Tawmaw and it makes about 10% of the entire area. This unit is also important due to the occurrence of secondary jadeite boulder in it. The Tertiary sandstone unit is only found at the southeastern corner of the area where Uru boulder conglomerate overlain on it. This unit is composed about 3-5 % of the entire study area.

#### 2.3.1. Complex Cystalline Shist

The complex schists are composed by two different protolith associations. The western part of the area is made up of metapelitic rocks represented by garnet-mica schist. In the eastern part mafic rocks composed by glaucophane schist and epidote schist. These units have a main schistosity generally trending to N30-50°E direction with the mineral lineation oriented to 330°-150° with low dips. The occurrence of isoclinal folds and crenulation cleavages in thin section indicates the presence of relict S1 schistosity and suggests that the main schisotisty is S2. The best exposures are located along the Sanphe Chaung and at the SE of Tawmaw-Lonkhin car road.

Garnet-mica schist occurs at the western part of Tawmaw area which is in tectonic contact with the serpentinized peridotite-dunite. The best exposures are found along the stream section and analysed samples were collected from the Sanphe Chaung (stream in Myanmar)(N 25° 43'03"E 96° 13'52"). It is composed of garnet, white mica, quartz, chlorite and feldspar with minor epidote and biotite. Garnet shows brownish to reddish brown euhedral porphyroblasts with maximum size of 1 cm in diameter and is highly fractured. Garnet shows snowball appearance in places. White mica and altered biotite can be seen with naked eyes. It shows medium to coarse-grained with yellowish brown on the fresh surface and reddish brown on the weathered surface glimmering by white micas. The matrix is composed of fine-grained muscovite-phengite, quartz, chlorite, feldspar (albite, which is partially altered), epidote, magnetite, rutile, titanite and the opaque and accessory phases: ilmenite, zircon and apatite.

The glaucophane schist and epidote schist are concordant and occur intercalated. The glaucophane-bearing schists GS occur in the eastern and south-eastern part of the study area (N 25° 40'38"E 96° 18'20"). Most of these units are highly weathered. These rocks show yellowish brown to brownish on the weathered surface and greenish blue to bluish on the fresh surface. Generally, the outcrops are highly weathered and the soil colour usually shows reddish brown. The major constituent minerals are quartz, feldspar (albite), glaucophane, epidote, chlorite, magnetite, rutile, ilmenite, relict garnet and accessory apatite, zircon, titanite, plagioclase and potassic white mica (phengite). The amount of amphibole is variable in concentration. The porphyroblast and the matrix minerals have not too much difference in

grain sizes. Amphiboles in these rocks consist of sodic, sodic-calcic and also calcic amphiboles such as glaucophane, ferroglaucophane, riebeckite, magnesioriebeckite, barrosite, ferrobarrosite, winchite, richterite, magnesiokatophorite and actinolite. This rock contains relict garnet which is altered to chlorite and also surrounded by potassic white mica and epidote. Garnet can be seen as well subhedral to euhedral crystal in some rock.

Epidote schist is exposed at the southeastern part of the Tawmaw area along the Tawmaw-Lonkhin car road (N 25° 40'30"E 96° 18'35"). The contact of serpentinized peridotite and epidote schist is not clearly to see. The latter is medium-grained, with reddish brown to yellow on the weathered surface and whitish green on the fresh surface. There is no amphibole, but a lot of epidote and white mica in this rock. Other constituents are quartz, albite, white mica, chlorite, titanite, magnetite, rutile and ilmenite. Zircon, apatite and plagioclase occur as accessory phases. Feldspar is usually albite showing subhedral to anhedral grains. Epidote and quartz are present in equal amounts.

#### 2.3.2. Serpentinized Ultramafic Rocks

In the study area, the ultramafic rocks are represented by serpentinized peridotite and serpentinized dunite.

Serpentinized peridotite is the most important rock unit of the study area. It has locally a tectonic contact with the complex crystalline schist unit along the shear zone of the Tawmaw fault line. This body is roughly oval in shape and probably about 20 km long and about 6.5 km in width. The major Tawmaw fault is roughly NNE-SSW and the elongation of this serpentinized body is closely parallel to this trend. So, the emplacement of this unit is probably due to this fault system. The direct contact of the complex crystalline schist and this serpentinized peridotite unit are covered by soil. Dunite is the other ultramafic rock and the relation between the two could be transitional. The rock is dark-green, medium to fine-grained with granular texture and contains yellowish to yellowish green serpentine minerals. It shows medium to fine-grained hypidiomorphic granular texture with highly jointed contacts. Relic olivine, pyroxene and black opaque minerals such as chromite can be seen. Serpentinized peridotite show crushed and sheared appearances which are directly related to the fault movement and their crushing directions are roughly parallel to the strike of the faults. Outer parts of the rocks are more or less weathered and serpentinized. Iron ore such as isolated block of hematite is found inside of this unit near Lamong village.

Serpentinized dunite is dark green to greenish body and the olivines are subhedral granular grains and transform to serpentine along the fracture and the grain boundaries. Accessory is chromite, magnetite and serpentine minerals. Small veinlets of silica have found in places as a

product of serpentinization. Shear plane can be seen along some minor fault and slippery nature is noticable. Larger chrysotile crystals up to 30 cm are found in the serpentinized ultramafic rocks.

#### 2.3.3. Jadeitite, Albite-jadeitite Rocks and Albitite

In the research area, jadeitite is found in associated to albite-jadeite rock and albitite which occurs as vein-like bodies within the serpentinized peridotite-dunite. Sometimes, it occurs as lens-shaped bodies with 10 x 6 meters. The width of jadeitite is variable. At Natmaw (S of Tawmaw), where the jadeitite body show about 15x6x9 metre whereas at JadeLand and Jingphaw Academy worksites at Tawmaw, the size of the body (recently mined) are ranging about 2x3x3 metre. The jadeitite unit roughly strikes NE-SW with a dip ranging from nearly vertical to 30°. Jadeitite forms lenses surrounded by chlorite schist or amphibole felses and the albitite unit. Generally, the intersection of faults in the serpentinized peridotite at Tawmaw area shows the zonation pattern with jadeitite found as an innermost core surrounded by albitite and albite-jadeite rock, then amphibole felses or amphibole bearing unit (sometimes found as actinolite schist) and in the outer zone thin layers of chlorite schist which is sometime are abscent. The country rock is serpentinized peridotite-dunite (Fig. 2.4). This unit and outer unit of amphibole felses are sometimes fringed and interlaced forming an intermingeling of amphibole felses and jadeitite. Representative samples are collected from Tawmaw (Jingphaw Academy worksite, JadeLand worksite, Aung Sein worksite, Khatta worksite, YiKuu worksite, Sama worksite, LonSein worksite, Thein Than worksite) and Natmaw worksite (world-largest jadeitite body) where the jadeite body is in contact with serpentinized peridotite. Jadeitite generally shows granoblastic texture and fibrous texture in some samples. The grain size varies from very fine-grained to medium-grained (0.05 to 0.5 mm). Hard and compact nature is characteristic due to the interlocking structure of the included minerals. The fresh surface shows dull white, white, pale greenish white, green, mauve, bluish green, dark green to rarely emerald green, lavender blue and yellowish green. On the weathered surface, most of the surface is covered with whitish to greyish white skin which is about 5 to 10 mm thick. The noticeable higher density of jadeitite is characteristics to distinguish it from similar looking albitite. Apple green coloured kosmochlor occurs in the albitite and albite-jadeite unit as well as in the innermost jadeitite unit.

The albite-jadeite unit is found between the jadeitite and albitite unit. The width of this unit is variable, centimeter to sometimes meter in size. It shows a medium- to- coarse-grained, granoblastic texture. Fresh surfaces are white in color, and weathered surfaces grayish white. Mesoscopically, the rock shows a white to light green colour and is heavier in weight than the
albitite but lighter than jadeitite. The outer part of the unit is more or less albitized, soft and friable. The albite-jadeite unit is found at the outer part of the main jadeitite unit which in contact with albitite. In most occurrences, the contact is gradational and sometimes irregular. Albitite shows grayish white to whitish colours on weathered surfaces, and, on fresh surfaces, light green, bluish green, white and greyish white colours. It is normally fine-grained but sometimes medium to coarse-grained, and soft and light compare with jadeitite. Generally, it is more fine-grained than jadeitite. The outcrop appearance is similar to jadeitite, but less compact and lighter weight.

#### 2.3.4. Tertiary sandstone

This unit is mainly exposed at the southeastern part, especially near the Lonkhin village. The Uru boulder conglomerate is deposited on this unit and covers about 2-5 % of the entire area. This unit is mainly composed of medium-to-thick bedded, compact sandstone, occasionally with pebbles and carbonaceous fossil wood fragments. It shows grey colour on fresh surface and yellowish on weathered surface.

#### **2.3.5. Uru Boulder Conglomerate**

This unit is mainly found at the eastern and southern part of the study area. Uru boulder conglomerate is formed by the transportation and deposition of Uru River along. The detrital boulder deposits of the Uru boulder conglomerate include rounded boulders of various rocks including jadeite which derived from the Tawmaw plateau where the primary jadeite vein-like bodies are found in the serpentinized peridotite. Uru boulder conglomerate mainly consists of rounded pebbles of serpentinized peridotite, various varieties of schists, quartzite, limestone, gabbro, diorite, volcanic rocks and jadeite boulders. In this unit, the boulder varieties comprises ultramafic rock up of (40 %), various schists such as garnet-mica schist, epidote schist and glaucophane schist of (35 %), sandstone (8 %), quartz (5 %), limestone (5 %), volcanic rock (2 %) and accessory jadeitite. The size of the boulders is ranging from few meters to several meters. The colour of this unit is dark brown, black and sometimes yellowish brown on fresh surface. This unit can be regarded as polygenetic because of the presence of different rocks in it. The thickness of this unit is about 300 meter in some places and maximum width is about 6 km. Cross-bedding is sometimes observed in the outcrop.

## **CHAPTER**

## III

## **III.** Petrography of the studied samples

## **3.1. Ultramafic Rocks**

In the study area, the ultramafic rocks are represented by serpentinized peridotite and dunite which occur as host for the jadeititic bodies.

### 3.1.1. Serpentinized Peridotite

The studied samples were collected from the Tawmaw area where the jadeitite is in contact with serpentinized peridotite. Sample KT 33, KT 37, KT 39, LS2, YK 9, W6, 011/05, 015/05, 015/05, 015/05, 017/05, 021/05 and 037/05 were collected from Katta worksite, LonSein worksite, Yikuu worksite, JadeLand worksite and Jingphaw Academy worksite. Sample T11 and T 14 were taken from the Natmaw (N 25° 33' 11" E 96° 14' 30") where the world's largest jadeitite body occurred. Serpentinized peridotite shows yellowish brown to dark grey on weathered surface and dark green on the fresh surface. It is moderately to highly serpentinized at the outer part of the body having darker colour than the dunite.

#### **Megascopic Description**

Megascopically, it is a medium to coarse-grained holocrystalline xenomorphic granular rock. On the fresh surfaces, it is yellowish brown, dark green or dark grey colour with grain size variation from place to place. It is highly serpentinized showing a colour variation of dark greenish grey to yellowish brown and sometimes purplish brown. The outer part is moderately to highly weathered. On the weathered part, relict of olivine, magnetite, chromite and serpentine minerals can be observed. It shows sugary texture of olivine grains and which is darker in colour than the dunite. The grain size is ranging from 0.1 mm to 5 mm. It is made up of olivine, serpentine and black opaque mineral as accessory minerals. It also contains minor amount of pyroxene and amphibole.

#### **Microscopic Description**

The rock contains xenomorphic, non-equigranular grains of olivine, pyroxene, amphibole and black opaque minerals. Olivine made up about the 80% of the total volume, serpentine 15-16 vol.%, amphibole and pyroxene 1-2 vol.%, together with accessory black opaque mineral up to 2 vol.%. In samples KT40, T11, T14 and 037/05, the amounts of black opaque minerals range from 3-5 vol.%, and in sample 011/05, 015/05, 017/05, the concentration of black opaque mineral concentration is nearly 20 vol.% of the sample.

In the analysed samples, olivine generally shows medium-grained, inequigranular texture with pale green to colourless colour under polarised light. The size of olivine grains is > 200  $\mu$ m, forming subhedral and moderately to highly serpentinized crystals. Serpentinization is mainly found along the irregular cracks of olivine forming mesh-like texture with veins and veinlets. Olivine includs black opaque minerals of irregular shape with varying size. Small recrystallized olivine grains ranging the size from 5-100  $\mu$ m are found between the larger olivine grains (sample T11).

Pyroxene occurs as accessory mineral with subhedral to euhedral prismatic grains in this rock (Sample T11, KT39, KT41, 017/05). The size of pyroxene is ranging from 200-500  $\mu$ m. The colour of pyroxene is colourless under polarised light and greyish to yellowish between crossed-polars (Fig. 3.1).

Amphibole occurs between the olivine grains with sizes ranging from 50 to 300  $\mu$ m (sample 011/05, T11, Fig. 3.2). It shows subhedral to euhedral crystals.Generally, amphibole is colourless with polarised light. It is more or less altered at the boundaries and along the cleavages.

Black opaque minerals are chromite and magnetite which occur as accessory minerals with size varying from about 200  $\mu$ m to 2 mm. They have subhedral to anhedral grains and are included within the olivine grains or occur between the grain boundaries. In sample 021/05, chromite grains show perfect octahedral cleavage in three directions (Fig. 3.3). In some serpentinized peridotite, these black opaque mineral shows a certain alignment in a foliation (T11, Fig. 3.4).

Olivine is altered to antigorite and lizardite forming typical mesh textures. In some serpentinized peridotite samples (T11), olivine grains are highly crushed and form aggregates of the grains with a certain alignment (Fig.3.4). The common serpentine mineral is antigorite. Most of the antigorite shows a bladed form, a flaky form and mesh-like pattern. In sample (W6), serpentinization is intense resulting in a totally serpentinized rock with trace of the relict olivine (Fig. 3.5). Chlorite is also found within the olivine grains with size ranging from 100-105  $\mu$ m. It shows subhedral to anhedral grains with 100-300  $\mu$ m in size which is colourless under polarised light and greyish to bluish grey in crossed polars. Chlorite occur only accessory mineral (017/05).



Fig. 3.1: Pyroxene in serpentinized peridotite from Tawmaw area (sample 017/05). Crossed-polars.



Fig. 3.2: Amphibole showing basal section with typical amphibole cleavages in serpentinized peridotite from Natmaw area (sample T11). Crossed-polars.



Fig. 3.3: Black opaque subhedral chromite grains showing perfect octahedral cleavage in 3 directions in serpentinized peridotite from Tawmaw area (sample 021/05). Crossed-polars.



Fig. 3.4: Alignment of black opaque minerals and crushed olivine grains in a certain direction in serpentinized peridotite from Natmaw area (sample T11). Crossed-polars.

## 3.1.2. Serpentinized Dunite

#### **Megascopic Description**

Serpentinized dunite is sporadically exposed in the main ultramafic body of Tawmaw. The studied samples were collected from the Jingphaw Academy worksite and Jade Land worksite of Tawmaw ultramafic body (Sample JFa/05, JF8, JF11, 001/05 and 028/05). It is essentially composed of olivine and black opaque minerals as accessory. Generally, dunite shows sugary texture in hand specimen due to the olivine grains. It occurs as medium-grained holocrystalline, allotriomorphic granular texture. Typical olive green colour is characteristic and there is some variation in colour from yellowish green, green to yellowish brown. It shows grain size ranging from 0.1 mm to 3 mm. On the fresh surface, it shows olive green colour to yellowish green colour and sometimes greenish brown colour. On the weathered surface, it shows yellow, greyish blue to purplish grey colour. It is more or less serpentinized and in this part which contain serpentine mineral, antigorite in minor amount.

## **Microscopic Description**

The rock is medium to coarse-grained, allotriomorphic granular texture. The grain size is ranging from 50  $\mu$ m to 6000  $\mu$ m. It is a holocrystalline rock principally composed of olivine and accessory black opaque minerals. The mineral constituent of olivine is about 90-93 % of the total volume, which also contains serpentine fibers of 6-8 vol.%. Black opaque minerals of magnetite and chromite are the remaining constituent.

Olivine shows subhedral grains with polygonal shape and size ranging from 200  $\mu$ m to 6000  $\mu$ m with equigranular xenomorphic texture. Most of the grains are highly fractured and traversed by serpentine (Fig. 3.6). The rock also contains veinlets of serpentine which are derived from the olivine. The grade of serpentinization is medium and veins appear as a network. Olivine also occurs as small secondary grains with size ranging from 0.001 to 0.1  $\mu$ m at the grain boundaries of the larger one (Fig. 3.7).

Serpentine occurs as yellow to pale yellowish green mineral under polarised light and forms network like veins. It also shows bluish grey to grey between crossed polars (Fig. 3.8). Black opaque minerals with subhedral to anhedral shapes are included in the olivine grains and also at the grain boundaries. The sizes of these black opaque (magnetite and chromite) minerals are ranging from 100 to 1500  $\mu$ m and some of which are surrounded by serpentine. These black opaques also form a certain foliation similar as in serpentinized peridotite.



Fig. 3.5: Relict, highly fractured and distorted, olivine in highly serpentinized peridotite from Tawmaw area (sample W6). Crossed-polars.



Fig. 3.6: Highly fractured olivine in dunite which is serpentinized along the fractures, from Tawmaw area (sample JFa/05). Crossed-polars.



Fig. 3.7: Crushed olivine forming secondary fine-grained in serpentinized peridotite from Tawmaw area (sample JF11). Crossed-polars.



Fig. 3.8: Serpentine in serpentinized dunite from Tawmaw area showing the typical mesh-texture (sample 001/05). Crossed-polars.

## **3.1.3.** Chlorite Schist

This unit is well developed at the contact between the serpentinized peridotite and outermost zone of jadeitite bodies. Analysed samples were taken from the Yi Khuu (YK1, YK11) worksite N  $25^{\circ}$  41' 10" E  $96^{\circ}$  13' 40" and Katta (KT42) worksite N  $25^{\circ}$  39' 58" E  $96^{\circ}$  15' 55" and Aung Chan Thar worksite (005) N  $25^{\circ}$  41'50" E  $96^{\circ}$  14' 45". Adjacent to this unit, sometimes amphibole felses unit rim the jadeitite bodies. Chlorite schists occur as alteration product between the serpentinized peridotite and jadeitite units separating the later from the former one.

Megascopically, chlorite schist formed at the outermost part of serpentinized peridotite body with up to 20 cm in thickness. It shows green to light green colour, and whitish to whitish green on the weathered surface. This unit is soft and friable.

Microscopically, it is mainly composed of chlorite up to 99 vol.% and a black opaque accessory makes the rest volume. Chlorite generally shows colourless, pale yellow to pale green and yellowish to yellowish brown in plane polarized light. It is moderately pleochroic from pale green to pale yellow and yellowish to brownish in some chlorite. Chlorite shows grey, bluish-grey and yellowish brown colour between the crossed polars. The texture is medium to fine-grained lepidoblastic. It shows flaky, subhedral prismatic, fibrous and scaly aggregate forms. The size of chlorite grains is up to 600  $\mu$ m but generally the grains are less than 200  $\mu$ m. The flakes of chlorite are usually parallel to the direction of foliation. Folded chlorite is also found with the size of these veins is about 600  $\mu$ m. Moreover, brownish chlorite surrounded the chromite grains (YK1, Fig. 3.9 b).

### 3.1.4. Amphibole felses

Amphibole felses are rocks mainly composed of amphiboles with some other accessory minerals. This unit occurs between the wall rock of jadeitite hosting serpentinized peridotite and a jadeitite bearing unit. Amphibole felses are mainly composed of bluish green to dark green amphiboles. In some samples, it contains chromium rich pyroxene, kosmochlor and jadeite (JF9, KT 34). In some work-site, this unit is separated from serpentinized peridotite by the chlorite schist. Sometimes, at the contact between serpentinized peridotite and inner jadeitite and related units, chlorite zone is missing and instead of it, amphibole felses unit formed as direct contact with serpentinized peridotite (T12, KT34, 019/05, KT17, 024/05, JL1/05, 020/05, 027/05, JF9). Sometimes, it is direct contact with the jadeitite unit



Fig. 3.9: a. Chlorite in chlorite schist which is folded in direction of foliation (YK1), Polarised light ; b. Chlorite surrounded the relict black opaque chromite (YK1), Polarised light ; c. Zoining of euhedral basal amphiboles in amphibole felses (KT34), Crossed polars and d. Kosmochlor in amphibole having more intense colour beside the chromite grain (KT34), Polarised light.

(Natmaw, T15). The colour of this amphibole felses are varying from green, dark-green, darkbluish green and dark blue.

Microscopically, most of the amphiboles show subhedral to euhedral prismatic, fibrous and bladed forms. It grain size is variable from medium to fine-grained showing a nematoblastic texture. The amphibole is colourless in polarised light and weak pleochroism in some amphiboles (KT 34). The amphibole felses is composed of 90-95 vol.% amphibole, 2-3 vol.% chlorite and 1-2 vol.% jadeite, kosmochlor and chromite. It shows foliated and micro folded structure (027/05). The larger grains in sample (027/05) are highly fractured. The sizes of these larger grains and the relict larger grain boundary can be traceable. The sizes of these larger grains are up to 500 µm and the finer prismatic grains are not larger than 50 µm.

In sample KT34, amphibole shows medium to coarse-grained, nematoblastic texture with grain size range from 200-1000  $\mu$ m. Most of the amphiboles in this sample are colourless in polarised light. Zoning is common in this sample (Fig. 3.9 c). Fibrous amphiboles are also found between the larger grain boundaries with the size <5  $\mu$ m. In this sample, jadeitic pyroxene and kosmochlore are present up of 2 vol.% together with chlorite (3 vol.%). Jadeitic pyroxene occurs as subhedral prismatic crystal. Kosmochlor is found as subhedral prismatic and anhedral aggregate which is formed as replacement of the chromite. It shows pale green to greenish colour but it is more intense at the border of chromite grains (Fig. 3.9 d). A strong pleochroism from pale green through green to yellowish green can be observed. The size of kosmochlor ranges from 10-500  $\mu$ m. This mineral occurs within the grain boundaries and as inclusion in the pyroxene and amphibole. Chromite occurs as relict mineral surrounded by kosmochlor. The size of chromite is up to 600  $\mu$ m with irregular and rounded shapes.

In sample JF9, the amphiboles are coarse-grained, subhedral to euhedral form. The outer part of the amphibole is altered to chlorite. Kosmochlor is also occurs as transformation product of chromite and relict chromite are occur within the core. Kosmochlor occurs as subhedral to anhedral aggregate and also small prismatic inclusion within the amphiboles.

In some sample (AungSein), amphiboles show fine to medium-grained, prismatic as well as fibrous forms with size  $<50 \mu$ m. Finer grains are more common and show radiated fan-shaped aggregates (Fig.3.10 a). Accessories include jadeite with subhedral to anhedral prismatic grains with size  $> 200 \mu$ m.

In sample T15, which is direct contact with the serpentinized peridotite and jadeitite, amphiboles are highly altered and among the alteration products, relict prismatic amphibole and jadeite are left (Fig. 3.10 b).



Fig. 3.10: a. Fan-shaped amphiboles in amphibole felses (AS); b. Highly altered amphibole felses containing amphibole and jadeite (T 15); c. Basal section of amphibole with characteristic cleavages and zoning in actinolite schist (KT24); and d. Twinning in amphibole of actinolite schist (KT 44). Crossed-polars.

In sample 012/05, the contact of amphibole felse and impure jadeite can be clearly observed. In this sample, amphiboles show fine-grained, fibrous to thin prismatic forms. Jadeite is also incorporated within the amphiboles.

#### **3.1.5.** Actinolite Schist

This unit is a found between the chlorite schist and amphibole felses, but sometimes this unit is missing. The studied rock samples were taken from the Katta worksite, Yi Kuu worksite, and Thein Than worksite from Tawmaw area (YK4, YK5, YK8, YK21a, KT24, KT44, Thein Than, JF5/05).

Megascopically, actinolite schist is a green to dark green rock and constituent amphiboles can be identified with naked eyes. Most of the amphiboles have grains size ranging from 2 to 10 mm. Actinolite usually shows long prismatic euhedaral to subhedral crystals. It is soft and less compact at the outcrop.

Microscopically, this unit shows medium to coarse-grained, nematoblastic schistose texture. Amphiboles in this unit show subhedral to euhedral long prismatic form sometime with braded out lines. Moreover, basal section of amphiboles also occurs in this unit and showing characteristic amphibole cleavages (KT24, KT44, Fig. 3.10 c). Twinning is common in some amphiboles and showing simple contact twinning (KT24, KT44, Fig. 3.10 d). Finer fibrous amphiboles are found between the grain boundaries and most of these finer amphiboles are altered to chlorite. It is mainly composed of actinolite (richterite) (microprobe analyses with Leake et al. amphibole classification indicate that majority of these actinolite minerals are fall in Richterite) 95 (90 vol. % richterite, 2 vol.% edenite and 3 vol.% actinolite), finer fibrous amphibole (edenite) of 5 vol.%, 2 vol.% chlorite and kosmochlor and chromite as accessory minerals. The size of larger amphiboles is  $> 50 \mu m$  and the finer fibrous amphiboles are < 5um. Under plane polarised light, richterite and actinolite show colourless to pale green. These amphiboles show 2<sup>nd</sup> order brighter colour of yellow, brown, orange, purplish yellow, and grey colour between crossed polars. Fine, fibrous amphiboles show grey, yellow and brown colour. Chlorite also shows pale yellow to brown colour which are the alteration product of these amphiboles. Generally, long axis of amphiboles is oriented along the direction of foliation (Thein Than, Fig. 3.11 a) and most of the amphibole grains are fractured. Alteration occurred along these fractures, grain boundaries and along the cleavage planes.

Kosmochlor and chromite occur as accessory minerals. Kosmochlor shows bright green colour and showing strong pleochroism from green, yellowish green to deep green. It show brighter yellowish bright green colour between the crossed-polars. Kosmochlor in this unit



occur as two types, one is aggregate which replaced the chromite grains and the other is fine, subhedral prism which included within the amphiboles. Aggregate type kosmochlor is found as rounded grains or sometimes with irregular outlines which have with or without chromite relict in the core. The large aggregate type kosmochlor is range from 200-400  $\mu$ m and fine prismatic kosmochlor is range from 1-5  $\mu$ m (KT 24, KT44, Fig. 3.11 b-d).

#### 3.2. Mafic Rocks

#### 3.2.1. Glaucophane Schist

This unit is cropped out at the eastern part of the study area (033/05, 034/05, 035/05, 041/05). On the fresh surface, it shows yellowish brown to brownish on the weathered surface and white with greenish to greenish blue on the fresh surface. It shows medium to fine-grained schistose texture. The major constituent minerals assemblage are amphiboles (glaucophane) (7-30 vol.%), epidote (10-40 vol.%), quartz (5-15 vol.%), feldspar (albite) (10-30 vol.%), chlorite (10-18 vol.%), magnetite, rutile, ilmenite, relict garnet and accessory apatite, zircon, titanite, plagioclase and potassic white mica (phengite). The amphiboles are difference in composition such as riebeckite, magnesio-riebeckite, ferroglaucophane, glaucophane, richterite, magnesiokatophorite, ferrobarrosite, barrosite and winchite. These amphiboles are heterogeneous and show mineralogical zonal appearance especially in sample 034/05 and 041/05.

Microscopically, glaucophane schist can be classified into two groups: amphibole richepidote poor (Type I) and amphibole poor-epidote rich (Type II).

In type I, sample 033/05 and 034/05 composed of amphibole (20-30 vol.%), albitic feldspar (15-30 vol.%) with 10-300  $\mu$ m in grain size, epidote (10-20 vol.%) with 10-200  $\mu$ m in grain size, chlorite (15-80 vol.%), quartz (5-7 vol.%) with grain size up to 0.5 mm, white mica including phengite (1-3 vol.%), rutile (1-3 vol.%) and opaques and other accessory minerals make (1-3 vol.%). Moreover, (2-3 vol.%) of relict garnet is also occurs in sample 034/05. The out line of relict garnet can be traced up to 4 mm in size, but these garnets are highly altered to chlorite. Amphiboles in type I are usually glaucophane and are showing the zonal appearance with subhedral to euhedral grains with blue, bluish green, greenish blue and purplish blue colour and showing strong pleochroism from greenish blue to violetish. These amphiboles show prismatic as well as basal form and size ranges up to 0.4 mm and also small needle-like prisms ranging from 0.01-150  $\mu$ m. Most of the blue amphiboles are transformed to chlorite at the boundary, some are completely replaced by chlorite and developed together with epidote, albite and quartz along the foliation. Epidote, phengite and zircon occur as inclusions in glaucophane and quartz. Epidote occurs as anhedral to subhedral grains showing

compositional variation. Epidote shows colourless and greyish or yellowish colour in polarised light. Rutile occurs as subhedral to anhedral aggregate, some shows spindle shape in outline and sometimes intergrowth with epidote and blue amphiboles. White mica is not common and espically found in the relict part of garnet and can also found in the matrix.

In type II, (035/05, 041/05), epidote is more abundant than amphibole. The size of epidote is range from 5-400 µm with subhedral prismatic to anhedral rounded grains. It is composed of (25-40 vol.%). The colour of epidote is yellowish brown to brownish in plane polarised light and 2<sup>nd</sup> to 3<sup>rd</sup> order brighter colour in crossed polars. Spindle-shaped basal section of epidote is rarely found. Feldspar is the second most abundant mineral and it made up of (10-25 vol.%). Most of the feldspar shows subhedral prismatic form. Quartz is next abundant to feldspar and made up of (10-15 vol.%). Generally, quartz grains show anhedral form with irregular outlines. Wavy extinction is common. The size of quartz grains not exceed than 0.4 mm. Blue amphiboles made up of (7-15 vol.%) in this type II rock. This amphibole usually shows subhedral to euhedral prismatic form and also shows needle-like small prisms. The size of this amphibole is up to 0.3 µm. Basal form of amphibole is sometimes found and typical amphibole cleavage is characteristics. Zoning is also common in some grains and better seen in the basal sections. Generally, these amphiboles are transformed to chlorite at the grain boundary or along the cleavage. Chlorite show subhedral to anhedral flakes with pale green to green in polarised light. In crossed polars, it shows brownish to yellowish brown colour. Total content of chlorite is range between 10-15 vol.%. Moreover, chlorite is also associated with epidote, albite, quartz and white mica in the foliation plane. The amount of white mica is not more than 2 vol.%. Garnet is also occurring in this type II rocks which made up of 2-3 vol.%. The size of relict garnet is ranging about 0.5 to 2 mm in diameter. The porphyroblastic outline is still remaining but forming a lot of relict island within the chlorite. Generally, most part of garnet is altered or replaced by chlorite and occurs as relict form. This relict part is surrounded by amphibole, epidote and chlorite and sometimes white mica is also found in this relict part. Rutile is formed as subhedral to anhedral grains and range between 1-3 vol.%. It occurs as inclusions in the amphiboles and also within the grains boundaries of amphiboles and epidotes. Spindle shape rutile is occasionally found. The size of rutile range from 1 to 200 um. Black opaque and other accessories such as magnetite, ilmenite, apatite, titanite and zircon which composed of 1-2 vol.% in this type II rocks.

#### 3.2.2. Epidote Schist

This unit crop out at the eastern and southern part of Tawmaw area (030/05, 031/05 and 032/05). It shows yellowish white on the weathered surface and whitish green to bluish white on the fresh surface.

Samples of the epidote schists show two main foliations S1 and S2. S1 is relict, identified in F2 isoclinal folds and S2 is the regional foliation. In thin section, it shows medium to finegrained, porphyroblastic schistose texture and mainly composed of albite, quartz, white mica, epidote, chlorite, titanite, phengite, rutile and accessory magnetite, ilmenite, plagioclase, apatite and zircon. These rocks generally have lack of amphiboles and the most epidote rich one and sample 030/05 has high content of white mica than other ES rocks. Smaple 030/05 is composed of albite (40-45 vol.%), quartz (20-25 vol.%), white mica (10-12 vol.%), epidote (8-10 vol%), chlorite (5-6 vol.%), titanite, rutile and other accessory minerals such as magnetite, ilmenite, apatite and zircon. The size of albite in this rock is range from 20-200 µm and showing subhedral to anhedral outlines. This albite show simple twinning and the grains are fractured. Some twin bands in albite are curved which is roughly parallel to foliation. Quartz is the second most abundant mineral and showing anhedral larger grains and smaller grains which are formed by the recrystallization with size ranging from 0.001 to 0.3 mm. White mica including potassic one is form as isolated grains and sometimes as fan-shaped aggregate. Kink banding of white mica is found in the sample (030/05). Epidote in this sample occurs as large porphyroblasts in the matrix with the size up to 1 mm. It also occurs as smaller grains. Epidote in this sample shows subhedral to anhedral grains and sometimes as spindle-shaped basal section. It occurs as inclusion in the albite and quartz. In this sample, there has no relict of garnet but large cluster of chlorite may probably be the pseudomorphs of garnet. Chlorite also found at the surrounding of albite, epidote and white mica.

In sample 031/05, it is made up of albite (30-35 vol.%), quartz (20-25 vol.%), epidote (20-25 vol.%), chlorite (7-10 vol.%), white mica (1-2 vol.%), titanite (1-2 vol.%), black opaque (2 vol.%) and rutile and other accessories (1 vol.%). Albite in this sample shows subhedral to anhedral grains. The amount of epidote and quartz in this sample is nearly equal. Epidote porphyroblasts with size up to 1 mm are found as subhedral prismatic to elongated grains which are parallel to the direction of foliation. It shows yellowish-brown under plane polarized light and 3<sup>rd</sup> order bright green, orange and yellow between crossed-polars. Some of the epidote grains are surrounded by the chlorite. The out line of chlorite is sometimes look like as a pseudomorph after the garnet although there has no relict garnet in the sample. Quartz in this sample is also as larger anhedral grains and smaller secondary recrystallized grains showing granular mosaic texture. Some of the quartz grains are elongated in shape and

show undulatory extinction. Inclusion of small quartz grains are also found in the albite and epidote.

In sample 032/05, it is composed of albite (30-40 vol.%), quartz (20-25 vol.%), epidote (15-20 vol.%), chlorite (3-6 vol.%), garnet (2-3 vol.%), white mica (3-4 vol.%) and rutile, black opaque and other accessories (1 vol.%). Albite is the most abundant mineral with size up to 2.5 mm. Most of the albite grains are subhedral form. Quartz is the second most abundant mineral and occurs as subhedral to anhedral grains showing granular mosaic texture. In this sample, epidote is lesser in volume than quartz and showing as a subhedral porphyroblasts among the albite and quartz matrix. The size of epidote porphyroblast is about 1 mm. In this sample, relict garnet is also found among the chlorite. The relict out line of garnet can be trace up to 2 mm in size. Rutile and other black opaque minerals occur as inclusions in the quartz, albite, epidote and also in the garnet. Zircon and apatite occur as accessory and as inclusions in quartz.

## 3.3. Metapelitic rocks

#### 3.3.1. Garnet-mica schist

Garnet-mica schist is found at the western part of the study area and the samples were collected from the Sanphe stream (017, 018 and 019). It shows medium to coarse-garined, porphyroblastic schistose texture with grayish white on the fresh surface and greyish brown on the weathered surface.

In thin section, it shows medium to coarse-grained, porphyroblastic texture. There are 2 main of foliation S1 and S2 where S1 is the main foliation and S2 is the syntectonic with garnet rotation. The matrix is made up of fine-grained white micas, quartz, chlorite, magnetite, rutile, epidote, albite, opaque and accessory ilmenite, zircon and apatite. In studied samples, white mica is the most abundant constituent minerals which include muscovite, paragonite and phengite. Sample 017 and 018 have nearly the same amount of white mica, 35-42 vol.%, where as sample 019 have less concentration of white mica, 30-37 vol.%. The size of micas is ranging about 0.001 to 0.1 mm. It shows subhedral prismatic crystals and sometimes, fibrous and fan-shaped muscovites are found within the foliation. There are at least two direction of foliation which can be traced by the parallel arrangement of micas. Potassic variety, phengite occur among the other white mica with its noticably high interference colour and found as inclusuion in garnet and also found within the foliation. Intergrowth of quartz and white mica is common in sample 017 and 019. Most of the white micas are more or less altered to paragonite. Relict of biotite is observed in sample 019 and are altered to chlorite. Zircon, titanite and magnetite are included in white mica. Quartz is second most abundant mineral in

this rock. In sample 017 and 018 have the same concentration of guartz, 25-30 vol.%, but in sample 019 have slightly higher concentration than the other and which is made up of 30-35 vol.%. The size is variable, in the foliation, it show medium to fine-grained with the size ranging from 0.1-2 mm, but as inclusion in the garnet, it is so small up to 5 µm. Undulatory extinction is common in quartz. Most of the quartz grains shows anhedral granular mosaic and with suture contact between the grain boundaries. Tiny white mica and zircon inclusions are observed in some quartz grains. Elongated quartz grains are also observed and other mineral inclusions in quartz are epidote, phengite, apatite, zircon and rutile. Garnets occur as euhedral to subhedral porphyroblasts and are highly fractured. Garnet from the studied samples 017 and 019 have nearly the same concentration (10-12 vol.%), but sample 018 have slightly lower concentration, 8-10 vol.%. In sample 017 and 019, it shows syntectonic trails of micas as inclusions. In sample 017, the outer part of garnet show darker rim. The size of garnets is ranging from 0.1 to 8 mm in diameter. It shows sponge-like appearance due to the presence of inclusions of quartz, white mica, magnetite, epidote and zircon but quartz is the most abundant one. Alteration of garnet is formed along the fracture and the outer part of the grains and the alteration product is chlorite. Albitic feldspar which is partially altered and mainly made up of 2-4 vol.% in sample 017 and 019, but it is more enrich in sample 018 and which is made up of 5-10 vol.%. Most of the feldspar grains are subhedral to anhedral grains. Chlorite occur as anhedral form and also fibrous along the fracture of garnet. It also occurs as relict mineral probably from the biotite (sample 017 and 019). It shows green to yellowish brown colour. Epidote occurs as 1-3 vol.% in the studied samples. It shows subdedral prismatic grains with brownish colour. It usually found in the matrix and which is sometimes surrounded by opaques. It also occurs as inclusion in the garnet. Titanite occurs as 0.05 to 0.1 mm size brownish yellow, subhedral to anhedral accessory mineral within the matrix and also as inclusions in the garnet. Rutile and black opaque minerals occur as accessory with size ranges from 0.05 to 0.2 mm size. These grains show subhedral to anhedral shapes and dispersed in the matrix and also as inclusions in the garnet.

#### 3.4. Jadeitite and Related Rocks

#### 3.4.1. Jadeitite

The studied jadeitite samples were collected from Natmaw, Tawmaw and surrounding worksites. In Tawmaw, jadeitite samples were collected from Jade Land worksite, Jingphaw Academy worksite, Sama worksite, Khine Kyin worksite, Katta worksite, Yi Kuu worksite and Aung Sein worksite (JL, JF, SMJD, MJ, KT, YK, AS).

The colour of fresh jadeitite surface shows dull white, white, pale greenish white, green, mauve, bluish green, dark green to rarely emerald green, lavender blue and yellowish green. Whitish to greyish white colour can be seen on the weathered surface.

In thin section, it can be classified in to two types: pure jadeite and impure jadeite. Pure jadeitite is mainly made up of jadeite (98-99 vol. %) where as impure jadeite is made up of 85-95 vol.% jadeite and kosmochlor and amphibole as the remaining constituent. In both pure and impure jadeite, it shows variable in texture such as granular with more or less equidimensional grains. Sometimes, within a single sample, coarser granular grains are set within the finer grains. Moreover, porphyroblastic texture, interlocking texture and cataclastic texture are also found. Jadeite grains also show shubhedral to anhedral form with variable appearances such as long prismatic, short prismatic, fibrous, bladed, fan-shape, granular and radiated. The size of jadeite grains range from 0.1-5 mm. Most of the jadeite grains are colourless and very rarely pleochroic in some chromium rich jadeite show pale green to green pleochroism. Common form of jadeite grains show as long and short prismatic, fibrous aggregate, radiated crystals and granular grain. Interlocking nature of prismatic jadeite grains also observed. In some sections, it shows larger porphyroblastic grains within the smaller grains (Fig. 3.12 a-h). Basal section of jadeite shows typical pyroxene cleavage and on the prismatic section, one set of cleavage is pronounced. Some jadeite grains are turbid due to the high concentration of tiny inclusions such as rutile which is parallel to the cleavage in prismatic jadeite grains. Some grains contain inclusions of amphiboles, albite and rare zircon. Sometimes, the grains are bent due to the tectonism and showing suture contact (MJ12, Fig. 3.12 d). Twinning is common and contact twinning is found. Zoning can also be found in some grains (sample 013/05, MJ 13, Fig. 3.13 a). Most of the grains show the wavy or undulatory extinction due to the strong deformation. In sample (AS 3a), the grains of the jadeite are highly crumbled and crushed (Fig. 3.13 b). Kosmochlor in jadeite is found within the jadeite grain (AS1, Fig. 3.13 c). It size is ranging from 0.05 to 2 mm. Its colour is noticeable apple green, yellowish green to deep green. The shape of kosmochlor is prismatic and sometimes showing subhedral or rounded aggregate. The pleochroism of kosmochlor is so distinct and show from yellowish-green to deep-green to bluish-green. Kosmochlor is formed by the decomposition of chromite and which surrounded the chromite grains. Omphacite is found as associated mineral in jadeite (MJ4, MJ20, MJ14, 012/05, KT23, KT28). The size of omphacite is about 0.05 to 1 mm. It shows white in polarised light and pleochroism is not common. But under the crossed-polar, it shows more higher interference colour than jadeite. Omphacite usually show subhedral prismatic form. One set of cleavage is sometime pronounced. The outermost part of the omphacite is usually altered.



Fig. 3.12: a. Fan-shaped prismatic jadeite (029/05); b. radiated aggregate of jadeite (SMJD); c. granular grains of jadeite with various sizes (MJ12) and d. Jadeite grains with suture contact (MJ12), Crossed Polars.



Fig.3.12: e. Long and short prismatic jadeite (013/05); f. zoning in long prism of jadeite associated with short prism of jadeite (013/05); g. interlocking of fibrous jadeite grains with porphyritic larger jadeite (KT 20) and h. long prismatic jadeite which is bent due to deformation (KT 17), Crossed Polars.



Fig. 3.13: a. Zoning in jadeite (MJ13); b. highly curshed jadeite grains (AS 3a); c. kosmochlor in jadeite which surrounded the relict chromite (AS1) and d. jadeite (lower right) associated with twinned albite (top left and centre) and amphibole (lower right).

Amphibole associated in some sample as accessory (KT17, KT18, JL1/05, SMJD, 012/05, Fig. 3.13 d). The size of amphibole is about 0.005 to 0.1 mm. Generally, amphiboles are colourless. The higher interference colour and lower extinction angle of amphibole is noticeable in crossed-polars. It shows prismatic and fibrous form. These amphiboles are more or less sub-hedral to euhedral grains. Basal section of amphibole is sometime occurred in jadeitite (SMJD). Sometimes it shows one perfect cleavage. Amphiboles are included by smaller jadeite grains and tiny rutile, zircon and black opaques minerals. As like as jadeite, amphiboles also show deformation features such as bent crystal form. Finer grain amphiboles are more or less parallel to the direction of foliation within the jadeitite. In the analysed sample (SMJD, Fig. 3.13 d), jadeite is associated with albite. In sample (SMJD), albite is associated together with the amphiboles. Albite occurs as medium to fine-grained, anhedral form as well as subhedral prismatic grains. It also shows albite twinning.

Vesuvianite is rarely found as accessory mineral in jadeitite together with limonite and altered sheet silicate, smectite (MJ11, Fig. 3.14 a).

The mineral assemblage of pure jadeite is jadeite + accessory and for impure jadeite is jadeitie is jadeite + kosmochlor + omphacite  $\pm$  amphiboles + albite.

#### 3.4.2. Albite-Jadeite Rocks

This unit is the transistion between inner core unit of jadeitite and outer rim albitite unit (005/05, KT34, KT23). The nature of this unit looks like both of jadeitite and albitite. It is also lenses or vein-like body and its limit is variable from centimeter to meter and difficult to demarcate the exact boundary between the core jadeitite and outer rim albitite. The weathered surface shows grayish white and fresh surface shows white colour.

Microscopically, the albite-jadetite rocks are composed by albite and jadeite with 80% jadeite component and 20 % albite. The size of jadeitite is ranging from 0.05 to 0.5 mm. Most of the jadeite grains show white with prismatic form. The grains are usually prismatic sub-hedral to euhedral. Pyroxene cleavage is common on the basal section and prismatic section shows one distinct cleavage (Fig. 3.14 b). Most of the inclusions are jadeitite itself. Granoblastic texture is common. In this unit, albite grains are finer than jadeite grains ranging from 0.001 to 0.2 mm. The colour of albite is usually white. Albite usually shows granular and prismatic forms with subhedral to anhedral nature. Inclusion is not common in albite grains. The grain boundaries are more or less suture contact. Twinning is not common in albite especially on the smaller grains. Both albite and jadeite grains in this unit show undulatory extinction. Thin banding of 0.1 to 5 mm of the chlorite is also found in albite-jadeite unit and which have some movement in banding (005/05).



#### 3.4.3 Albitite

Albitite is the outermost unit and which show greyish white on the weathered surface and fresh surface as light green, bluish green, white and greyish white colour (008/05, 010/05,). This unit is more or less weathered in its outer part and sometime friable. The outcrop nature is look like as jadeite and albite-jadeite rocks, but has more lighter weight than the former.

In thin section, Its can be observed as fine to medium-grained with grains size ranging from 0.001 to 0.1 mm. Most of the albite grains are white and shows subhedral to anhedral grains and sometimes show prismatic forms. It shows granoblastic texture with angular grain contact. Sometimes, larger albite grains of more than 1 mm in diameter are found as euhedral prophyroblasts crystals. In this case, twinning is common in these larger crystals, but generally the finer grains rarely show twinning. Albite grains are parallel along the direction of foliation (Fig. 3.14 c).

## 3.4.4. Maw-sit-sit

Maw-sit-sit is a kind of rock which usually composed of kosmochlor, amphibole, albite and chromite, named after the locality Maw-sit-sit where it was found. It occurs as minor unit among the amphibole felses but the contact nature have not yet clearly recognized in the field. Megascopically, it is mainly made up of kosmochlor, amphiboles, albite and chromite. The weight of this rock is also heavy. On the fresh surface, it shows dark green to black and greenish black to deep green on fresh. The size of the grains are variable from 0.01 to 5 mm. Microscopically, kosmochlor is the most constituent mineral with its characteristics deep green colour. In sample (MJ17) kosmochlor is made up of (70 vol.%) together with 15 vol.% amphibole, 10 vol.% albite and 5 vol.% chromite. The size of kosmochlor is about 0.1 to 5 mm. Kosmochlor show pleochroism from yellowish-green to deep-green to bluish-green. The grains also show prismatic and aggregate form with subhedral to anhedral nature (MJ 17, Fig. 3.14 d). Kosmochlor is also replaced by the chromium rich jadeite (MJ 17, Fig. 3.15 a). Chromite of larger grains (0.1 to 5 mm) is surrounded by kosmochlor. Chromite shows subhderal to anhedral grains, which are break down and transformed to kosmochlor (MJ 17, Fig. 3.15 b). Albite in these rocks are described by (Gübelin, 1965) but (Naing, 1990) argued for the presence of albite in Maw-sit-sit. She suggests that this may be misnomer for the Maw-sit-sit which contains albite. But, there may be variation in constituent and concentration of mineral in Maw-sit-sit which can only be found in Tawmaw area.

The studied sample MJ 17 contains albite which is made up of (10 vol.%) with fine-grained, subhedral to anhedral forms Albite in these samples is range from 0.05 to 2 mm and more or



Fig. 3.15: a. Kosmochlor replaced by chromium jadeite in Maw-sit-sit (MJ17); b. relict chromite at the core showing that kosmochlor was formed by the deformation of chromite (MJ 17): c. relict chromite surround by kosmochlor in Maw-sit-sit (MJ 18), Polarised Light.

less prismatic but granular form is also found. Most of albites are subhderal to anhedral grains. The grains boundary has angular contact and sometimes shows suture contact. But, albite is missing in other two Maw sit sit samples, MJ18 and MJ19. In MJ 18, relict chromite is surrounded by kosmochlor but the concentration of chromite is relatively smaller than MJ 17 (Fig. 3.15 c). In MJ19, there has little or no chromite left in the sample and the rock is mainly composed of kosmochlor and amphiboles (Fig. 3.15 d). Amphiboles which included in this unit are usually white with size ranging from 0.005 to 0.1 mm. Most of the amphiboles show prismatic, fibrous and small needle shape crystals. Usually, these amphiboles are subhedral grains.

| Table 1. Mineral association of the analysed rocks. |  |
|---|--|
|---|--|

| Sample no. | Rock Type                   | Mineral association              | Localities                     | Occurrence  |
|------------|-----------------------------|----------------------------------|--------------------------------|---|
| 017        | Garnet-mica<br>Schist       | Gt+Phg+Mus+Par+Qtz+<br>Ab+Ilm+Zr | Sanphe Chaung,<br>NW of Tawmaw | Adjacent to Serpentinized<br>Peridotite               |
| 019        | Garnet-mica<br>Schist       | Gt+Phg+Mus+Qtz+Ab                | Sanphe Chaung,<br>NW of Tawmaw | Adjacent to Serpentinized<br>Peridotite               |
| 031/05     | Epidote-schist              | Epi+Qtz+Ab+Rut                   | SE of Tawmaw                   | Adjacent to Serpentinized<br>Peridotite               |
| 034/05     | Glaucophane<br>Schist       | Gln+Qtz+Ab+Rib+Gt                | SE of Tawmaw                   | Adjacent to Serpentinized<br>Peridotite               |
| YK1        | Chlorite schist             | Chl+Chr                          | SE of Tawmaw                   | Adjacent to Serpentinized<br>Peridotite               |
| 020/05     | Amphibole felses            | Eck+ Rich                        | Tawmaw                         | Adjacent to Jadeitite                                 |
| 024/05     | Amphibole felses            | Eck+Rich+Jd                      | Tawmaw                         | Adjacent to Serpentinized<br>Peridotite and Jadeitite |
| 027/05     | Amphibole felses            | Jd+Eck                           | Tawmaw                         | Adjacent to Amphibole felses                          |
| JF9        | Amphibole felses            | Jd+Ko+Eck                        | Tawmaw                         | Adjacent to Amphibole felses                          |
| KT 34      | Amphibole felses            | Jd+Ko+Rich                       | Tawmaw                         | Adjacent to Amphibole felses                          |
| MJ11       | Jadeitite                   | Jd+Ves                           | Tawmaw                         | Jadeitite block                                       |
| MJ14       | Jadeitite                   | Jd+Om                            |                                | Jadeitite block                                       |
| MJ20       | Jadeitite                   | Jd+Om                            | Tawmaw                         | Jadeitite block                                       |
| 012/05     | Jadeitite                   | Jd                               | Tawmaw                         | Adjacent to Albitite                                  |
| MJ 21      | Jadeitite                   | Jd+Eck+Rich+Gln                  | Tawmaw                         | Jadeitite bolck                                       |
| 012/05     | Jadeitite with Amphibole    | Jd+Eck+Rich                      | Tawmaw                         | Adjacent to Amphibole felses                          |
| 008/05     | Albitite                    | Ab+Om                            | Tawmaw                         | Adjacent to Jadeitite                                 |
| 010/05     | Albitite                    | Ab                               | Tawmaw                         | Adjacent to Jadeitite                                 |
| KT 23      | Albite jadeite<br>rock      | Jd+Ab                            | Tawmaw                         | Adjacent to albitite                                  |
| 011/05     | Serpentinized<br>Peridotite | Olv+Liz+Mgt+Chr                  | Tawmaw                         | Adjacent to Jadeitite                                 |
| 028/05     | Serpentinized<br>Peridotite | Olv+Liz+Ilm+Chr                  | Tawmaw                         | Adjacent to Jadeitite                                 |
| 001a/05    | Serpentinized<br>Peridotite | Ant+Liz+Mgt+Chr                  | Tawmaw                         | Adjacent to Jadeitite                                 |
| 017/05     | Serpentinized<br>Dunite     | Olv+Liz+Ant+Chr                  | Tawmaw                         | Adjacent to Jadeitite                                 |
| MJ17       | Maw-sit-sit                 | Eck+Rich+Ko+Chr+Ab               | Tawmaw                         | Not specified contact                                 |
| MJ18       | Maw-sit-sit                 | Eck+Rich+Ko+Chr+Ab               | Tawmaw                         | Not specified contact                                 |

Abbreviations: Ab, albite; Ant, antigorite; Chl, chlorite; Chr, chromite; Eck, eckermannite; Epi, epidote; Gln, glaucophane; Gt, garnet; Ilm, ilmenite; Jd, jadeite; Ko, kosmochlor; Liz, lizardite; Mgt, magnetite; Mus, muscovite; Olv, olivine; Om, omphacite; Par, paragonite; Phg, phangite; Qtz, quartz; Rut, Rutile; Rich, richterite; Vs, vesuvianite; Zr, zircon

# CHAPTER

## IV

## **IV.** Petrochemistry

## 4.1. Ultramafic Rocks

Three representative samples of ultramafic rocks were analysed. Chemical analyses of ultramafic rocks from the Tawmaw area show that these rocks contain 34 to 37 % SiO<sub>2</sub>, 37 to 42 % MgO and 10-12.1 % FeO in wt. %. In these rocks, Cr and Ni are the most abundant trace elements range from 0.0032 to 0.12 % Cr and 0.0011-0.0015 % Ni. Generally, serpentinized dunite has more MgO (42 %) than the serpentinized peridotite. The REE patterns are generally similar to the oceanic peridotite composition.

## 4.2. Mafic Rocks

Five representative samples of these rocks are analysed for chemical analyses.

## 4.2.1. Glaucophaen Schist

In these rocks, SiO<sub>2</sub> is ranging from 53 to 60 %, Al<sub>2</sub>O<sub>3</sub> 15-18 %, Fe<sub>2</sub>O<sub>3</sub> 7 to 9 %, CaO 2 to 10 %, Na<sub>2</sub>O 1 to 7 % and MgO 2 to 3 %.

### 4.2.2. Epidote Schist

Major oxide analyses of epidote schist shows the composition of higher SiO2 content ranging from 66-74 %,  $Al_2O_3$  12 to 14 %, CaO 2 to 5 %,  $Na_2O$  3.5 % and  $Fe_2O_3$  3 to 6 %.

## 4.3. Metapelitic Rock

Two samples of metapelitic rocks are analysed for the chemical analyses.

## 4.3.1. Garnet-mica schist

Metapelitic rock of garnet-mica schist from Tawmaw area is mainly composed with SiO<sub>2</sub> 64-65 %, Al<sub>2</sub>O<sub>3</sub> 16 to 17 %, Fe<sub>2</sub>O<sub>3</sub> 5 to 6 %, MgO 1 to 2 %, K<sub>2</sub>O 1.8 to 2 % and CaO 1 to 1.4 % and Na<sub>2</sub>O 1.2 %.

## 4.4. Jadeitite and Related Rocks

## 4.4.1. Jadeitite

16 jadeitite samples were analysed for chemical analyses and two samples for albite-jadeite rocks and 1 samples for albitite were analysed.

Analysed jadeitite from the Tawmaw are indicate that these rocks are made up of SiO<sub>2</sub> 56 to 62 %, Al<sub>2</sub>O<sub>3</sub> 13 to 26 %, Na<sub>2</sub>O 11 to 14.8 %, Fe<sub>2</sub>O<sub>3</sub> 0.02 to 3 %, MgO 0.2 to 10.7 % and CaO 0.13 to 2.63 %.

## 4.4.2. Albitite-Jadeitite Rocks

This rock is made up of SiO<sub>2</sub> 50 to 57 %, Al<sub>2</sub>O<sub>3</sub> 21 to 23 %, Na<sub>2</sub>O 10 to 14 %, MgO 1 to 4 % and CaO 0.7 to 1.23 %.

## 4.4.3. Albitite

Albitite shows SiO<sub>2</sub> 66 %, Al<sub>2</sub>O<sub>3</sub> 18 %, Na<sub>2</sub>O 11 %, MgO 0.6 % and CaO 0.4 %.

### 4.4.4. Maw-sit-sit

Chemical analyses on three samples of Maw-sit-sit show that these rocks are made up of  $SiO_2$  43 to 63 %,  $Al_2O_3$  13 to 15 %,  $Na_2O$  3 to 11 %, MgO 5 to 19 % and  $Fe_2O_3$  2 to 6 %. The concentration of Cr is ranging from 0.0014 to 0.016 %.

Chemical analyses of studied rock samples are shown in Table 2. Chondrite-normalized REEs patterns for analysed rocks are also shown in (Fig. 4.1) indicating that positive Sm anomaly in epidote schist, glaucophane schist, albitite and jadeitite.

|                                | Jadeitite   |   |   |   |   |   |                     |  |  |  |
|--------------------------------|---|---|---|---|---|---|---------------------|--|--|--|
|                                | MJ 1  | MJ 3  | MJ 4  | MJ 5  | MJ 11   | MJ 12   | MJ 13               |  |  |  |
| SiO <sub>2</sub>               | 58.43   | 57.91   | 58.9  | 59.35   | 59.08   | 59.3  | 59.26               |  |  |  |
| Al <sub>2</sub> O <sub>3</sub> | 23.51   | 13.47   | 23.54   | 23.95   | 25.13   | 25.17   | 24.16               |  |  |  |
| MnO                            | 0.01  | 0.06  | 0.02  | 0.01  | 0.01  | 0.01  | 0.02                |  |  |  |
| MgO                            | 1.31  | 10.42   | 0.78  | 0.84  | 0.22  | 0.09  | 0.77                |  |  |  |
| CaO                            | 1.23  | 2.63  | 1.16  | 1.07  | 0.36  | 0.13  | 0.67                |  |  |  |
| Na <sub>2</sub> O              | 13.76   | 10.73   | 14.26   | 14.32   | 14.41   | 14.88   | 14.49               |  |  |  |
| K <sub>2</sub> O               | 0   | 0.18  | <lld< th=""><th><lld< th=""><th>0.01</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th>0.01</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                | 0.01  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| TiO                            | 0.04  | 0.01  | 0.02  | 0.01  | 0.01  | <lld< th=""><th>0.01</th></lld<>                | 0.01                |  |  |  |
| P.O.                           | <ud< th=""><th><u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><ud< th=""></ud<></th></u></th></u></th></u></th></u></th></u></th></ud<>     | <u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><ud< th=""></ud<></th></u></th></u></th></u></th></u></th></u>   | <u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><ud< th=""></ud<></th></u></th></u></th></u></th></u>   | <u d<="" th=""><th><u d<="" th=""><th><u d<="" th=""><th><ud< th=""></ud<></th></u></th></u></th></u>   | <u d<="" th=""><th><u d<="" th=""><th><ud< th=""></ud<></th></u></th></u>   | <u d<="" th=""><th><ud< th=""></ud<></th></u>   | <ud< th=""></ud<>   |  |  |  |
|                                | 1 20  | < <u>LLD</u>  | < <u>LED</u>  | < <u>LLD</u>  | < <u>LLD</u>  | < <u>LED</u>                                    | <u> </u>            |  |  |  |
|                                | 0.62  | 2.94  | 0.99  | 0.30  | 0.20  | 0.02  | 0.4                 |  |  |  |
| H <sub>2</sub> O               | 0.62  | 1.48  | 0.12  | 0.14  | 0.34  | 0.16  | 0.15                |  |  |  |
| CO <sub>2</sub>                | 0.06  | 0.12  | 0.06  | 0.1   | 0.09  | 0.16  | 0.16                |  |  |  |
| Trace                          | 0.05  | 0.24  | 0.03  | 0.02  | 0.03  | 0.02  | 0.03                |  |  |  |
| Total                          | 100.31  | 100.17  | 99.88   | 100.17  | 99.93   | 99.94   | 100.1               |  |  |  |
| Trace (ppm)                    |   |   |   |   |   |   |                     |  |  |  |
| Sc                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.475</th><th>0.65</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.475</th><th>0.65</th></lld<></th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.475</th><th>0.65</th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th><lld< th=""><th>0.475</th><th>0.65</th></lld<></th></lld<>                              | <lld< th=""><th>0.475</th><th>0.65</th></lld<>                              | 0.475   | 0.65                |  |  |  |
| V                              | 2.71  | 6.97  | 4.24  | 1.4   | 0.53  | 1.58  | 7.92                |  |  |  |
| Cr                             | 13.49   | 1156.51   | 36.2  | 5.37  | 3.71  | 11.14   | 39.18               |  |  |  |
| Co                             | 18.32   | 30.58   | 12.59   | 17.72   | 21.96   | 17.41   | 17.65               |  |  |  |
| Ni                             | 140.41  | 259.676   | <lld< th=""><th><lld< th=""><th>162.589</th><th><lld< th=""><th>11.64</th></lld<></th></lld<></th></lld<>                           | <lld< th=""><th>162.589</th><th><lld< th=""><th>11.64</th></lld<></th></lld<>                           | 162.589   | <lld< th=""><th>11.64</th></lld<>               | 11.64               |  |  |  |
| Cu                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>      | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>      | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></lld<></th></lld<></th></lld<>      | <lld< th=""><th><lld< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></lld<></th></lld<>      | <lld< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></lld<>      | <lld< th=""><th>&lt;<u>LLD</u></th></lld<>      | < <u>LLD</u>        |  |  |  |
| Zn                             | 6.63  | 14.2  | 21.58   | 4.57  | 22.35   | 13.29   | < <u>LLD</u>        |  |  |  |
| Ga                             | 16.76   | 7.96  | 15.5  | 12.4  | 12.45   | 14.42   | 14.17               |  |  |  |
| Ge                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Asi                            | 0.56  | 0.45  | 0.25  | <lld< th=""><th>0.02</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                | 0.02  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Se<br>D::                      | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                    | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                    | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th></th></lld<></th></lld<></th></lld<></th></lld<>                    | <lld< th=""><th><lld< th=""><th><lld< th=""><th></th></lld<></th></lld<></th></lld<>                    | <lld< th=""><th><lld< th=""><th></th></lld<></th></lld<>                    | <lld< th=""><th></th></lld<>                    |                     |  |  |  |
| Br<br>Dh                       | < <u>LLD</u>  | <lld<br>1.84</lld<br>   |   |   | <lld<br>0.10</lld<br>   | <lld<br>0.25</lld<br>                           |                     |  |  |  |
| KU<br>Sr1                      | 0.1   | 1.04  | <lld<br>50.52</lld<br>  | ~LLD<br>21.38   | 20.43   | 0.33<br>8.47                                    | <u> </u>            |  |  |  |
| V                              | 0.67  | 0.9   | 0.59  | 0.25  | 20.43   | 0.53  | 45.50               |  |  |  |
| I<br>Zr1                       | 38.29   | 12.42   | 16.64   | 22.95   | 8.89  | 15.21   | 11.18               |  |  |  |
| Nh                             | <ud< th=""><th>0.1</th><th><ud< th=""><th><ud< th=""><th><ud< th=""><th><ud< th=""><th><ud< th=""></ud<></th></ud<></th></ud<></th></ud<></th></ud<></th></ud<>                             | 0.1   | <ud< th=""><th><ud< th=""><th><ud< th=""><th><ud< th=""><th><ud< th=""></ud<></th></ud<></th></ud<></th></ud<></th></ud<>           | <ud< th=""><th><ud< th=""><th><ud< th=""><th><ud< th=""></ud<></th></ud<></th></ud<></th></ud<>         | <ud< th=""><th><ud< th=""><th><ud< th=""></ud<></th></ud<></th></ud<>       | <ud< th=""><th><ud< th=""></ud<></th></ud<>     | <ud< th=""></ud<>   |  |  |  |
| Mo                             | <lld< th=""><th><u.d< th=""><th>0.11</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></u.d<></th></lld<>                | <u.d< th=""><th>0.11</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></u.d<>                | 0.11  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Ασ                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Cd                             | 2.79  | 3.84  | 4.21  | 2.23  | 2.07  | 2.92  | 2.85                |  |  |  |
| Sn                             | 5.56  | 6.01  | 4.93  | 4.99  | 5.27  | 6.3   | 4.88                |  |  |  |
| Sb                             | 0.53  | 1.44  | 1.1   | 0.23  | 0.01  | 0.91  | 0.25                |  |  |  |
| Te                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Ι                              | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Cs                             | 2.36  | <lld< th=""><th>2.22</th><th>2.54</th><th>0.38</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | 2.22  | 2.54  | 0.38  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Ba                             | 134.31  | 505.3   | 37.16   | 5.73  | 30.18   | 22.06   | 5.5                 |  |  |  |
| La                             | <lld< th=""><th>5.5</th><th>1.5</th><th>2.36</th><th>4.11</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>   | 5.5   | 1.5   | 2.36  | 4.11  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Ce                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>7.56</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th><lld< th=""><th>7.56</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th>7.56</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th>7.56</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                | 7.56  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Pr                             | 2.01  | <lld< th=""><th><lld< th=""><th>2.087</th><th>3.25</th><th>3.2</th><th>0.96</th></lld<></th></lld<>   | <lld< th=""><th>2.087</th><th>3.25</th><th>3.2</th><th>0.96</th></lld<>   | 2.087   | 3.25  | 3.2   | 0.96                |  |  |  |
| Nd                             | 4.57  | 4.47  | 2.44  | 4.394   | 7.14  | 2.89  | 1.08                |  |  |  |
| Sm                             | 0.97  | 2.01  | 0.29  | 3.861   | 1.92  | 3.07  | 0.94                |  |  |  |
| Yb                             | 1.34  | 3.8   | <lld< th=""><th><lld< th=""><th>2.4</th><th>0</th><th>1.94</th></lld<></th></lld<>  | <lld< th=""><th>2.4</th><th>0</th><th>1.94</th></lld<>  | 2.4   | 0   | 1.94                |  |  |  |
| Hf                             | <lld< th=""><th>1.19</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                | 1.19  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Ta                             | 2.77  | 1.22  | 2.14  | 1.43  | 1.99  | 2.9   | 4.02                |  |  |  |
| W                              | 176.37  | 48.49   | 135.59  | 168.99  | 85.65   | 180.7   | 185.74              |  |  |  |
| TI                             | <lld< th=""><th><lld< th=""><th>0.24</th><th>0.39</th><th>0.24</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th>0.24</th><th>0.39</th><th>0.24</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | 0.24  | 0.39  | 0.24  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Pb1                            | 2.52  | 1.1   | 2.32  | 3.19  | 3.27  | 2   | 2.56                |  |  |  |
| Bi                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| Th                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |  |  |  |
| U                              | <lld< th=""><th>1.54</th><th><lld< th=""><th>0.06</th><th>1.76</th><th><lld< th=""><th>0.03</th></lld<></th></lld<></th></lld<>   | 1.54  | <lld< th=""><th>0.06</th><th>1.76</th><th><lld< th=""><th>0.03</th></lld<></th></lld<>  | 0.06  | 1.76  | <lld< th=""><th>0.03</th></lld<>                | 0.03                |  |  |  |
| Sum                            | 0.05  | 0.24  | 0.03  | 0.02  | 0.03  | 0.02  | 0.03                |  |  |  |

Table 2.1. Chemical composition of analysed rocks from the study area.

|                                | Jadeitite   |   |   |   |   |   |  |   |                                |  |
|--------------------------------|---|---|---|---|---|---|--|---|--------------------------------|--|
|                                | MJ 14   | MJ 16   | MJ 20   | MJ 21   | MJ 22   | MJ 27   | 013E/05  | 013/05  | 019/05                         |  |
| SiO <sub>2</sub>               | 58.67   | 62.41   | 58.92   | 59.58   | 60.04   | 57.95   | 56.95  | 57.11   | 56.15                          |  |
| Al <sub>2</sub> O <sub>3</sub> | 23.2  | 26.12   | 23.03   | 24.57   | 24.61   | 24.58   | 24.05  | 23.96   | 21.56                          |  |
| MnO                            | 0.01  | 0.01  | 0.01  | 0.01  | 0   | 0.01  | 0.01   | 0.01  | 0.01                           |  |
| MgO                            | 1.14  | 0.31  | 1.39  | 0.59  | 0.7   | 0.77  | 0.2  | 0.17  | 2.23                           |  |
| CaO                            | 1.5   | 0.46  | 1.98  | 0.76  | 0.93  | 1.08  | 0.17   | 0.16  | 1.73                           |  |
| Na <sub>2</sub> O              | 13.91   | 13.48   | 13.76   | 14.34   | 14.25   | 14.49   | 14.19  | 14.24   | 12.73                          |  |
| K <sub>2</sub> O               | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.19</th><th><lld< th=""><th>0</th><th>0</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.19</th><th><lld< th=""><th>0</th><th>0</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.19</th><th><lld< th=""><th>0</th><th>0</th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>0.19</th><th><lld< th=""><th>0</th><th>0</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th>0.19</th><th><lld< th=""><th>0</th><th>0</th></lld<></th></lld<>  | 0.19  | <lld< th=""><th>0</th><th>0</th></lld<>                                      | 0   | 0                              |  |
| TiO <sub>2</sub>               | 0.06  | <lld< th=""><th>0.01</th><th>0.02</th><th>0.01</th><th>0.01</th><th>0.02</th><th>0.01</th><th>0.02</th></lld<>  | 0.01  | 0.02  | 0.01  | 0.01  | 0.02   | 0.01  | 0.02                           |  |
| $P_2O_5$                       | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<></th></lld<>  | <lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<>  | 0.01   | 0.01  | 0.01                           |  |
| Fe <sub>2</sub> O <sub>3</sub> | 0.93  | 0.09  | 0.6   | 0.26  | 0.24  | 0.55  | 0.23   | 0.23  | 0.84                           |  |
| H <sub>2</sub> O               | 0.18  | 0.16  | 0.11  | 0.13  | 0.12  | 0.14  | 0.14   | 0.1   | 0.23                           |  |
| CO <sub>2</sub>                | 0.1   | 0.1   | 0.12  | 0.11  | 0.12  | 0.1   | 0.16   | 0.12  | 0.86                           |  |
| Trace                          | 0.07  | 0.03  | 0.04  | 0.03  | 0.04  | 0.03  | 0.08   | 0.08  | 0.31                           |  |
| Total                          | 99.75   | 103.16  | 99.96   | 100.4   | 101.05  | 99.88   | 96.19  | 96.2  | 96.7                           |  |
| Trace (ppm)                    |   |   |   |   |   |   |  |   |                                |  |
| Sc                             | 0.46  | <lld< th=""><th><lld< th=""><th>0.15</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>35.17</th><th>3.58</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th>0.15</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>35.17</th><th>3.58</th></lld<></th></lld<></th></lld<></th></lld<>   | 0.15  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>35.17</th><th>3.58</th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th><lld< th=""><th>35.17</th><th>3.58</th></lld<></th></lld<>                              | <lld< th=""><th>35.17</th><th>3.58</th></lld<>                               | 35.17   | 3.58                           |  |
| V                              | 3.97  | 3.04  | 16.74   | 1.17  | 4.67  | 3.06  | 2.41   | 2.74  | 8.26                           |  |
| Cr                             | 14.26   | 5.3   | 113.96  | 17.04   | 209.14  | 40.33   | 30.72  | 2.62  | 1.53                           |  |
| Co                             | 29.22   | 17.9  | 18.94   | 19.74   | 16.97   | 13.52   | 32.06  | 23.26   | 386.7                          |  |
| Ni                             | 21.48   | <lld< th=""><th>1.41</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.07</th><th>15.33</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>   | 1.41  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.07</th><th>15.33</th></lld<></th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.07</th><th>15.33</th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th><lld< th=""><th>0.07</th><th>15.33</th></lld<></th></lld<>                              | <lld< th=""><th>0.07</th><th>15.33</th></lld<>                               | 0.07  | 15.33                          |  |
| Cu                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>1.38</th><th>0.58</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>1.38</th><th>0.58</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>1.38</th><th>0.58</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>1.38</th><th>0.58</th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th><lld< th=""><th>1.38</th><th>0.58</th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th>1.38</th><th>0.58</th></lld<></th></lld<>                               | <lld< th=""><th>1.38</th><th>0.58</th></lld<>                                | 1.38  | 0.58                           |  |
| Zn                             | 6.11  | 0.79  | 3.14  | 10.16   | 0.57  | 4.75  | 6.7  | 5.51  | 4.97                           |  |
| Ga                             | 16.06   | 11.47   | 9.32  | 11.74   | 7.55  | 12.68   | 10.85  | 10.65   | 13.5                           |  |
| Ge                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.68</th><th>0.1</th><th>3.8</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.68</th><th>0.1</th><th>3.8</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.68</th><th>0.1</th><th>3.8</th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.68</th><th>0.1</th><th>3.8</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>0.68</th><th>0.1</th><th>3.8</th></lld<></th></lld<>  | <lld< th=""><th>0.68</th><th>0.1</th><th>3.8</th></lld<>  | 0.68   | 0.1   | 3.8                            |  |
| As1                            | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>2.54</th><th>3.05</th><th>12.02</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>2.54</th><th>3.05</th><th>12.02</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>2.54</th><th>3.05</th><th>12.02</th></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th><lld< th=""><th>2.54</th><th>3.05</th><th>12.02</th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th>2.54</th><th>3.05</th><th>12.02</th></lld<></th></lld<>   | <lld< th=""><th>2.54</th><th>3.05</th><th>12.02</th></lld<>   | 2.54   | 3.05  | 12.02                          |  |
| Se                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Br                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Rb<br>C-1                      | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.66</th><th><lld< th=""><th>18.48</th><th>14.03</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.66</th><th><lld< th=""><th>18.48</th><th>14.03</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.66</th><th><lld< th=""><th>18.48</th><th>14.03</th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>0.66</th><th><lld< th=""><th>18.48</th><th>14.03</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th>0.66</th><th><lld< th=""><th>18.48</th><th>14.03</th></lld<></th></lld<>  | 0.66  | <lld< th=""><th>18.48</th><th>14.03</th></lld<>                              | 18.48   | 14.03                          |  |
| Sr1<br>V                       | 39.78   | 0.42  | 34.02   | 106   | 0.55  | 38.04   | 5.0<br>0.47  | 5.99  | 54./9                          |  |
| 1<br>7r1                       | 51.0  | 11.43   | 11.07   | 11.00   | 0.55  | 3.15  | 16.45  | LLD   | 21.00                          |  |
| Nh                             | <11D  | <11.45  | <11.07  | <11.2<br><11.D  | <11D  | <11D  | <ud< th=""><th><ud< th=""><th>&lt;11.77</th></ud<></th></ud<>                | <ud< th=""><th>&lt;11.77</th></ud<>             | <11.77                         |  |
| Mo                             | 0.176   | <lld< th=""><th>0.1</th><th><lld< th=""><th>0.15</th><th><lld< th=""><th><lld< th=""><th>1.06</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>   | 0.1   | <lld< th=""><th>0.15</th><th><lld< th=""><th><lld< th=""><th>1.06</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                               | 0.15  | <lld< th=""><th><lld< th=""><th>1.06</th><th><lld< th=""></lld<></th></lld<></th></lld<>                | <lld< th=""><th>1.06</th><th><lld< th=""></lld<></th></lld<>                 | 1.06  | <lld< th=""></lld<>            |  |
| Ag                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Cd                             | 2.87  | 2.54  | 3.22  | 2.46  | 1.49  | 1.66  | <lld< th=""><th>0.74</th><th>0.11</th></lld<>                                | 0.74  | 0.11                           |  |
| Sn                             | 5.31  | 4.77  | 5.16  | 5.02  | 5   | 4.25  | 2.95   | 0.14  | <lld< th=""></lld<>            |  |
| Sb                             | 0.07  | <lld< th=""><th><lld< th=""><th>1.19</th><th><lld< th=""><th><lld< th=""><th>0.77</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th>1.19</th><th><lld< th=""><th><lld< th=""><th>0.77</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | 1.19  | <lld< th=""><th><lld< th=""><th>0.77</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th>0.77</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                | 0.77   | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Te                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>2.99</th><th>2.81</th><th>4.25</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>2.99</th><th>2.81</th><th>4.25</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>2.99</th><th>2.81</th><th>4.25</th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>2.99</th><th>2.81</th><th>4.25</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>2.99</th><th>2.81</th><th>4.25</th></lld<></th></lld<>  | <lld< th=""><th>2.99</th><th>2.81</th><th>4.25</th></lld<>  | 2.99   | 2.81  | 4.25                           |  |
| Ι                              | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>9.58</th><th>1.25</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>9.58</th><th>1.25</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>9.58</th><th>1.25</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th><lld< th=""><th>9.58</th><th>1.25</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th>9.58</th><th>1.25</th><th><lld< th=""></lld<></th></lld<></th></lld<>                               | <lld< th=""><th>9.58</th><th>1.25</th><th><lld< th=""></lld<></th></lld<>                               | 9.58   | 1.25  | <lld< th=""></lld<>            |  |
| Cs                             | 4.23  | 3.72  | 6.57  | 3.87  | 9.27  | 3.22  | 1.96   | 3.19  | <lld< th=""></lld<>            |  |
| Ba                             | 3.51  | 10.56   | 10.76   | 17.4  | 10.66   | 71.68   | 3.14   | 4.61  | 6.75                           |  |
| La                             | 1.7   | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>2.51</th><th>1.75</th><th>7.73</th><th>3.98</th></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th><lld< th=""><th>2.51</th><th>1.75</th><th>7.73</th><th>3.98</th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th>2.51</th><th>1.75</th><th>7.73</th><th>3.98</th></lld<></th></lld<>   | <lld< th=""><th>2.51</th><th>1.75</th><th>7.73</th><th>3.98</th></lld<>   | 2.51  | 1.75   | 7.73  | 3.98                           |  |
| Ce                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th>3.28</th><th><lld< th=""><th><lld< th=""><th>2.41</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th><lld< th=""><th>3.28</th><th><lld< th=""><th><lld< th=""><th>2.41</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | <lld< th=""><th>3.28</th><th><lld< th=""><th><lld< th=""><th>2.41</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                               | 3.28  | <lld< th=""><th><lld< th=""><th>2.41</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th>2.41</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                | 2.41   | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Pr                             | 0.54  | 2.04  | 1.3   | 3.99  | 2.51  | 2.35  | 3.83   | 5.9   | 6.32                           |  |
| Nd                             | 4.81  | 3.98  | 6.26  | 2.91  | 3.66  | 3.42  | 5.75   | 0.99  | 9.4                            |  |
| Sm                             | 6.25  | 1.41  | 0.98  | 2.09  | <lld< th=""><th>0.7</th><th>2.28</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                                | 0.7   | 2.28   | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Yb                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
|                                | 0.07  | 0.97  | <lld< th=""><th><lld<br>4 72</lld<br></th><th><lld< th=""><th><lld<br>1.60</lld<br></th><th>2.09</th><th>0.54</th><th><lld< th=""></lld<></th></lld<></th></lld<>                           | <lld<br>4 72</lld<br>   | <lld< th=""><th><lld<br>1.60</lld<br></th><th>2.09</th><th>0.54</th><th><lld< th=""></lld<></th></lld<>                             | <lld<br>1.60</lld<br>   | 2.09   | 0.54  | <lld< th=""></lld<>            |  |
| 1 a<br>\\\/                    | 4.08  | 2.40  | 2.33  | 4.72  | 3.0   | 1.09  | 0.38<br>707 16   | 622.77  | >LLD<br>2600.94                |  |
| TI                             | <[] D   | 0.41  | 200.20<br><11 D   | <11D  | <[]]  | <[] D   | <iid< th=""><th>&lt;[] D</th><th>2009.00<br/><lid< th=""></lid<></th></iid<> | <[] D   | 2009.00<br><lid< th=""></lid<> |  |
| Ph1                            | 1 48  | 2.17  | 2.21  | 2.12  | 1 76  | 23  |  |   | <lld< th=""></lld<>            |  |
| Ri                             | <lid< th=""><th><lid< th=""><th><lld< th=""><th><lid< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lid<></th></lld<></th></lid<></th></lid<> | <lid< th=""><th><lld< th=""><th><lid< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lid<></th></lld<></th></lid<> | <lld< th=""><th><lid< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lid<></th></lld<> | <lid< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lid<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Th                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| U                              | 0.03  | <lld< th=""><th>0.32</th><th>0.29</th><th><lld< th=""><th>0.87</th><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | 0.32  | 0.29  | <lld< th=""><th>0.87</th><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                | 0.87  | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>            |  |
| Sum                            | 0.07  | 0.03  | 0.04  | 0.03  | 0.04  | 0.03  | 0.08   | 0.08  | 0.31                           |  |

Table 2.1. (Contd.) Chemical composition of analysed rocks from the study area.

|                                |   | Maw-sit-sit   | •   | Albite  | Albitite  |                          |
|--------------------------------|---|---|---|---|---|--------------------------|
|                                | MJ 17   | MJ 18   | MJ 19   | 012/05  | JF1/05  | JF4/05                   |
| SiO <sub>2</sub>               | 59.63   | 62.92   | 42.69   | 50.19   | 56.79   | 66.01                    |
| Al <sub>2</sub> O <sub>3</sub> | 13.52   | 15.29   | 15.32   | 21.03   | 22.87   | 18.53                    |
| MnO                            | 0.06  | 0.03  | 0.05  | <lld< th=""><th>0.01</th><th>0</th></lld<>                                  | 0.01  | 0                        |
| MgO                            | 5.47  | 6.38  | 18.97   | 4.55  | 1.23  | 0.61                     |
| CaO                            | 0.39  | 0.89  | 0.29  | 1.26  | 0.67  | 0.43                     |
| Na <sub>2</sub> O              | 10.27   | 10.7  | 3.08  | 10.23   | 13.76   | 10.65                    |
| K <sub>2</sub> O               | 0.13  | 0.22  | 5.68  | 0.23  | <lld< th=""><th>0.28</th></lld<>                | 0.28                     |
| TiO <sub>2</sub>               | 0.16  | 0.13  | 0.21  | 0.05  | 0.02  | 0.01                     |
| P <sub>2</sub> O <sub>5</sub>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<></th></lld<>  | <lld< th=""><th>0.01</th><th>0.01</th><th>0.01</th></lld<>  | 0.01  | 0.01  | 0.01                     |
| Fe <sub>2</sub> O <sub>3</sub> | 2.91  | 1.91  | 5.85  | 0.77  | 0.68  | 0.13                     |
| H <sub>2</sub> O               | 1.38  | 0.86  | 2.57  | 0.3   | 0.73  | 0.14                     |
| CO <sub>2</sub>                | 0.33  | 0.1   | 0.86  | 2.27  | 0.6   | 0.25                     |
|                                | 2.39  | 0.19  | 2.12  | 4.16  | 0.04  | 0.12                     |
| Total                          | 96.65   | 99.61   | 97.68   | 95.04   | 97.41   | 97.17                    |
| Trace (ppm)                    |   |   |   |   |   |                          |
| Sc                             | 2.57  | 0.19  | 1.38  | 22.19   | 24.3  | 30.12                    |
| V                              | 27.41   | 8.74  | 40.79   | <lld< th=""><th>10.55</th><th>0.21</th></lld<>                              | 10.55   | 0.21                     |
| Cr                             | 23472.9   | 1376.52   | 16121.83  | 62.55   | 3.77  | 12.55                    |
| Со                             | 26.26   | 12.08   | 29.36   | 11.07   | 15.5  | 8.21                     |
| Ni                             | 235.58  | 177.308   | 83.79   | 23.86   | 6.94  | 5.28                     |
| Cu                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th>2.48</th><th>1.06</th><th>0.57</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>2.48</th><th>1.06</th><th>0.57</th></lld<></th></lld<>  | <lld< th=""><th>2.48</th><th>1.06</th><th>0.57</th></lld<>  | 2.48  | 1.06  | 0.57                     |
| Zn                             | 49.63   | 20.74   | 27.83   | 6.91  | 2.64  | 0.48                     |
| Ga                             | 17.4  | 22.55   | 11.38   | <lld< th=""><th>13.34</th><th>9.11</th></lld<>                              | 13.34   | 9.11                     |
| Ge                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.11</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.11</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th>0.11</th><th><lld< th=""></lld<></th></lld<></th></lld<>                | <lld< th=""><th>0.11</th><th><lld< th=""></lld<></th></lld<>                | 0.11  | <lld< th=""></lld<>      |
| Asl                            | <lld< th=""><th>1.2</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                 | 1.2   | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| Se                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| Br                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| KD<br>Sr1                      | 1.23  | 0.82  | 138.42  | 1.97  | 10.//   | 212.57                   |
| V                              | 0.43  | 1 18  | 1 22  | 0.23  |   | <112.57                  |
| Zr1                            | 4 01  | 33.16   | 2.78  | 96.6  | 41.09   | 1.6                      |
| Nb                             | 1.03  | <lld< th=""><th>4.25</th><th>1.38</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                               | 4.25  | 1.38  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| Мо                             | 0.06  | <lld< th=""><th><lld< th=""><th>0.54</th><th>1.18</th><th>1.03</th></lld<></th></lld<>  | <lld< th=""><th>0.54</th><th>1.18</th><th>1.03</th></lld<>  | 0.54  | 1.18  | 1.03                     |
| Ag                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.73</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.73</th></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.73</th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th>0.73</th></lld<></th></lld<>                | <lld< th=""><th>0.73</th></lld<>                | 0.73                     |
| Cd                             | 1.65  | 3   | 4.13  | 14.54   | 1.65  | 2.4                      |
| Sn                             | 5.16  | 6.63  | 9.32  | 18.45   | 1.45  | 1.11                     |
| Sb                             | <lld< th=""><th>2.1</th><th>2.95</th><th><lld< th=""><th>0.35</th><th>0.24</th></lld<></th></lld<>  | 2.1   | 2.95  | <lld< th=""><th>0.35</th><th>0.24</th></lld<>                               | 0.35  | 0.24                     |
| Te                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>5.49</th><th>2.7</th></lld<></th></lld<></th></lld<></th></lld<>                                | <lld< th=""><th><lld< th=""><th><lld< th=""><th>5.49</th><th>2.7</th></lld<></th></lld<></th></lld<>                                | <lld< th=""><th><lld< th=""><th>5.49</th><th>2.7</th></lld<></th></lld<>                                | <lld< th=""><th>5.49</th><th>2.7</th></lld<>                                | 5.49  | 2.7                      |
| I                              | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>1.93</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>1.93</th></lld<></th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th><lld< th=""><th>1.93</th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th>1.93</th></lld<></th></lld<>                | <lld< th=""><th>1.93</th></lld<>                | 1.93                     |
| Cs                             | 10.59   | 3.6   | 47.57   | 24.73   | 1.73  | <lld< th=""></lld<>      |
| Ba                             | 132.42  | 133.22  | 4705.77   | 40997.92  | 11.09   | 731.9                    |
| La                             | <lld< th=""><th><lld< th=""><th>10.11</th><th><lld< th=""><th>6.16</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th>10.11</th><th><lld< th=""><th>6.16</th><th><lld< th=""></lld<></th></lld<></th></lld<>                              | 10.11   | <lld< th=""><th>6.16</th><th><lld< th=""></lld<></th></lld<>                | 6.16  | <lld< th=""></lld<>      |
| Ce                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th>120.18</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>              | <lld< th=""><th><lld< th=""><th>120.18</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>              | <lld< th=""><th>120.18</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>              | 120.18  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| Pr<br>Nd                       | <lld< th=""><th>0.47</th><th><lld< th=""><th><lld< th=""><th>5.03</th><th>4.38</th></lld<></th></lld<></th></lld<>  | 0.47  | <lld< th=""><th><lld< th=""><th>5.03</th><th>4.38</th></lld<></th></lld<>                               | <lld< th=""><th>5.03</th><th>4.38</th></lld<>                               | 5.03  | 4.38                     |
| ING<br>Sm                      | 18.24   | 3.37  | /.11  |   | 2.84  | 3.3<br><ud< th=""></ud<> |
|                                | 0.08  | LLD<br>1.07   | <lld<br>0.70</lld<br>   |   |   |                          |
| 10<br>Hf                       | - 1.47<br><[ ] D  | 2 10  | 1 1 2   | >LLD<br>11.05   |   |                          |
| Тя                             | 1 11  | 3 36  | 2.5   | 0.55  | 0.69  | 0.73                     |
| W                              | 39.45   | 45.81   | 12.29   | 119.58  | 237.25  | 176.92                   |
| TI                             | 0.35  | <lld< th=""><th><ltd< th=""><th><ltd< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></ltd<></th></ltd<></th></lld<>      | <ltd< th=""><th><ltd< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></ltd<></th></ltd<>      | <ltd< th=""><th><lld< th=""><th>&lt;<u>LLD</u></th></lld<></th></ltd<>      | <lld< th=""><th>&lt;<u>LLD</u></th></lld<>      | < <u>LLD</u>             |
| Pb1                            | 4.09  | 2.75  | 2.81  | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| Bi                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| Th                             | <lld< th=""><th><lld< th=""><th>1.75</th><th>2.96</th><th><lld< th=""><th>0.07</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th>1.75</th><th>2.96</th><th><lld< th=""><th>0.07</th></lld<></th></lld<>  | 1.75  | 2.96  | <lld< th=""><th>0.07</th></lld<>                | 0.07                     |
| U                              | 0.81  | 0.11  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<>      |
| Sum                            | 2.39  | 0.19  | 2.12  | 4.16  | 0.04  | 0.12                     |

Table 2.1. (Contd.) Chemical compositon of analysed rocks from the study area.

|                                | Ultramafic rocks   |  | ks   | Act schist Garnet-mica schist  |  |  | Epidote schist  |   | Glaucophane schist  |   |                     |
|--------------------------------|--|--|--|--|--|--|---|---|---|---|---------------------|
|                                | 015/05   | 017/05   | 028/05   | #008   | #017   | #019   | 030/05  | 031/05  | 034/05  | 035/05  | 041/05              |
| SiO <sub>2</sub>               | 37.44  | 34.45  | 34.22  | 48.44  | 63.84  | 64.93  | 73.60   | 65.80   | 60.35   | 53.44   | 53.45               |
| Al2O3                          | 0.37   | 0.89   | 0.15   | 13.38  | 16.91  | 17.29  | 12.71   | 13.62   | 14.87   | 17.79   | 15.85               |
| MnO                            | 0.13   | 0.16   | 0.14   | 0.18   | 0.07   | 0.14   | 0.03  | 0.08  | 0.13  | 0.16  | 0.17                |
| MgO                            | 37.43  | 38.91  | 42.62  | 4.92   | 1.92   | 1.43   | 0.65  | 1.47  | 2.34  | 3.25  | 3.01                |
| CaO                            | 0.14   | 0.02   | 0.09   | 6.71   | 1.02   | 1.41   | 2.28  | 4.65  | 2.41  | 7.00  | 9.55                |
| Na <sub>2</sub> O              | <lld< th=""><th><lld< th=""><th><lld< th=""><th>3.92</th><th>1.24</th><th>1.19</th><th>3.39</th><th>3.50</th><th>7.29</th><th>4.70</th><th>1.85</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>3.92</th><th>1.24</th><th>1.19</th><th>3.39</th><th>3.50</th><th>7.29</th><th>4.70</th><th>1.85</th></lld<></th></lld<>  | <lld< th=""><th>3.92</th><th>1.24</th><th>1.19</th><th>3.39</th><th>3.50</th><th>7.29</th><th>4.70</th><th>1.85</th></lld<>  | 3.92   | 1.24   | 1.19   | 3.39  | 3.50  | 7.29  | 4.70  | 1.85                |
| K <sub>2</sub> O               | 0.00   | <lld< th=""><th><lld< th=""><th>0.33</th><th>1.88</th><th>2.00</th><th>0.47</th><th>0.02</th><th>0.21</th><th>0.03</th><th>0.07</th></lld<></th></lld<>  | <lld< th=""><th>0.33</th><th>1.88</th><th>2.00</th><th>0.47</th><th>0.02</th><th>0.21</th><th>0.03</th><th>0.07</th></lld<>  | 0.33   | 1.88   | 2.00   | 0.47  | 0.02  | 0.21  | 0.03  | 0.07                |
| TiO <sub>2</sub>               | 0.01   | 0.02   | 0.01   | 2.87   | 0.81   | 0.66   | 0.40  | 0.73  | 0.82  | 1.19  | 1.23                |
| P <sub>2</sub> O <sub>5</sub>  | 0.10   | 0.01   | 0.01   | 0.31   | 0.13   | 0.08   | 0.04  | 0.16  | 0.07  | 0.11  | 0.13                |
| Fe <sub>2</sub> O <sub>2</sub> | 12.02  | 12.08  | 10.03  | 14.99  | 6.44   | 5.38   | 2.61  | 5.63  | 7.85  | 7.42  | 9.23                |
| H <sub>2</sub> O               | 1.64   | 0.32   | 0.31   | 0.08   | 3.06   | 1.29   | 0.16  | 0.16  | 0.10  | 0.14  | 0.20                |
| CO <sub>2</sub>                | 10.85  | 9.15   | 11.15  | 2.41   | 2.70   | 3.37   | 1.78  | 2.06  | 1.49  | 2.50  | 2.93                |
| Trace                          | 0.46   | 1.31   | 0.59   | 0.12   | 0.14   | 0.12   | 0.05  | 0.05  | 0.07  | 0.08  | 0.07                |
| Total                          | 100.57   | 97.31  | 99.31  | 98.65  | 100.14   | 99.29  | 98.17   | 97.93   | 97.98   | 97.81   | 97.74               |
| Trace (ppm)                    |  |  |  |  |  |  |   |   |   |   |                     |
| Sc                             | 63.51  | 70.62  | 57.34  | 15.94  | 15.4   | 9.05   | <lld< th=""><th>4.54</th><th>5.32</th><th>12.61</th><th><lld< th=""></lld<></th></lld<>                               | 4.54  | 5.32  | 12.61   | <lld< th=""></lld<> |
| v                              | 17.8   | 60.53  | 13.54  | 343.51   | 149.11   | 114.82   | 22.29   | 54.44   | 135.4   | 130.98  | 186.19              |
| Cr                             | 3167.49  | 11771.6  | 4129.7   | 33.63  | 89.34  | 75.55  | 2.43  | 63.37   | 32.13   | 41.07   | 6.68                |
| Co                             | 133.58   | 126.89   | 117.59   | 38.7   | 15.68  | 19.05  | 6.78  | 15.63   | 24.03   | 16.97   | 18.88               |
| Ni                             | 1123.42  | 1335.66  | 1554.6   | 20.6   | 7.71   | 6.14   | 0.86  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>1.995</th></lld<></th></lld<></th></lld<>               | <lld< th=""><th><lld< th=""><th>1.995</th></lld<></th></lld<>               | <lld< th=""><th>1.995</th></lld<>               | 1.995               |
|                                | 9.99   | 10.78  | 7.15   | 4.92   | <lld< th=""><th><pre><lld 50.82<="" pre=""></lld></pre></th><th>1.59</th><th><lld< th=""><th><lld< th=""><th><lld<br>20.45</lld<br></th><th>11.4/8</th></lld<></th></lld<></th></lld<> | <pre><lld 50.82<="" pre=""></lld></pre>  | 1.59  | <lld< th=""><th><lld< th=""><th><lld<br>20.45</lld<br></th><th>11.4/8</th></lld<></th></lld<>           | <lld< th=""><th><lld<br>20.45</lld<br></th><th>11.4/8</th></lld<>           | <lld<br>20.45</lld<br>                          | 11.4/8              |
| Zn<br>Ca                       | 38.39  | 44.5   | 30.49  | 119.97   | /0.39  | 50.85  | 2.38  | 8.0   | <u> </u>  | 30.45   | 16.20               |
| Ga                             | 0.61   | 0.82   | 0.79   | 0.09   | 0.07   | 0.1  | 0.62  | 0.32  | 0.62  | 0.56  | 0.92                |
| As1                            | <lld< th=""><th>3.86</th><th>2.63</th><th>2.33</th><th>2.01</th><th><lld< th=""><th>2.08</th><th>3.22</th><th>4.7</th><th>3.32</th><th><lld< th=""></lld<></th></lld<></th></lld<>   | 3.86   | 2.63   | 2.33   | 2.01   | <lld< th=""><th>2.08</th><th>3.22</th><th>4.7</th><th>3.32</th><th><lld< th=""></lld<></th></lld<>   | 2.08  | 3.22  | 4.7   | 3.32  | <lld< th=""></lld<> |
| Se                             | 0.58   | 1.9  | 0.83   | 1.06   | 0.44   | <lld< th=""><th>0.18</th><th>0.47</th><th><lld< th=""><th><lld< th=""><th>0.022</th></lld<></th></lld<></th></lld<>                              | 0.18  | 0.47  | <lld< th=""><th><lld< th=""><th>0.022</th></lld<></th></lld<>               | <lld< th=""><th>0.022</th></lld<>               | 0.022               |
| Br                             | <lld< th=""><th>0.35</th><th><lld< th=""><th>0.03</th><th><lld< th=""><th><lld< th=""><th>0.15</th><th>1.38</th><th>0.14</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>   | 0.35   | <lld< th=""><th>0.03</th><th><lld< th=""><th><lld< th=""><th>0.15</th><th>1.38</th><th>0.14</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                              | 0.03   | <lld< th=""><th><lld< th=""><th>0.15</th><th>1.38</th><th>0.14</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th>0.15</th><th>1.38</th><th>0.14</th><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<>                               | 0.15  | 1.38  | 0.14  | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |
| Rb                             | 18.81  | 18.91  | 18.72  | 3.29   | 86.5   | 83.1   | 17.12   | <lld< th=""><th><lld< th=""><th>0.514</th><th>3.494</th></lld<></th></lld<>                             | <lld< th=""><th>0.514</th><th>3.494</th></lld<>                             | 0.514   | 3.494               |
| Sr1                            | 37.34  | 1.39   | 2.65   | 126.84   | 221.97   | 178.98   | 90.25   | 131.17  | 219.66  | 40.26   | 320.96              |
| Y                              | <lld< th=""><th><lld< th=""><th><lld< th=""><th>35.48</th><th>22.94</th><th>27.02</th><th>37.68</th><th>34.63</th><th>33.6</th><th>32.64</th><th>32.29</th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th>35.48</th><th>22.94</th><th>27.02</th><th>37.68</th><th>34.63</th><th>33.6</th><th>32.64</th><th>32.29</th></lld<></th></lld<>   | <lld< th=""><th>35.48</th><th>22.94</th><th>27.02</th><th>37.68</th><th>34.63</th><th>33.6</th><th>32.64</th><th>32.29</th></lld<>   | 35.48  | 22.94  | 27.02  | 37.68   | 34.63   | 33.6  | 32.64   | 32.29               |
| Zrl                            | <lld< th=""><th><lld< th=""><th><lld< th=""><th>217.64</th><th>7.46</th><th>129.08</th><th>16/.04</th><th>118.55</th><th>149.04</th><th>165.83</th><th>92.19</th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th>217.64</th><th>7.46</th><th>129.08</th><th>16/.04</th><th>118.55</th><th>149.04</th><th>165.83</th><th>92.19</th></lld<></th></lld<>   | <lld< th=""><th>217.64</th><th>7.46</th><th>129.08</th><th>16/.04</th><th>118.55</th><th>149.04</th><th>165.83</th><th>92.19</th></lld<>   | 217.64   | 7.46   | 129.08   | 16/.04  | 118.55  | 149.04  | 165.83  | 92.19               |
| Mo                             | 2.00   | 2.00   | 0.02   | 0.42   | 0.7  | 0.86   | 0.15  | 1.40  | 0.2   | 1.04<br><11 D                                   | 4.00                |
| Ag                             | 1.02   | 0.96   | 0.02   | 0.38   | <lld< th=""><th>0.33</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.453</th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                         | 0.33   | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>0.453</th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th>0.453</th></lld<></th></lld<></th></lld<>               | <lld< th=""><th><lld< th=""><th>0.453</th></lld<></th></lld<>               | <lld< th=""><th>0.453</th></lld<>               | 0.453               |
| Cd                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>1.2</th><th><lld< th=""><th>0.33</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""><th>1.2</th><th><lld< th=""><th>0.33</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th>1.2</th><th><lld< th=""><th>0.33</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th>1.2</th><th><lld< th=""><th>0.33</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | 1.2  | <lld< th=""><th>0.33</th><th><lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<> | 0.33  | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |
| Sn                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th>1.37</th><th>0.61</th><th>0.69</th><th>1.39</th><th>1.92</th><th>1.22</th><th>1.92</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th><lld< th=""><th>1.37</th><th>0.61</th><th>0.69</th><th>1.39</th><th>1.92</th><th>1.22</th><th>1.92</th><th><lld< th=""></lld<></th></lld<></th></lld<>   | <lld< th=""><th>1.37</th><th>0.61</th><th>0.69</th><th>1.39</th><th>1.92</th><th>1.22</th><th>1.92</th><th><lld< th=""></lld<></th></lld<>   | 1.37   | 0.61   | 0.69   | 1.39  | 1.92  | 1.22  | 1.92  | <lld< th=""></lld<> |
| Sb                             | 0.69   | 0.49   | 0.5  | 0.12   | <lld< th=""><th><lld< th=""><th>1.07</th><th><lld< th=""><th>0.93</th><th>0.95</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>   | <lld< th=""><th>1.07</th><th><lld< th=""><th>0.93</th><th>0.95</th><th><lld< th=""></lld<></th></lld<></th></lld<>                               | 1.07  | <lld< th=""><th>0.93</th><th>0.95</th><th><lld< th=""></lld<></th></lld<>                               | 0.93  | 0.95  | <lld< th=""></lld<> |
| Te                             | 1.62   | 3.63   | 2.95   | <lld< th=""><th><lld< th=""><th><lld< th=""><th>2.65</th><th><lld< th=""><th>1.15</th><th>21.59</th><th>0.1</th></lld<></th></lld<></th></lld<></th></lld<>                              | <lld< th=""><th><lld< th=""><th>2.65</th><th><lld< th=""><th>1.15</th><th>21.59</th><th>0.1</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th>2.65</th><th><lld< th=""><th>1.15</th><th>21.59</th><th>0.1</th></lld<></th></lld<>  | 2.65  | <lld< th=""><th>1.15</th><th>21.59</th><th>0.1</th></lld<>  | 1.15  | 21.59   | 0.1                 |
| I                              | 0.98   | 0.89   | <lld< th=""><th>6.98</th><th>0.64</th><th><lld< th=""><th><lld< th=""><th>4.18</th><th>7.73</th><th>88.58</th><th>0.51</th></lld<></th></lld<></th></lld<>   | 6.98   | 0.64   | <lld< th=""><th><lld< th=""><th>4.18</th><th>7.73</th><th>88.58</th><th>0.51</th></lld<></th></lld<>   | <lld< th=""><th>4.18</th><th>7.73</th><th>88.58</th><th>0.51</th></lld<>  | 4.18  | 7.73  | 88.58   | 0.51                |
| Cs                             | <lld< th=""><th>6.97</th><th><lld< th=""><th><lld< th=""><th>11.26</th><th>6.86</th><th><lld< th=""><th>0.42</th><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>                             | 6.97   | <lld< th=""><th><lld< th=""><th>11.26</th><th>6.86</th><th><lld< th=""><th>0.42</th><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<></th></lld<>              | <lld< th=""><th>11.26</th><th>6.86</th><th><lld< th=""><th>0.42</th><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>              | 11.26  | 6.86   | <lld< th=""><th>0.42</th><th><lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>  | 0.42  | <lld< th=""><th><lld< th=""><th><lld< th=""></lld<></th></lld<></th></lld<> | <lld< th=""><th><lld< th=""></lld<></th></lld<> | <lld< th=""></lld<> |
| Ва                             | 29.99  | <lld< th=""><th><lld< th=""><th>44.0/</th><th>255.78</th><th>280.53</th><th>39.15</th><th>12.91</th><th>10.0/</th><th>04.08</th><th>80.04</th></lld<></th></lld<>  | <lld< th=""><th>44.0/</th><th>255.78</th><th>280.53</th><th>39.15</th><th>12.91</th><th>10.0/</th><th>04.08</th><th>80.04</th></lld<>  | 44.0/  | 255.78   | 280.53   | 39.15   | 12.91   | 10.0/   | 04.08   | 80.04               |
|                                | 1.4<br><[.].D  | 1.4/<br><[.].D   | 4.83   | 24.42  | 53.42  | 40.09  | 16.22   | 13.08   | ~LLD<br>6.87  | 3.13<br><[.].D                                  | LLD<br>13.96        |
| Pr                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th><lld< th=""><th>7.83</th><th>6.89</th><th>5.36</th><th>1.66</th><th>2.86</th><th>1.42</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>7.83</th><th>6.89</th><th>5.36</th><th>1.66</th><th>2.86</th><th>1.42</th><th><lld< th=""></lld<></th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>7.83</th><th>6.89</th><th>5.36</th><th>1.66</th><th>2.86</th><th>1.42</th><th><lld< th=""></lld<></th></lld<></th></lld<>  | <lld< th=""><th>7.83</th><th>6.89</th><th>5.36</th><th>1.66</th><th>2.86</th><th>1.42</th><th><lld< th=""></lld<></th></lld<>  | 7.83   | 6.89   | 5.36  | 1.66  | 2.86  | 1.42  | <lld< th=""></lld<> |
| Nd                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th>23.04</th><th>30.11</th><th>29.27</th><th>18.03</th><th>12.94</th><th>18.91</th><th>11.36</th><th>16.15</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>23.04</th><th>30.11</th><th>29.27</th><th>18.03</th><th>12.94</th><th>18.91</th><th>11.36</th><th>16.15</th></lld<></th></lld<>  | <lld< th=""><th>23.04</th><th>30.11</th><th>29.27</th><th>18.03</th><th>12.94</th><th>18.91</th><th>11.36</th><th>16.15</th></lld<>  | 23.04  | 30.11  | 29.27  | 18.03   | 12.94   | 18.91   | 11.36   | 16.15               |
| Sm                             | <lld< th=""><th>5.53</th><th><lld< th=""><th>4.47</th><th>5.65</th><th>7.21</th><th>6.93</th><th>5.98</th><th>2.43</th><th>3.88</th><th><lld< th=""></lld<></th></lld<></th></lld<>  | 5.53   | <lld< th=""><th>4.47</th><th>5.65</th><th>7.21</th><th>6.93</th><th>5.98</th><th>2.43</th><th>3.88</th><th><lld< th=""></lld<></th></lld<>   | 4.47   | 5.65   | 7.21   | 6.93  | 5.98  | 2.43  | 3.88  | <lld< th=""></lld<> |
| Yb                             | <lld< th=""><th><lld< th=""><th><lld< th=""><th>2.48</th><th>2.76</th><th>3.42</th><th>3.59</th><th>4.38</th><th>1.88</th><th>0.35</th><th>5.02</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>2.48</th><th>2.76</th><th>3.42</th><th>3.59</th><th>4.38</th><th>1.88</th><th>0.35</th><th>5.02</th></lld<></th></lld<>  | <lld< th=""><th>2.48</th><th>2.76</th><th>3.42</th><th>3.59</th><th>4.38</th><th>1.88</th><th>0.35</th><th>5.02</th></lld<>  | 2.48   | 2.76   | 3.42   | 3.59  | 4.38  | 1.88  | 0.35  | 5.02                |
| Hf                             | 2.18   | 1.1  | <lld< th=""><th>4.77</th><th>2.84</th><th>1.48</th><th>2.72</th><th>2.73</th><th><lld< th=""><th>1.97</th><th>4.9</th></lld<></th></lld<>  | 4.77   | 2.84   | 1.48   | 2.72  | 2.73  | <lld< th=""><th>1.97</th><th>4.9</th></lld<>                                | 1.97  | 4.9                 |
| Ta                             | 1.54   | <lld< th=""><th>1.51</th><th><lld< th=""><th>2.88</th><th>2.4</th><th>0.44</th><th>1.87</th><th>1.32</th><th><lld< th=""><th>0.41</th></lld<></th></lld<></th></lld<>  | 1.51   | <lld< th=""><th>2.88</th><th>2.4</th><th>0.44</th><th>1.87</th><th>1.32</th><th><lld< th=""><th>0.41</th></lld<></th></lld<>   | 2.88   | 2.4  | 0.44  | 1.87  | 1.32  | <lld< th=""><th>0.41</th></lld<>                | 0.41                |
| W                              | 26.49  | 46.6   | 55.31  | 71.97  | 100.89   | 96.59  | 116.1   | 96.01   | 67.71   | 49.71   | 150.69              |
| II<br>Dk1                      | <lld< th=""><th>1.48</th><th><lld< th=""><th>0.9</th><th>0.03</th><th>0.35</th><th>0.49</th><th>0.14</th><th>0.45</th><th><lld< th=""><th></th></lld<></th></lld<></th></lld<>   | 1.48   | <lld< th=""><th>0.9</th><th>0.03</th><th>0.35</th><th>0.49</th><th>0.14</th><th>0.45</th><th><lld< th=""><th></th></lld<></th></lld<>  | 0.9  | 0.03   | 0.35   | 0.49  | 0.14  | 0.45  | <lld< th=""><th></th></lld<>                    |                     |
| rui<br>Ri                      | LLD  | 3 56   | LLD<br>1 45  | ~LLD<br>2.54   | 19.18  | 1 25   |   | LLD<br>1 37   | 1.92  | >LLD<br>2 37                                    | \LLD<br>0.72        |
| Th                             | 0.32   | 1.83   | 0.22   | < <u>LLD</u>   | 5.96   | 7.56   | 1.37  | <lld< th=""><th><lld< th=""><th><lld< th=""><th>1.37</th></lld<></th></lld<></th></lld<>                | <lld< th=""><th><lld< th=""><th>1.37</th></lld<></th></lld<>                | <lld< th=""><th>1.37</th></lld<>                | 1.37                |
| U                              | 0.21   | <lld< th=""><th><lld< th=""><th><lld< th=""><th>2.1</th><th>2.64</th><th>0.83</th><th>0.53</th><th>0.35</th><th>0.2</th><th>0.2</th></lld<></th></lld<></th></lld<>  | <lld< th=""><th><lld< th=""><th>2.1</th><th>2.64</th><th>0.83</th><th>0.53</th><th>0.35</th><th>0.2</th><th>0.2</th></lld<></th></lld<>  | <lld< th=""><th>2.1</th><th>2.64</th><th>0.83</th><th>0.53</th><th>0.35</th><th>0.2</th><th>0.2</th></lld<>  | 2.1  | 2.64   | 0.83  | 0.53  | 0.35  | 0.2   | 0.2                 |
| Sum                            | 0.46   | 1.33   | 0.59   | 0.12   | 0.14   | 0.12   | 0.06  | 0.05  | 0.08  | 0.07  | 0.07                |
| ~                              |  |  |  |  |  |  |   |   | 2.00  | ,   |                     |

Table 2.1. (Contd.) Chemical compositon of analysed rocks from the study area.

|     | Ultramafic Rocks |         | Ep Schist | GI Schist | Albitite | Jadeitite |
|-----|------------------|---------|-----------|-----------|----------|-----------|
| ppb | 017/05           | 028/05  | 030/05    | 041/05    | JF4/05   | 019/05    |
| Sc  | 5.4156           | 2.5684  | 16.6834   | 43.1107   | 0.1607   | 0.2714    |
| Y   | 0.0598           | 0.0237  | 49.5456   | 40.2874   | 0.0983   | 0.3186    |
| La  | 0.0167           | 0.0633  | 10.8575   | 8.1236    | 0.0879   | 0.1845    |
| Ce  | 0.0481           | 0.1545  | 21.5603   | 19.2046   | 0.1166   | 0.352     |
| Pr  | 0.0036           | 0.01    | 3.9595    | 3.3539    | 0.0097   | 0.0367    |
| Nd  | 0.007            | 0.0314  | 19.2865   | 16.3095   | 0.0576   | 0.1248    |
| Sm  | 0.001            | 0.0051  | 5.5925    | 5.2243    | 0.0121   | 0.0322    |
| Eu  | -0.001           | -0.001  | 1.513     | 1.8534    | -0.001   | -0.001    |
| Gd  | -0.007           | -0.007  | 6.7514    | 6.022     | 0.017    | 0.0281    |
| Tb  | -0.001           | -0.001  | 1.1498    | 1.0387    | -0.001   | -0.001    |
| Dy  | -0.006           | -0.06   | 8.1541    | 7.1823    | 0.0138   | 0.0365    |
| Но  | -0.002           | -0.002  | 1.6989    | 1.4441    | -0.002   | -0.002    |
| Er  | -0.004           | -0.004  | 4.8126    | 4.5046    | 0.0049   | 0.0285    |
| Tm  | -0.001           | -0.001  | 0.6599    | 0.6286    | -0.001   | -0.001    |
| Yb  | -0.004           | -0.004  | 4.0082    | 4.1711    | 0.0159   | 0.0337    |
| Lu  | -0.001           | -0.001  | 0.5456    | 0.6174    | -0.001   | -0.001    |
| Та  | 0.6317           | 1.8952  | 2.4144    | 12.1551   | 1.8108   | 2.095     |
| Th  | -0.0642          | -0.0432 | 2.4253    | 1.165     | -0.0828  | 0.02      |
| U   | 0.0031           | 0.0096  | 0.3754    | 0.1807    | 0.0042   | 0.0178    |

Table 2.2.Analysed REE elements of the studied rocks by ICPMS.



Fig. 4.1: Chondrite-normalized REE patterns for studied rocks. Normalizing values after Sun & McDonough (1989).
# V. Mineral Chemistry

## 5.1. Olivine

The Mg/(Mg+Fe) value of olivine in dunite is higher than that of peridotite. Analysed data on the relic olivine in the dunite shows that it has higher in forsterite content ranging from 90 to 98.25 mol % (Table 3). In peridotite, the concentration of forsterite is ranging from 81.32 to 93.30 mol %.

|                                | #02105 | #02105 | #02105 | #02105 | #02105 | #02805 | #02805 | JFA    | JFA    | JFA    | JFA    | JFA    |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| wt. %                          |        |        |        |        |        |        |        | 05H    | 05H    | 05B    | 05B    | 05C    |
|                                | #27    | #32    | #33    | #38    | #65    | #93    | #99    | #56    | #59    | #29    | #30    | #33    |
| SiO <sub>2</sub>               | 41.00  | 41.25  | 41.05  | 40.90  | 40.41  | 40.55  | 40.36  | 40.56  | 40.62  | 40.82  | 40.46  | 40.93  |
| TiO <sub>2</sub>               | 0.01   | 0.00   | 0.01   | 0.00   | 0.01   | 0.00   | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   |
| Al <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| Cr <sub>2</sub> O <sub>3</sub> | 0.01   | 0.00   | 0.00   | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.01   | 0.01   |
| FeO                            | 4.84   | 5.86   | 6.58   | 6.17   | 8.19   | 7.52   | 6.99   | 11.77  | 11.35  | 10.78  | 11.85  | 11.46  |
| Fe <sub>2</sub> O <sub>3</sub> | 2.18   | 1.42   | 1.55   | 1.94   | 2.09   | 3.04   | 3.38   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| MgO                            | 52.68  | 52.27  | 51.59  | 51.71  | 49.92  | 50.71  | 50.87  | 45.94  | 46.17  | 46.42  | 45.88  | 45.93  |
| NiO                            | 0.04   | 0.05   | 0.18   | 0.16   | 0.21   | 0.24   | 0.21   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| CaO                            | 0.00   | 0.00   | 0.03   | 0.00   | 0.00   | 0.01   | 0.00   | 0.03   | 0.02   | 0.03   | 0.03   | 0.02   |
| Total                          | 100.76 | 100.85 | 100.98 | 100.88 | 100.83 | 102.07 | 101.81 | 98.31  | 98.16  | 98.05  | 98.25  | 98.35  |
|                                |        |        |        |        |        |        |        |        |        |        |        |        |
| Fe <sup>2</sup>                | 0.0968 | 0.1174 | 0.1321 | 0.1239 | 0.1662 | 0.1509 | 0.1404 | 0.2480 | 0.2391 | 0.2270 | 0.2498 | 0.2414 |
| Mn                             | 0.0054 | 0.0040 | 0.0027 | 0.0037 | 0.0043 | 0.0035 | 0.0033 | 0.0031 | 0.0036 | 0.0034 | 0.0050 | 0.0022 |
| Mg                             | 1.8772 | 1.8648 | 1.8470 | 1.8518 | 1.8063 | 1.8131 | 1.8216 | 1.7258 | 1.7336 | 1.7416 | 1.7241 | 1.7246 |
| Ni                             | 0.0008 | 0.0010 | 0.0035 | 0.0030 | 0.0041 | 0.0046 | 0.0041 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| sum6                           | 1.9803 | 1.9873 | 1.9853 | 1.9825 | 1.9808 | 1.9722 | 1.9695 | 1.9769 | 1.9763 | 1.9720 | 1.9790 | 1.9682 |
| Si                             | 0.9802 | 0.9873 | 0.9858 | 0.9825 | 0.9807 | 0.9726 | 0.9695 | 1.0221 | 1.0232 | 1.0272 | 1.0199 | 1.0309 |
| Ti                             | 0.0001 | 0.0000 | 0.0001 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Al                             | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Cr                             | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0002 |
| Fe <sup>3</sup>                | 0.0393 | 0.0255 | 0.0281 | 0.0351 | 0.0382 | 0.0549 | 0.0611 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ca                             | 0.0000 | 0.0000 | 0.0006 | 0.0000 | 0.0000 | 0.0004 | 0.0000 | 0.0008 | 0.0005 | 0.0008 | 0.0009 | 0.0006 |
| sum4                           | 1.0197 | 1.0127 | 1.0147 | 1.0175 | 1.0192 | 1.0278 | 1.0305 | 1.0231 | 1.0237 | 1.0280 | 1.0210 | 1.0318 |

Table 3. Representative analyses of olivine from serpentinized peridotite-dunite unit.

# 5.2. Chromite

In the dunite, chromite contains 39.79-43.94 wt. %Cr<sub>2</sub>O. The Cr/(Cr+Al) ratio is 0.64-0.99 (017/05) (Table 3). In KT34 of amphibole felses unit, chromite contains 42.04 to 43.45 wt. % Cr<sub>2</sub>O<sub>3</sub>. The Cr/(Cr+Al) ratio is 0.990-0.995.

|                                | 017    | 7/05   |        | KT39 & 057/05 | 5      |
|--------------------------------|--------|--------|--------|---------------|--------|
| WL. %                          | #7     | #8     | #4     | #24           | #28    |
| SiO <sub>2</sub>               | 0.02   | 0.00   | 0      | 0             | 0      |
| TiO <sub>2</sub>               | 0.18   | 0.25   | 0.69   | 0.51          | 0.69   |
| Al <sub>2</sub> O <sub>3</sub> | 16.33  | 0.39   | 0.13   | 0.27          | 0.10   |
| Cr <sub>2</sub> O <sub>3</sub> | 43.94  | 39.79  | 42.93  | 43.45         | 42.04  |
| FeO                            | 23.90  | 25.73  | 27.68  | 27.67         | 27.81  |
| Fe <sub>2</sub> O <sub>3</sub> | 7.65   | 27.73  | 24.33  | 23.39         | 25.06  |
| MnO                            | 0.66   | 1.12   | 0.91   | 0.87          | 0.99   |
| MgO                            | 6.43   | 2.88   | 2.10   | 1.92          | 1.90   |
| NiO                            | 0.05   | 0.03   | 0.23   | 0.22          | 0.27   |
| ZnO                            | 0.00   | 0.00   | 0.00   | 0.00          | 0.00   |
| CaO                            | 0.00   | 0.00   | 0.00   | 0.00          | 0.00   |
| Total                          | 99.16  | 97.90  | 99.00  | 98.30         | 98.86  |
|                                |        |        |        |               |        |
| Fe <sup>2</sup>                | 0.6657 | 0.8094 | 0.8664 | 0.8723        | 0.8733 |
| Mn                             | 0.0188 | 0.0356 | 0.0288 | 0.0277        | 0.0314 |
| Mg                             | 0.3191 | 0.1614 | 0.1174 | 0.1079        | 0.1066 |
| Ni                             | 0.0014 | 0.0008 | 0.0068 | 0.0067        | 0.0083 |
| Zn                             | 0.0000 | 0.0000 | 0.0000 | 0.0000        | 0.0000 |
| sum4                           | 1.0050 | 1.0072 | 1.0193 | 1.0146        | 1.0196 |
| Si                             | 0.0006 | 0.0000 | 0.0000 | 0.0000        | 0.0000 |
| Ti                             | 0.0044 | 0.0072 | 0.0193 | 0.0146        | 0.0196 |
| Al                             | 0.6410 | 0.0171 | 0.0058 | 0.0121        | 0.0043 |
| Cr                             | 1.1571 | 1.1834 | 1.2703 | 1.2953        | 1.2482 |
| Fe <sup>3</sup>                | 0.1919 | 0.7851 | 0.6852 | 0.6635        | 0.7083 |
| sum6                           | 1.9950 | 1.9928 | 1.9807 | 1.9854        | 1.9804 |

Table 4. Representative analyses of chromite in serpentinized peridotite-dunite and amphibole felses.

### 5.3. Pyroxenes

### 5.3.1. Jadeite

By using the CNMMNIMA nomenclature of pyroxene, the following pyroxene can be idenfied in the present work: Jadeite, kosmochlor and omphacite. Generally, pure jadeite is normally white and contains about 97 % of Jd component. Green jadeite contains  $Cr_2O_3$  up to 7.8 %. This rock composed of >90 % (volume) jadeititic pyroxene with minor secondary minerals. Generally, most of the jadeititc rocks contain < 20% pyroxene and alteration minerals such as albite and amphiboles especially in albite-jadeite rocks. Jadeitites show different microscopic textures such as microcrystalline, mosaic, granular and interlocking textures. Coarse-grained (0.5-10 mm) jadeitite shows sub-hedral to anhedral grains intergrowth with each other forming interlocking texture. Accessory minerals are generally amphiboles. Tiny zircon and fluid inclusions are observed. Mosaic texture is also common in coarse-grained jadeitite. Generally, jadeite crystals show rhythmic zoning. The size of the

zoning bands is ranging from 5-100  $\mu$ m. Quartz was not found in jadeitite of the present analyses although lawsonite in jadeitite from Nansibon (Goffé *et al.* 2000) had been reported, haven't identified in present studies. Chromite grains near the jadeitite and amphibolite are rimmed by the kosmochlor and the composition and colour decrease from the core of the chromite to the rim. The formation of kosmochlor is clearly related with chromite and which is formed from the chromite.

The composition of analysed jadeite in the jadeitite from the study area is shown in the (Fig. 5.1). The composition of jadeite is range from 89 to 100% in jadeitite. In the sample (012/05), the composition of jadeite range from 91.61 to 100 % Jd (Fig. 5.1)(Table 5), which is the contact of jadeitite with the amphibole felses, and contain some inclusions of amphiboles such as richterite and eckermanite from the surrounding amphibole felses.

At the same locality, where jadeitite which in contact with the amphibole felses, the composition of jadeite vary from pure jadeite to omphacite 54.1 to 100 % Jd (012/05a)(Fig. 5.2)(Table 6). The compositions of the amphibole felses (JF9, KT34) from the analysed samples indicate eckermannite and richterite (Fig. 5.3). In sample (KT23), jadeite is associated with albite where the contact of these two unit occur. In this sample composition of jadeite ranging from 96.81 to 100 % Jd (Fig. 5.1)(Table 5). In (019/05), composition of jadeite range from 86.38 to 100 % Jd (Fig. 5.1)(Table 5). In the zoning of jadeite crystal, there has a negative correlation of Na (Total) and Si p.f.u. and also positive correlation of Na (Total) and Al (Total) (013/05)(Fig. 5.4 a-c). The compositional map of jadeite grains in jadeitite is show in (Fig. 5.5).

| . 0/                           | KT23   | KT23   | AgSein | #1305  | #1305  | #01905 | #02405 | #02705 | #02705 | #01205a | #01205 |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|--------|
| wt. %                          | #107   | #108   | #23    | #71    | #21    | #31    | #62    | #150   | #140   | #72     | #145   |
| SiO <sub>2</sub>               | 59.61  | 59.94  | 58.53  | 58.31  | 59.06  | 57.86  | 59.79  | 59.90  | 59.98  | 59.76   | 59.98  |
| $P_2O_5$                       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00    | 0.00   |
| TiO <sub>2</sub>               | 0.08   | 0.00   | 0.15   | 0.04   | 0.00   | 0.03   | 0.01   | 0.00   | 0.00   | 0.00    | 0.00   |
| Al <sub>2</sub> O <sub>3</sub> | 22.55  | 25.39  | 21.62  | 23.48  | 24.79  | 23.08  | 25.00  | 25.13  | 24.29  | 25.59   | 25.33  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.01   | 0.00   | 0.02   | 0.00    | 0.01   |
| Fe <sub>2</sub> O <sub>3</sub> | 1.35   | 0.02   | 1.54   | 1.01   | 0.40   | 1.02   | 0.50   | 0.00   | 0.00   | 0.19    | 0.28   |
| FeO                            | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.05   | 0.73   | 0.00    | 0.00   |
| MnO                            | 0.00   | 0.01   | 0.00   | 0.00   | 0.01   | 0.02   | 0.02   | 0.02   | 0.00   | 0.00    | 0.00   |
| MgO                            | 1.58   | 0.32   | 2.00   | 1.03   | 0.14   | 1.36   | 0.42   | 0.08   | 0.46   | 0.02    | 0.19   |
| NiO                            | 0.00   | 0.04   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.05    | 0.00   |
| CaO                            | 1.22   | 0.28   | 2.71   | 0.77   | 0.24   | 1.94   | 0.35   | 0.07   | 0.63   | 0.06    | 0.29   |
| Na <sub>2</sub> O              | 15.03  | 15.75  | 14.38  | 14.57  | 15.36  | 14.57  | 15.66  | 15.38  | 14.95  | 15.55   | 15.61  |
| K <sub>2</sub> O               | 0.01   | 0.00   | 0.01   | 0.05   | 0.01   | 0.01   | 0.01   | 0.01   | 0.02   | 0.00    | 0.03   |
| Total                          | 101.43 | 101.75 | 100.95 | 99.25  | 100.01 | 99.90  | 101.77 | 100.64 | 101.08 | 101.23  | 101.71 |
|                                |        |        |        |        |        |        |        |        |        |         |        |
| Si                             | 1.9856 | 1.9776 | 1.9663 | 1.9859 | 1.9880 | 1.9571 | 1.9759 | 2.0035 | 2.0059 | 1.9862  | 1.9837 |
| Р                              | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000  | 0.0000 |
| Al_T                           | 0.0144 | 0.0224 | 0.0337 | 0.0141 | 0.0120 | 0.0429 | 0.0241 | 0.0000 | 0.0000 | 0.0138  | 0.0163 |
| sum4                           | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0035 | 2.0059 | 2.0000  | 2.0000 |
| Al_O                           | 0.8708 | 0.9649 | 0.8222 | 0.9284 | 0.9713 | 0.8773 | 0.9496 | 0.9904 | 0.9576 | 0.9885  | 0.9710 |
| Ti                             | 0.0020 | 0.0000 | 0.0037 | 0.0009 | 0.0000 | 0.0008 | 0.0002 | 0.0000 | 0.0000 | 0.0000  | 0.0000 |
| Cr                             | 0.0000 | 0.0001 | 0.0003 | 0.0001 | 0.0001 | 0.0000 | 0.0003 | 0.0000 | 0.0004 | 0.0000  | 0.0002 |
| Fe <sup>3</sup>                | 0.0339 | 0.0005 | 0.0390 | 0.0259 | 0.0101 | 0.0260 | 0.0124 | 0.0000 | 0.0001 | 0.0048  | 0.0069 |
| Fe <sup>2</sup>                | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0015 | 0.0205 | 0.0000  | 0.0000 |
| Mn                             | 0.0000 | 0.0003 | 0.0000 | 0.0000 | 0.0004 | 0.0006 | 0.0007 | 0.0004 | 0.0000 | 0.0000  | 0.0000 |
| Mg                             | 0.0784 | 0.0155 | 0.1001 | 0.0525 | 0.0069 | 0.0686 | 0.0208 | 0.0041 | 0.0227 | 0.0011  | 0.0093 |
| Ni                             | 0.0000 | 0.0009 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0014  | 0.0000 |
| Ca                             | 0.0436 | 0.0098 | 0.0974 | 0.0280 | 0.0085 | 0.0704 | 0.0124 | 0.0024 | 0.0226 | 0.0022  | 0.0101 |
| Na                             | 0.9708 | 1.0077 | 0.9369 | 0.9619 | 1.0024 | 0.9559 | 1.0031 | 0.9972 | 0.9691 | 1.0021  | 1.0012 |
| K                              | 0.0005 | 0.0002 | 0.0004 | 0.0022 | 0.0004 | 0.0005 | 0.0005 | 0.0004 | 0.0010 | 0.0000  | 0.0012 |
| sum6                           | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 1.9965 | 1.9941 | 2.0000  | 2.0000 |
| Na_start                       | 0.9708 | 1.0077 | 0.9369 | 0.9619 | 1.0024 | 0.9559 | 1.0031 | 0.9939 | 0.9675 | 1.0021  | 1.0012 |
| components                     |        |        |        |        |        |        |        |        |        |         |        |
| Diopside                       | 0.0308 | 0.0000 | 0.0670 | 0.0126 | 0.0000 | 0.0271 | 0.0000 | 0.0012 | 0.0114 | 0.0000  | 0.0000 |
| Hedenbergite                   | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0004 | 0.0102 | 0.0000  | 0.0000 |
| Jadeite                        | 0.9354 | 1.0072 | 0.8943 | 0.9373 | 0.9927 | 0.9295 | 0.9907 | 0.9975 | 0.9695 | 0.9973  | 0.9953 |
| Opx                            | 0.0000 | 0.0000 | 0.0000 | 0.0078 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0073 | 0.0000  | 0.0000 |
| Tschermakite                   | 0.0123 | 0.0224 | 0.0301 | 0.0132 | 0.0000 | 0.0421 | 0.0240 | 0.0000 | 0.0000 | 0.0138  | 0.0163 |
| Rest                           | 0.0364 | 0.0021 | 0.0434 | 0.0291 | 0.0109 | 0.0279 | 0.0140 | 0.0008 | 0.0015 | 0.0062  | 0.0083 |

Table 5. Representative analyses of jadeite from Jadeitite.

| wt 0/                          | MJ11A1 | KT28_C | MJ2-G  | MJ4_E  | MJ12_E | MJ1-B  | MJ1-G  | MJ22_E | MJ21   | MJ11_D | MJ16A  |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| wt. 70                         | #12    | #50    | #66    | #33    | #21    | #71    | #120   | #61    | #10    | #32    | #3     |
| SiO <sub>2</sub>               | 59.02  | 59.06  | 59.04  | 59.06  | 58.99  | 59.21  | 59.07  | 58.96  | 58.80  | 58.86  | 59.34  |
| $P_2O_5$                       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| TiO <sub>2</sub>               | 0.00   | 0.07   | 0.01   | 0.00   | 0.00   | 0.03   | 0.00   | 0.00   | 0.02   | 0.01   | 0.00   |
| Al <sub>2</sub> O <sub>3</sub> | 25.66  | 23.83  | 24.53  | 25.32  | 24.93  | 25.25  | 24.74  | 25.05  | 24.58  | 25.01  | 25.21  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.01   | 0.00   | 0.01   | 0.00   | 0.02   | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   |
| Fe <sub>2</sub> O <sub>3</sub> | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.01   | 0.01   |
| FeO                            | 0.02   | 0.91   | 0.28   | 0.02   | 0.07   | 0.18   | 0.26   | 0.11   | 0.18   | 0.05   | 0.05   |
| MnO                            | 0.00   | 0.00   | 0.00   | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.03   | 0.00   | 0.02   |
| MgO                            | 0.00   | 0.49   | 0.43   | 0.00   | 0.26   | 0.09   | 0.25   | 0.07   | 0.36   | 0.18   | 0.09   |
| NiO                            | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| CaO                            | 0.07   | 0.79   | 0.64   | 0.05   | 0.39   | 0.23   | 0.44   | 0.15   | 0.66   | 0.36   | 0.17   |
| Na <sub>2</sub> O              | 15.20  | 14.63  | 14.81  | 15.21  | 14.98  | 15.14  | 14.95  | 15.09  | 14.79  | 15.00  | 15.20  |
| K <sub>2</sub> O               | 0.00   | 0.02   | 0.02   | 0.01   | 0.00   | 0.00   | 0.01   | 0.03   | 0.01   | 0.00   | 0.01   |
| Total                          | 99.98  | 99.80  | 99.77  | 99.67  | 99.66  | 100.14 | 99.74  | 99.46  | 99.44  | 99.48  | 100.09 |
|                                |        |        |        |        |        |        |        |        |        |        |        |
| Si                             | 1.9866 | 2.0034 | 1.9967 | 1.9941 | 1.9941 | 1.9921 | 1.9972 | 1.9962 | 1.9948 | 1.9930 | 1.9961 |
| Р                              | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Al T                           | 0.0134 | 0.0000 | 0.0033 | 0.0059 | 0.0059 | 0.0079 | 0.0028 | 0.0038 | 0.0052 | 0.0070 | 0.0039 |
| sum4                           | 2.0000 | 2.0034 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 |
| Al O                           | 1.0048 | 0.9526 | 0.9744 | 1.0017 | 0.9875 | 0.9935 | 0.9831 | 0.9959 | 0.9776 | 0.9911 | 0.9956 |
| Ti                             | 0.0000 | 0.0017 | 0.0004 | 0.0000 | 0.0000 | 0.0009 | 0.0000 | 0.0000 | 0.0005 | 0.0002 | 0.0000 |
| V                              | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Cr                             | 0.0002 | 0.0000 | 0.0002 | 0.0000 | 0.0006 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Fe <sup>3</sup>                | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 | 0.0001 | 0.0002 | 0.0002 |
| Fe <sup>2</sup>                | 0.0006 | 0.0258 | 0.0080 | 0.0007 | 0.0021 | 0.0049 | 0.0074 | 0.0032 | 0.0051 | 0.0015 | 0.0013 |
| Mn                             | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0003 | 0.0000 | 0.0000 | 0.0000 | 0.0009 | 0.0000 | 0.0005 |
| Mg                             | 0.0000 | 0.0247 | 0.0217 | 0.0000 | 0.0133 | 0.0047 | 0.0126 | 0.0034 | 0.0183 | 0.0093 | 0.0045 |
| Ni                             | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Са                             | 0.0024 | 0.0288 | 0.0233 | 0.0018 | 0.0140 | 0.0082 | 0.0160 | 0.0055 | 0.0240 | 0.0131 | 0.0059 |
| Na                             | 0.9918 | 0.9621 | 0.9714 | 0.9955 | 0.9820 | 0.9875 | 0.9801 | 0.9907 | 0.9731 | 0.9846 | 0.9914 |
| К                              | 0.0000 | 0.0008 | 0.0007 | 0.0003 | 0.0002 | 0.0000 | 0.0005 | 0.0014 | 0.0004 | 0.0000 | 0.0004 |
| sum6                           | 2.0000 | 1.9966 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 |
| Na start                       | 0.9489 | 0.9447 | 0.9507 | 0.9709 | 0.9405 | 0.9608 | 0.9457 | 0.9612 | 0.9376 | 0.9416 | 0.9647 |
| components                     |        |        |        |        |        |        |        |        |        |        |        |
| Diopside                       | 0.0000 | 0.0145 | 0.0144 | 0.0000 | 0.0066 | 0.0006 | 0.0080 | 0.0001 | 0.0141 | 0.0053 | 0.0008 |
| Hedenbergite                   | 0.0000 | 0.0152 | 0.0053 | 0.0000 | 0.0010 | 0.0006 | 0.0047 | 0.0001 | 0.0039 | 0.0009 | 0.0002 |
| Jadeite                        | 0.9914 | 0.9612 | 0.9715 | 0.9959 | 0.9815 | 0.9865 | 0.9804 | 0.9921 | 0.9729 | 0.9842 | 0.9917 |
| Opx                            | 0.0058 | 0.0083 | 0.0047 | 0.0024 | 0.0038 | 0.0042 | 0.0034 | 0.0025 | 0.0025 | 0.0023 | 0.0022 |
| Tschermakite                   | 0.0134 | 0.0000 | 0.0029 | 0.0059 | 0.0059 | 0.0070 | 0.0028 | 0.0038 | 0.0047 | 0.0069 | 0.0039 |
| Rest                           | 0.0004 | 0.0026 | 0.0012 | 0.0003 | 0.0012 | 0.0011 | 0.0007 | 0.0014 | 0.0019 | 0.0004 | 0.0011 |

Table 5. (Contd.) Representative analyses of jadeite from Jadeitite.

| wt 0/                          | #01205 | #01205 | #01005 | #01005 | #00805 | #00805 | #00805 | #00805 |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| wt. 70                         | #4     | #34    | #56    | #129   | #139   | #143   | #145   | #146   |
| BaO                            | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| SiO <sub>2</sub>               | 57.94  | 58.45  | 55.32  | 55.25  | 56.74  | 56.18  | 56.81  | 56.46  |
| $P_2O_5$                       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| TiO <sub>2</sub>               | 0.04   | 0.04   | 0.78   | 2.00   | 0.03   | 0.13   | 0.19   | 0.06   |
| Al <sub>2</sub> O <sub>3</sub> | 14.24  | 14.10  | 2.59   | 3.65   | 12.67  | 10.41  | 11.31  | 11.47  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.01   | 0.01   | 0.13   | 0.19   | 0.04   | 0.03   | 0.01   | 0.02   |
| Fe <sub>2</sub> O <sub>3</sub> | 1.17   | 0.09   | 5.84   | 6.73   | 4.08   | 4.24   | 5.40   | 3.44   |
| FeO                            | 0.00   | 0.89   | 1.06   | 1.17   | 0.55   | 2.31   | 0.00   | 2.04   |
| MnO                            | 0.02   | 0.03   | 0.10   | 0.07   | 0.09   | 0.13   | 0.08   | 0.13   |
| MgO                            | 7.86   | 7.77   | 12.81  | 10.77  | 7.01   | 7.30   | 7.46   | 6.99   |
| NiO                            | 0.02   | 0.02   | 0.00   | 0.00   | 0.00   | 0.00   | 0.03   | 0.02   |
| CaO                            | 10.96  | 10.55  | 18.00  | 14.78  | 12.24  | 13.51  | 11.92  | 12.94  |
| Na <sub>2</sub> O              | 9.22   | 8.98   | 4.26   | 6.14   | 8.41   | 7.44   | 8.51   | 7.83   |
| K <sub>2</sub> O               | 0.02   | 0.00   | 0.01   | 0.00   | 0.02   | 0.01   | 0.02   | 0.00   |
| Total                          | 101.50 | 100.93 | 100.90 | 100.76 | 101.88 | 101.70 | 101.75 | 101.41 |
|                                |        |        |        |        |        |        |        |        |
| Si                             | 1.9805 | 2.0111 | 1.9919 | 1.9890 | 1.9696 | 1.9780 | 1.9783 | 1.9821 |
| Р                              | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Al_T                           | 0.0195 | 0.0000 | 0.0081 | 0.0110 | 0.0304 | 0.0220 | 0.0217 | 0.0179 |
| sum4                           | 2.0000 | 2.0111 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 |
| Al_O                           | 0.5541 | 0.5718 | 0.1017 | 0.1440 | 0.4881 | 0.4102 | 0.4425 | 0.4567 |
| Ti                             | 0.0009 | 0.0010 | 0.0212 | 0.0541 | 0.0007 | 0.0035 | 0.0049 | 0.0016 |
| Cr                             | 0.0004 | 0.0002 | 0.0037 | 0.0055 | 0.0012 | 0.0007 | 0.0003 | 0.0005 |
| Fe3                            | 0.0302 | 0.0024 | 0.1583 | 0.1822 | 0.1065 | 0.1124 | 0.1416 | 0.0908 |
| Fe2                            | 0.0000 | 0.0257 | 0.0318 | 0.0352 | 0.0161 | 0.0680 | 0.0000 | 0.0600 |
| Mn                             | 0.0007 | 0.0008 | 0.0031 | 0.0022 | 0.0027 | 0.0039 | 0.0024 | 0.0040 |
| Mg                             | 0.4005 | 0.3987 | 0.6874 | 0.5779 | 0.3626 | 0.3831 | 0.3872 | 0.3657 |
| Ni                             | 0.0005 | 0.0005 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0008 | 0.0006 |
| Ca                             | 0.4014 | 0.3890 | 0.6946 | 0.5699 | 0.4553 | 0.5098 | 0.4448 | 0.4868 |
| Na                             | 0.6107 | 0.5987 | 0.2977 | 0.4288 | 0.5660 | 0.5081 | 0.5747 | 0.5332 |
| K                              | 0.0007 | 0.0000 | 0.0004 | 0.0002 | 0.0008 | 0.0003 | 0.0009 | 0.0001 |
| sum6                           | 2.0000 | 1.9889 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 |
| Na start                       | 0.6107 | 0.5987 | 0.2977 | 0.4288 | 0.5660 | 0.5081 | 0.5747 | 0.5332 |
| components                     |        |        |        |        |        |        |        |        |
| Diopside                       | 0.3809 | 0.3652 | 0.6731 | 0.5756 | 0.4043 | 0.4138 | 0.4238 | 0.4002 |
| Hedenbergite                   | 0.0000 | 0.0236 | 0.0312 | 0.0351 | 0.0179 | 0.0734 | 0.0000 | 0.0656 |
| Jadeite                        | 0.5800 | 0.5952 | 0.1149 | 0.1871 | 0.4585 | 0.3917 | 0.4288 | 0.4404 |
| Opx                            | 0.0000 | 0.0123 | 0.0073 | 0.0011 | 0.0000 | 0.0182 | 0.0000 | 0.0000 |
| Tschermakite                   | 0.0186 | 0.0000 | 0.0000 | 0.0000 | 0.0297 | 0.0185 | 0.0168 | 0.0163 |
| Rest                           | 0.0333 | 0.0049 | 0.1868 | 0.2442 | 0.1118 | 0.1208 | 0.1509 | 0.0976 |

Table 6. Representative analyses of omphacite in jadeitite and albitite.



Fig. 5.1: Ternary plot of pyroxene from the study area. a. Pyroxene from the jadeitite 012/05, KT23 01305, MJ1, Mj11 and MJ12.



Fig. 5.2: a. Ternary plot of pyroxene from the amphibole felses (Aung Sein), b. jadeitite (012/05) and c. albitite 010/05.



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amphibole felses); c. Na-Ca amphibole in amphibole felses and d. Ca amphiboles in jadeitite.





Fig.5.5: Colour distribution maps of jadeite grains in jadeitite. Scale indicate count per seconds. (MJ 5 and MJ22).

### 5.3.1.1. Jadeite components in Myanmar Jadeitites

Microprobe analyses of Myanmar jadeitite yield the following range of end member composition.

MJ 1: Jd 0.995 Diop0.001 Hed0.001 to Jd0.8514 Diop1.248 Hed 0.0147 Opx0.0035 Tsch 0.0042 MJ 2 : Jd 0.9966 Hed 0.0026 to Jd 0.8947 Diop 0.0817 Hed 0.0132 Opx 0.0055 Tsch 0.0004 MJ 4: Jd 0.9959 Opx0.0024 Tsch 0.0059 to Jd 0.8403 Diop 0.0007 Hed 0.0215 Opx 0.0163 Tsch 0.0005 MJ 5: Jd<sub>0.996</sub> Opx 0.003 Tsch0.003 to Jd<sub>0.089</sub> Diop0.085 Hed<sub>0.013</sub> Opx0.009 Tsch0.002 MJ 8: Jd 0.9406 Diop0.0272 Hed0.0072 Opx0.0119 Tsch 0.0106 to Jd 0.8855 Diop 0.0453 Hed 0.0371 Opx 0.0292 MJ 11: Jd<sub>0.996</sub> Opx<sub>0.001</sub> Tsch<sub>0.005</sub> to Jd<sub>0.946</sub>Diop<sub>0.018</sub> Hed<sub>0.01</sub>Opx<sub>0.013</sub> Tsch<sub>0.012</sub> MJ 12: Jd<sub>0.9979</sub>Opx<sub>0.0011</sub>Tsch<sub>0.0017</sub> to Jd <sub>0.9815</sub> Diop <sub>0.0066</sub> Hed <sub>0.0010</sub> Opx <sub>0.0038</sub> Tsch <sub>0.0059</sub> MJ 13: Jd<sub>0.978</sub> Diop<sub>0.03</sub> Hed<sub>0.001</sub>Opx<sub>0.004</sub>Tsch<sub>0.008</sub> to Jd<sub>0.95</sub> Diop<sub>0.034</sub> Hed<sub>0.008</sub> Opx<sub>0.079</sub> Tsch<sub>0.00</sub> MJ 14: Jd 0.9915 Opx 0.0038 Tsch 0.0063 to Jd 0.8815 Diop 0.0840 Hed 0.0200 Opx 0.0079 MJ 16: Jd<sub>0.995</sub> Opx<sub>0.021</sub> Tsch<sub>0.037</sub> to Jd<sub>0.97</sub> Diop<sub>0.0132</sub> Hed<sub>0.004</sub> Opx<sub>0.007</sub> Tsch<sub>0.006</sub> MJ 20: Jd 0.9956 Hed0.0001 Opx 0.0011 Tsch 0.0025 to Jd 0.4401 Diop 0.4884 Hed 0.0540 Opx 0.0013 MJ 21: Jd<sub>0.979</sub> Diop 0.008 Hed<sub>0.005</sub> Opx 0.007 Tsch<sub>0.002</sub> to Jd 0.922 Diop 0.046 Hed<sub>0.017</sub> Opx 0.013 MJ 22: Jd<sub>0.995</sub> Opx<sub>0.004</sub> Tsch<sub>0.007</sub> to Jd<sub>0.8316</sub> Diop<sub>0.101</sub> Hed<sub>0.025</sub> Opx<sub>0.029</sub> Tsch<sub>0.012</sub> MJ 27: Jd<sub>0.98</sub>Opx<sub>0.0085</sub>Tsch<sub>0.0132</sub> to Jd <sub>0.906</sub> Diop<sub>0.037</sub> Hed <sub>0.028</sub> Tsch<sub>0.028</sub> KT 20: Jd 0.9949 Opx 0.002 Tsch 0.0052 to Jd 0.9386 Diop 0.0453 Hed 0.0038 Opx 0.0073 Tsch 0.0046 YK 22: Jd 0.9797Diop0.0038Hed 0.0033Opx0.0078 Tsch 0.0043 to Jd 0.9405 Diop 0.032 Hed 0.016 Opx 0.0107 KT 18: Jd 0.9967 to Jd 0.9814 Diop 0.0082 Hed 0.0014 Opx 0.0038 Tsch 0.0036

### 5.3.2. Omphacite

It occurs as minor mineral in jadeitite and also in albitite and albite-jadeite rocks. In (MJ 20), the composition of omphacite is represent as  $Jd_{0.44}Diop_{0.488}4Hed_{0.054}$  Opx<sub>0.013</sub> (Table 6). Omphacite in (012/05) show the variation from  $Jd_{0.54}$  Dio<sub>0.20</sub>Opx<sub>0.0004</sub>Tsch<sub>0.003</sub> to Jd<sub>0.63</sub> Dio<sub>0.38</sub> Opx<sub>0.19</sub>Tsch<sub>0.02</sub>. Omphacite is also found in the albitite (010/05) where the Mg content is a little bit higher than the other omphacite. In this rock, omphacite show the composition from Jd<sub>0.08</sub> Dio<sub>0.57</sub>Hed<sub>0.00</sub>Opx<sub>0.001</sub>Tsch<sub>0.002</sub> to Jd<sub>0.282</sub> Dio<sub>0.688</sub>Hed<sub>0.052</sub>Opx<sub>0.007</sub>Tsch<sub>0.008</sub> (Table 6).

#### 5.3.3. Kosmochlor

Other pyroxene, kosmochlor, is present in jadeitite and also in albite-jadeite rocks together with amphiboles. In the present study, kosmochlor is usually found as an aggregate. Kosmochlor is found in the jadeitite which in contact with amphibole felses (KT43 and JF9). The composition of kosmochlor in the study area is shown in the Ko-Aeg-Jd ternary diagram

(Fig. 5.6 a)(Table 7). In the analysed results, the chromium rich pyroxene ranging from 12.53 to 24.92 % of  $Cr_2O_3$  representing the 35.2 to 71.5 % of kosmochlor in (KT 34)(Fig: 5.6 b) and 12.48 to 29.65 % of  $Cr_2O_3$  representing the 36.13 to 77.37 % of kosmochlor in (JF9) (Fig: 5.6 a)(Table 7). Kosmochlor is formed by the expense of chromite grains and mostly it occurs around the chromite grains.

| wt %                           | JF9_A    | JF9_A    | JF9_A    | KT34     | KT34     | KT34     | KT34     | JF9     | JF9     | JF9     | JF9     |
|--------------------------------|----------|----------|----------|----------|----------|----------|----------|---------|---------|---------|---------|
| wt. 70                         | #5       | #7       | #8       | #29      | #33      | #37      | #40      | #17     | #18     | #19     | #20     |
| SiO <sub>2</sub>               | 54.3000  | 54.0100  | 54.2900  | 54.7300  | 53.3700  | 53.9300  | 53.4000  | 50.6600 | 51.7300 | 51.3600 | 51.8000 |
| TiO <sub>2</sub>               | 0.0800   | 0.0200   | 0.0300   | 0.0600   | 0.0600   | 0.0700   | 0.0100   | 0.0500  | 0.0300  | 0.0700  | 0.0900  |
| Al <sub>2</sub> O <sub>3</sub> | 5.1400   | 2.1700   | 2.4800   | 6.5400   | 6.2500   | 7.4000   | 4.0200   | 2.6800  | 3.0300  | 3.0500  | 3.4400  |
| Cr <sub>2</sub> O <sub>3</sub> | 14.4300  | 26.1500  | 24.7400  | 17.2300  | 18.5900  | 12.5200  | 24.9200  | 26.6400 | 25.7100 | 24.8900 | 25.4400 |
| Fe <sub>2</sub> O <sub>3</sub> | 4.8000   | 2.3800   | 2.9800   | 4.5700   | 4.4200   | 5.9700   | 2.8000   | 2.2900  | 2.4000  | 2.6300  | 2.6100  |
| FeO                            | 0.0000   | 0.0000   | 0.0000   | 0.0800   | 0.0000   | 0.0000   | 0.0000   | 0.0000  | 0.0000  | 0.0000  | 0.0000  |
| MnO                            | 0.0600   | 0.0900   | 0.0600   | 0.1200   | 0.0400   | 0.0900   | 0.0700   | 0.0800  | 0.0700  | 0.0900  | 0.0600  |
| MgO                            | 4.7500   | 1.6500   | 2.0800   | 2.6900   | 2.3400   | 3.7600   | 0.8700   | 0.9600  | 0.9000  | 1.3300  | 0.8800  |
| NiO                            | 0.0000   | 0.0000   | 0.0000   | 0.0500   | 0.0300   | 0.0400   | 0.0100   | 0.0000  | 0.0000  | 0.0300  | 0.0000  |
| CaO                            | 6.7900   | 2.3900   | 2.9000   | 3.6300   | 3.4600   | 5.4000   | 1.3600   | 1.2700  | 1.2800  | 1.8200  | 1.2900  |
| Na <sub>2</sub> O              | 10.3700  | 12.7300  | 12.4200  | 12.0300  | 12.5300  | 11.4900  | 13.4500  | 13.3400 | 13.6300 | 12.8300 | 13.3800 |
| K <sub>2</sub> O               | 0.0100   | 0.0100   | 0.0000   | 0.0100   | 0.0000   | 0.0000   | 0.0000   | 0.0100  | 0.0100  | 0.0100  | 0.0100  |
| Total                          | 100.7200 | 101.6100 | 101.9700 | 101.7400 | 101.1000 | 100.6800 | 100.9100 | 97.9800 | 98.8000 | 98.1000 | 99.0100 |
|                                |          |          |          |          |          |          |          |         |         |         |         |
| Si                             | 1.9800   | 1.9800   | 1.9900   | 1.9724   | 1.9342   | 1.9456   | 1.9624   | 1.9228  | 1.9397  | 1.9458  | 1.9417  |
| Al T                           | 0.0200   | 0.0200   | 0.0100   | 0.0276   | 0.0658   | 0.0544   | 0.0376   | 0.0772  | 0.0603  | 0.0542  | 0.0583  |
| sum4                           | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000  | 2.0000  | 2.0000  | 2.0000  |
| Al O                           | 0.2000   | 0.0800   | 0.0900   | 0.2501   | 0.2013   | 0.2604   | 0.1363   | 0.0427  | 0.0736  | 0.0820  | 0.0937  |
| Ti                             | 0.0000   | 0.0000   | 0.0000   | 0.0016   | 0.0015   | 0.0019   | 0.0004   | 0.0015  | 0.0009  | 0.0021  | 0.0024  |
| Cr                             | 0.4100   | 0.7600   | 0.7200   | 0.4910   | 0.5328   | 0.3570   | 0.7241   | 0.7994  | 0.7620  | 0.7457  | 0.7541  |
| Fe <sup>3</sup>                | 0.1300   | 0.0700   | 0.0800   | 0.1240   | 0.1205   | 0.1620   | 0.0774   | 0.0654  | 0.0678  | 0.0750  | 0.0737  |
| Fe <sup>2</sup>                | 0.0000   | 0.0000   | 0.0000   | 0.0024   | 0.0000   | 0.0000   | 0.0000   | 0.0000  | 0.0000  | 0.0000  | 0.0000  |
| Mn                             | 0.0000   | 0.0000   | 0.0000   | 0.0036   | 0.0012   | 0.0027   | 0.0023   | 0.0025  | 0.0022  | 0.0027  | 0.0020  |
| Mg                             | 0.2600   | 0.0900   | 0.1100   | 0.1447   | 0.1264   | 0.2023   | 0.0475   | 0.0545  | 0.0504  | 0.0753  | 0.0494  |
| Ni                             | 0.0000   | 0.0000   | 0.0000   | 0.0015   | 0.0009   | 0.0013   | 0.0002   | 0.0000  | 0.0000  | 0.0010  | 0.0000  |
| Са                             | 0.2600   | 0.0900   | 0.1100   | 0.1403   | 0.1345   | 0.2089   | 0.0534   | 0.0515  | 0.0514  | 0.0737  | 0.0518  |
| Na                             | 0.7300   | 0.9100   | 0.8800   | 0.8405   | 0.8808   | 0.8035   | 0.9582   | 0.9818  | 0.9912  | 0.9422  | 0.9724  |
| K                              | 0.0000   | 0.0000   | 0.0000   | 0.0003   | 0.0000   | 0.0001   | 0.0001   | 0.0007  | 0.0005  | 0.0004  | 0.0005  |
| sum6                           | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000   | 2.0000  | 2.0000  | 2.0000  | 2.0000  |
| Na start                       | 0.7300   | 0.9100   | 0.8800   | 0.8405   | 0.8808   | 0.8035   | 0.9582   | 0.9818  | 0.9912  | 0.9422  | 0.9724  |
| components                     |          |          |          |          |          |          |          |         |         |         |         |
| Ko                             | 0.4200   | 0.7600   | 0.7200   | 0.5007   | 0.5248   | 0.3527   | 0.7158   | 0.7737  | 0.7309  | 0.7340  | 0.7363  |
| Acm                            | 0.1300   | 0.0700   | 0.0800   | 0.1264   | 0.1187   | 0.1600   | 0.0765   | 0.0633  | 0.0650  | 0.0738  | 0.0720  |
| JD                             | 0.2000   | 0.0800   | 0.0900   | 0.2550   | 0.1983   | 0.2572   | 0.1348   | 0.0413  | 0.0706  | 0.0807  | 0.0915  |
| Rest                           | 0.2500   | 0.1000   | 0.1100   | 0.1179   | 0.1583   | 0.2301   | 0.0729   | 0.1217  | 0.1335  | 0.1115  | 0.1002  |
|                                |          |          |          |          |          |          |          |         |         |         |         |

Table 7. Representative analyses of kosmochlor in amphibole felses and Jadeitite.







Fig. 5.8 a- d: Si (p.f.u) versus  $Mg/(Mg+Fe^{2+})$  diagram for amphiboles in amphibole felses after Leake et al., (1999). a-b. Ca amphiboles in AgSein; c. Na amphiboles in 027/05 and d. Na amphiboles in 024/05.



Fig. 5.9: Compositonal map of Ca in calcic amphibole zoning in amphibole felses (020/05).

#### 5.4. Albite

Albite in the albitite shows the Ab<sub>99.1-99.7</sub>-An<sub>0.9-0.3</sub>, indicating that nearly pure albite (008/05) (Fig. 5.7 a)(Table 8). In this rock, it is also associated with other calcium rich pyroxene which fall in the omphacite range (Fig. 5.1)(Table 6). In the (010/05), it shows banded structure and also associated with calcium rich pyroxene range (Fig. 5.7 b)(Table 8). The composition of albite in this albitite shows  $Ab_{91-100}$ -An<sub>0-9</sub>. Omphicite and amphiboles are included as accessories. Albitite show banded nature with green omphacite and amphiboles which are displaced by later earth movement. With the increase amount of albite in altered jadeitie, it will transform into albitite. Quartz is generally absent also in albitite. Accessories include jadeite (relict), amphiboles, omphacite (012/05). The composition of amphiboles in albitite is ranging from richterite to eckermanite.

### 5.5. Amphiboles

By using teh IMA amphibole nomenclature by Leake *et al.* (1997), the following amphiboles can be identified in the present research work: Glaucophane, ferroglaucophane, richterite, riebeckite, magnesioriebeckite, winchite, barrosite, ferrobarrosite, magnesiokatophorite and tremolite and actinolite. Chemical analyses for the amphibole felses from the Tawmaw area shows that eckermannite, richterite, riebeckite and tremolite. These analyses shows that amphiboles from the studied amphibole felses are Na, Ca and Na-Ca rich types (Fig. 5.8)(Table 9).

In the amphibole felses, amphibole also show the zoning and composition of this zoining is analysed by compositional map (Fig. 5.9)(Table 9). Moreover, kosmochlor is associated with amphiboles in the amphibole felses.

#### 5.6. Vesuvianite

In the analysed jadeitite, there has no trace of vesuvianite, except one sample, MJ11. In this sample show the occurrence of relict vesuvianite with jadeite were observed where the vesuvianite is surrounded by altered rim of smectite like mineral (Table 10)(Fig. 5.10 a, b). This vesuvianite is not a normal type and having the unsual higher concentration of Na and Ti which have 1.5 wt.% Na<sub>2</sub>O that is higher than for vesuvianite described from elsewhere. The composition of this vesuvianite is not homogeneous, but characterized by a relatively Na-Ti rich core. This core grades into Na-Ti poor vesuvianite which is getting again continuously richer in Na and Ti towards the outer rim. There has a sharp break between the core and rim composition related to this Na and Ti.

| wt 0/                          | KT23   | KT23   | KT23   | KT23   | #00805 | #00805 | #00805 | #010/05 | #010/05 | #010/05 |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|
| wt. 70                         | #112   | #115   | #116   | #117   | #129   | #132   | #135   | #161    | #162    | #167    |
| SiO <sub>2</sub>               | 69.17  | 69.46  | 69.23  | 69.39  | 69.31  | 69.54  | 69.40  | 69.38   | 69.60   | 69.03   |
| TiO <sub>2</sub>               | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.01   | 0.00    | 0.00    | 0.00    |
| Al <sub>2</sub> O <sub>3</sub> | 19.73  | 19.55  | 20.03  | 19.51  | 19.79  | 19.91  | 19.96  | 19.43   | 19.30   | 19.50   |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.01    | 0.03    | 0.00    |
| Fe <sub>2</sub> O <sub>3</sub> | 0.00   | 0.04   | 0.00   | 0.00   | 0.00   | 0.02   | 0.00   | 0.01    | 0.01    | 0.04    |
| Mn <sub>2</sub> O <sub>3</sub> | 0.00   | 0.01   | 0.00   | 0.00   | 0.04   | 0.00   | 0.00   | 0.03    | 0.00    | 0.00    |
| MgO                            | 0.00   | 0.02   | 0.01   | 0.01   | 0.02   | 0.00   | 0.01   | 0.00    | 0.01    | 0.01    |
| CaO                            | 0.00   | 0.01   | 0.02   | 0.00   | 0.00   | 0.02   | 0.00   | 0.00    | 0.03    | 0.00    |
| Na <sub>2</sub> O              | 12.36  | 12.32  | 12.32  | 12.27  | 12.35  | 12.38  | 12.55  | 12.19   | 11.78   | 12.09   |
| K <sub>2</sub> O               | 0.01   | 0.03   | 0.10   | 0.01   | 0.07   | 0.07   | 0.06   | 0.10    | 0.07    | 0.07    |
| BaO                            | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00    | 0.00    | 0.00    |
| Total                          | 101.27 | 101.45 | 101.70 | 101.19 | 101.58 | 101.96 | 101.98 | 101.15  | 100.83  | 100.74  |
|                                |        |        |        |        |        |        |        |         |         |         |
| Si                             | 2.9877 | 2.9947 | 2.9790 | 2.9975 | 2.9859 | 2.9847 | 2.9798 | 2.9993  | 3.0115  | 2.9955  |
| Al                             | 1.0042 | 0.9935 | 1.0159 | 0.9932 | 1.0047 | 1.0073 | 1.0101 | 0.9899  | 0.9844  | 0.9972  |
| Fe <sup>3</sup>                | 0.0000 | 0.0014 | 0.0000 | 0.0000 | 0.0000 | 0.0006 | 0.0000 | 0.0004  | 0.0004  | 0.0012  |
| Mn <sup>3</sup>                | 0.0000 | 0.0003 | 0.0000 | 0.0000 | 0.0012 | 0.0001 | 0.0000 | 0.0011  | 0.0000  | 0.0000  |
| Cr                             | 0.0001 | 0.0002 | 0.0000 | 0.0001 | 0.0000 | 0.0001 | 0.0000 | 0.0003  | 0.0011  | 0.0000  |
| Ti                             | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0003 | 0.0000  | 0.0000  | 0.0000  |
| su1                            | 3.9921 | 3.9914 | 3.9956 | 3.9915 | 3.9933 | 3.9930 | 3.9908 | 3.9910  | 3.9983  | 3.9945  |
| Ba                             | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000  | 0.0000  | 0.0000  |
| Ca                             | 0.0000 | 0.0005 | 0.0008 | 0.0000 | 0.0000 | 0.0008 | 0.0000 | 0.0001  | 0.0012  | 0.0000  |
| Na                             | 1.0356 | 1.0297 | 1.0276 | 1.0279 | 1.0319 | 1.0305 | 1.0450 | 1.0217  | 0.9881  | 1.0176  |
| K                              | 0.0006 | 0.0018 | 0.0055 | 0.0006 | 0.0038 | 0.0041 | 0.0030 | 0.0056  | 0.0039  | 0.0041  |
| su2                            | 1.0362 | 1.0320 | 1.0340 | 1.0285 | 1.0357 | 1.0354 | 1.0480 | 1.0275  | 0.9932  | 1.0218  |
| components                     |        |        |        |        |        |        |        |         |         |         |
| ANORTHITE                      | 0.0000 | 0.0005 | 0.0008 | 0.0000 | 0.0001 | 0.0008 | 0.0000 | 0.0001  | 0.0012  | 0.0000  |
| HIGH_ALBITE                    | 0.9994 | 0.9978 | 0.9939 | 0.9994 | 0.9963 | 0.9952 | 0.9971 | 0.9944  | 0.9949  | 0.9960  |
| K-FELDSPAR                     | 0.0006 | 0.0017 | 0.0053 | 0.0006 | 0.0036 | 0.0039 | 0.0029 | 0.0055  | 0.0040  | 0.0040  |

Table 8. Representative analyses of albite in albitite and jadeitite contact.

| . 0/                           |                  | 012/05           |                 |                    | KT34               |                 | 012             | 2/05            |                  | MJ 21            |                  |
|--------------------------------|------------------|------------------|-----------------|--------------------|--------------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|
| wt. %                          | #244             | #229             | #299            | #192               | #197               | #202            | #286            | #287            | #45              | #57              | #60              |
| SiO <sub>2</sub>               | 58.10            | 56.32            | 57.00           | 52.65              | 53.18              | 56.35           | 57.68           | 56.33           | 55.75            | 55.61            | 55.03            |
| TiO <sub>2</sub>               | 0.03             | 0.08             | 0.13            | 0.07               | 0.07               | 0.04            | 0.14            | 0.24            | 0.06             | 0.05             | 0.03             |
| Al <sub>2</sub> O <sub>3</sub> | 4.54             | 6.79             | 8.51            | 6.74               | 6.08               | 6.93            | 3.76            | 4.58            | 11.07            | 9.74             | 8.90             |
| FeO                            | 4.68             | 4.39             | 4.66            | 6.29               | 6.26               | 5.93            | 1.94            | 2.23            | 0.02             | 0.01             | 0.02             |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00             | 0.00             | 0.00            | 0.03               | 0.03               | 0.02            | 0.02            | 0.07            | 14.18            | 15.66            | 17.09            |
| MnO                            | 0.09             | 0.08             | 0.05            | 0.22               | 0.15               | 0.10            | 0.09            | 0.10            | 0.11             | 0.02             | 0.12             |
| MgO                            | 18.55            | 17.71            | 16.56           | 17.90              | 18.47              | 17.08           | 21.28           | 20.60           | 7.95             | 7.94             | 7.82             |
| CaO                            | 2.38             | 2.18             | 1.43            | 6.12               | 7.34               | 1.84            | 4.78            | 5.89            | 0.60             | 1.01             | 1.40             |
| Na <sub>2</sub> O              | 9.63             | 9.87             | 10.39           | 7.98               | 7.22               | 10.31           | 8.42            | 7.68            | 7.14             | 7.15             | 6.52             |
| K <sub>2</sub> O               | 0.46             | 0.44             | 0.28            | 0.16               | 0.15               | 0.06            | 0.42            | 0.48            | 0.03             | 0.01             | 0.00             |
| H <sub>2</sub> O               | 1.54             | 2.15             | 0.98            | 1.84               | 1.05               | 1.33            | 1.45            | 1.80            | 2.13             | 2.12             | 2.10             |
| Total                          | 100.00           | 100.00           | 100.00          | 100.00             | 100.00             | 100.00          | 99.99           | 99.99           | 99.06            | 99.31            | 99.03            |
|                                |                  |                  |                 |                    |                    |                 |                 |                 |                  |                  |                  |
| TSi                            | 7.9400           | 7.7500           | 7.7400          | 7.3800             | 7.4100             | 7.7100          | 7.8400          | 7.7400          | 7.8420           | 7.8741           | 7.8478           |
| Al                             | 0.0600           | 0.2500           | 0.2600          | 0.6200             | 0.5900             | 0.2900          | 0.1610          | 0.2600          | 0.1580           | 0.1259           | 0.1522           |
| Sum_T                          | 8.0000           | 8.0000           | 8.0000          | 8.0000             | 8.0000             | 8.0000          | 8.0000          | 8.0000          | 8.0000           | 8.0000           | 8.0000           |
| CAl                            | 0.6700           | 0.8500           | 1.1000          | 0.4900             | 0.4100             | 0.8200          | 0.4400          | 0.4800          | 1.6777           | 1.4995           | 1.3428           |
| CCr                            | 0.0000           | 0.0000           | 0.0000          | 0.0000             | 0.0000             | 0.0000          | 0.0000          | 0.0100          | 0.0026           | 0.0013           | 0.0018           |
| CFe <sup>3</sup>               | 0.0500           | 0.0400           | 0.0000          | 0.0900             | 0.0000             | 0.1800          | 0.0100          | 0.0000          | 0.3284           | 0.3437           | 0.5693           |
| CTi                            | 0.0000           | 0.0100           | 0.0100          | 0.0100             | 0.0100             | 0.0000          | 0.0200          | 0.0200          | 0.0067           | 0.0053           | 0.0034           |
| CMg                            | 3.7800           | 3.6300           | 3.3500          | 3.7400             | 3.8400             | 3.4800          | 4.3100          | 4.2200          | 1.6682           | 1.6755           | 1.6622           |
| CFe <sup>2</sup>               | 0.4900           | 0.4700           | 0.5300          | 0.6500             | 0.7300             | 0.5000          | 0.2100          | 0.2600          | 1.3036           | 1.4723           | 1.4062           |
| CMn                            | 0.0100           | 0.0100           | 0.0100          | 0.0300             | 0.0200             | 0.0100          | 0.0100          | 0.0100          | 0.0129           | 0.0023           | 0.0143           |
| Sum_C                          | 5.0000           | 5.0000           | 5.0000          | 5.0000             | 5.0000             | 5.0000          | 5.0000          | 5.0000          | 5.0000           | 5.0000           | 5.0000           |
| BCa                            | 0.3500           | 0.3200           | 0.2100          | 0.9200             | 1.1000             | 0.2700          | 0.7000          | 0.8700          | 0.0910           | 0.1532           | 0.2138           |
| BNa                            | 1.6500           | 1.6800           | 1.7900          | 1.0800             | 0.9100             | 1.7300          | 1.3000          | 1.1300          | 1.9090           | 1.8468           | 1.7862           |
| Sum_B                          | 2.0000           | 2.0000           | 2.0000          | 2.0000             | 2.0000             | 2.0000          | 2.0000          | 2.0000          | 2.0000           | 2.0000           | 2.0000           |
| ACa                            | 0.0000           | 0.0000           | 0.0000          | 0.0000             | 0.0000             | 0.0000          | 0.0000          | 0.0000          | 0.0000           | 0.0000           | 0.0000           |
| ANa                            | 0.9000           | 0.9500           | 0.9400          | 1.0900             | 1.0500             | 1.0100          | 0.9100          | 0.9100          | 0.0396           | 0.1156           | 0.0177           |
| AK                             | 0.0800           | 0.0800           | 0.0500          | 0.0300             | 0.0300             | 0.0100          | 0.0700          | 0.0800          | 0.0054           | 0.0018           | 0.0000           |
| Sum_A                          | 0.9800           | 1.0300           | 0.9900          | 1.1100             | 1.0700             | 1.0200          | 0.9900          | 1.0000          | 0.0449           | 0.1174           | 0.0177           |
| Name                           | Ecker-<br>manite | Ecker-<br>manite | Rich-<br>terite | Mg-Kato<br>phorite | Mg-Kato<br>phorite | Rich-<br>terite | Rich-<br>terite | Rich-<br>terite | Glauco-<br>phane | Glauco-<br>phane | Glauco-<br>phane |

| Table 9. Re | epresentative | analyses of | famphiboles | from amphibole | felses and in jadeitite. |
|-------------|---------------|-------------|-------------|----------------|--------------------------|
|-------------|---------------|-------------|-------------|----------------|--------------------------|



Fig. 5.10: BSE image of relict vesuvianite in jadeitite (MJ11). a. Overall view of vesuvianite in jadeitite, b. Close up view of lowerpart of relict vesuvianite, the mineral that surrounded the vesuvianite is smectite like minerals, and c. Closeup view of larger relict vesuvianite in a (red quadrangle).

| Table  | 10. Re | presentative | analyses | of ves | suvianite | in | iadeitite | (Rim to   | core)(MJ) | 11). |
|--------|--------|--------------|----------|--------|-----------|----|-----------|-----------|-----------|------|
| 1 4010 | 10.100 | presentative | anaryses | 01 100 |           |    | Jaaonne   | (10111 00 |           | ,.   |

| wt.%                           | #1     | #8     | #10    | #12    | #13    | #15    | #17    | #19    | #20    | #26    |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| SiO <sub>2</sub>               | 36.87  | 37.01  | 36.94  | 36.94  | 37     | 37.05  | 37.22  | 36.59  | 36.7   | 36.57  |
| TiO <sub>2</sub>               | 2.81   | 2.45   | 1.81   | 1.33   | 1.26   | 1.23   | 3.07   | 3.17   | 3.13   | 2.74   |
| Al <sub>2</sub> O <sub>3</sub> | 19.45  | 19.5   | 20.04  | 20.43  | 20.37  | 20.41  | 19.17  | 18.99  | 19.03  | 19.31  |
| FeO                            | 1.73   | 1.88   | 1.96   | 1.85   | 1.77   | 1.9    | 1.84   | 1.73   | 1.81   | 1.71   |
| MnO                            | 0.15   | 0.17   | 0.19   | 0.17   | 0.21   | 0.15   | 0.15   | 0.1    | 0.12   | 0.13   |
| MgO                            | 0.59   | 0.58   | 0.56   | 0.56   | 0.56   | 0.6    | 0.66   | 0.67   | 0.68   | 0.6    |
| $Ce_2O_3$                      | bdl    | bdl    | bdl    | bdl    | bdl    | bdl    | 0.11   | 0.07   | 0.17   | 0.15   |
| CaO                            | 33.89  | 34.28  | 34.36  | 34.71  | 34.59  | 34.96  | 33.38  | 33.79  | 33.88  | 33.71  |
| Na <sub>2</sub> O              | 1.25   | 1.28   | 1.14   | 1.12   | 1.15   | 1.09   | 1.31   | 1.26   | 1.28   | 1.33   |
| H <sub>2</sub> O               | 2.23   | 2.29   | 2.24   | 2.17   | 2.33   | 2.21   | 2.57   | 2.11   | 2.1    | 2.14   |
| Total                          | 99.01  | 99.46  | 99.3   | 99.32  | 99.22  | 99.62  | 99.48  | 98.49  | 98.91  | 98.38  |
|                                |        |        |        |        |        |        |        |        |        |        |
| Si                             | 18     | 18     | 18     | 18     | 18     | 18     | 18     | 18     | 18     | 18     |
| Ti                             | 1.03   | 0.897  | 0.664  | 0.488  | 0.46   | 0.449  | 1.116  | 1.173  | 1.157  | 1.014  |
| Al                             | 11.191 | 11.177 | 11.508 | 11.733 | 11.681 | 11.686 | 10.93  | 11.009 | 11.003 | 11.205 |
| Fe <sup>2+</sup>               | 0.705  | 0.765  | 0.8    | 0.754  | 0.72   | 0.77   | 0.746  | 0.71   | 0.741  | 0.703  |
| Mn                             | 0.06   | 0.07   | 0.078  | 0.07   | 0.086  | 0.062  | 0.062  | 0.042  | 0.05   | 0.055  |
| Mg                             | 0.427  | 0.422  | 0.405  | 0.408  | 0.407  | 0.435  | 0.477  | 0.491  | 0.501  | 0.437  |
| $\Sigma$ Y+T                   | 13.414 | 13.332 | 13.455 | 13.453 | 13.353 | 13.402 | 13.331 | 13.426 | 13.452 | 13.413 |
| Ce                             | 0.007  | 0      | 0.009  | 0.006  | 0      | 0.003  | 0.019  | 0.013  | 0.03   | 0.026  |
| Ca                             | 17.728 | 17.863 | 17.937 | 18.125 | 18.031 | 18.2   | 17.299 | 17.811 | 17.807 | 17.779 |
| Na                             | 1.185  | 1.211  | 1.08   | 1.061  | 1.081  | 1.031  | 1.23   | 1.199  | 1.214  | 1.266  |
| ΣΧ                             | 18.962 | 19.103 | 19.062 | 19.219 | 19.141 | 19.265 | 18.599 | 19.033 | 19.073 | 19.092 |
| OH                             | 7.257  | 7.426  | 7.273  | 7.057  | 7.55   | 7.171  | 8.29   | 6.932  | 6.861  | 7.039  |

(bdl= below detection limit).

| wt %                           | KT23   |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| wt. 70                         | #129   | #141   | #142   | #143   | #144   | #147   | #148   | #149   |
| SiO <sub>2</sub>               | 47.97  | 48.95  | 48.93  | 48.23  | 48.48  | 48.54  | 48.41  | 48.35  |
| TiO <sub>2</sub>               | 0.00   | 0.01   | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| Al <sub>2</sub> O <sub>3</sub> | 29.45  | 29.55  | 29.79  | 29.25  | 29.60  | 29.27  | 29.50  | 29.88  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00   | 0.00   | 0.00   | 0.02   | 0.00   | 0.00   | 0.00   |
| Fe <sub>2</sub> O <sub>3</sub> | 0.03   | 0.00   | 0.00   | 0.04   | 0.00   | 0.04   | 0.00   | 0.00   |
| Mn <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| MgO                            | 0.01   | 0.00   | 0.00   | 0.00   | 0.01   | 0.03   | 0.01   | 0.00   |
| NiO                            | 0.01   | 0.06   | 0.02   | 0.04   | 0.00   | 0.00   | 0.00   | 0.00   |
| CaO                            | 0.03   | 0.01   | 0.00   | 0.01   | 0.03   | 0.05   | 0.02   | 0.01   |
| Na <sub>2</sub> O              | 15.50  | 14.35  | 14.62  | 14.88  | 15.04  | 15.15  | 15.68  | 15.19  |
| K <sub>2</sub> O               | 0.10   | 0.03   | 0.01   | 0.01   | 0.02   | 0.03   | 0.02   | 0.02   |
| BaO                            | 0.02   | 0.00   | 0.00   | 0.00   | 0.02   | 0.00   | 0.00   | 0.00   |
| H <sub>2</sub> O               | 8.15   | 8.20   | 8.23   | 8.13   | 8.19   | 8.18   | 8.21   | 8.21   |
| Total                          | 101.26 | 101.16 | 101.61 | 100.59 | 101.42 | 101.30 | 101.86 | 101.67 |
|                                |        |        |        |        |        |        |        |        |
| Si                             | 1.7639 | 1.7893 | 1.7822 | 1.7788 | 1.7741 | 1.7793 | 1.7687 | 1.7659 |
| Al                             | 1.2760 | 1.2729 | 1.2787 | 1.2713 | 1.2768 | 1.2645 | 1.2703 | 1.2861 |
| Fe <sup>3</sup>                | 0.0008 | 0.0000 | 0.0000 | 0.0010 | 0.0000 | 0.0010 | 0.0000 | 0.0001 |
| Mn <sup>3</sup>                | 0.0000 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Cr                             | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0005 | 0.0000 | 0.0000 | 0.0000 |
| Ti                             | 0.0000 | 0.0002 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ba                             | 0.0003 | 0.0000 | 0.0000 | 0.0000 | 0.0003 | 0.0000 | 0.0000 | 0.0000 |
| Ca                             | 0.0010 | 0.0004 | 0.0000 | 0.0004 | 0.0012 | 0.0021 | 0.0008 | 0.0005 |
| Mg                             | 0.0007 | 0.0000 | 0.0000 | 0.0000 | 0.0004 | 0.0016 | 0.0005 | 0.0000 |
| Ni                             | 0.0002 | 0.0018 | 0.0006 | 0.0011 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Na                             | 1.1047 | 1.0172 | 1.0328 | 1.0642 | 1.0670 | 1.0771 | 1.1108 | 1.0754 |
| K                              | 0.0045 | 0.0013 | 0.0006 | 0.0006 | 0.0011 | 0.0015 | 0.0011 | 0.0011 |
| Н                              | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 | 2.0000 |

Table 11. Representative analyses of analcime in jadeitite.

# CHAPTER

## VI

### **VI.** Alteration

Most of the jadeite grains are altered along their boundaries and also along the cracks. Mostly, these alteration products are albite and analcime (Table 11). Kosmochlor is altered from chromite and there has a sharp boundary between the chromite and also there has sharp boundary between kosmochlor and jadeite.

### 6.1. Alteration in Jadeitite

Formation of albite is formed by the following reaction: NaAlSi<sub>2</sub>O<sub>6</sub> + H<sub>2</sub>O  $\rightarrow$  NaAlSi<sub>2</sub>O<sub>6</sub>. H<sub>2</sub>O $\rightarrow$  NaAlSi<sub>3</sub>O<sub>8</sub> + H<sub>2</sub>O Jadeite Analcime Albite Water Moreover, jadeititic pyroxene is breakdown to the amphiboles with variation in composition especially on sodic variety. With the higher concentration of Cr in pyroxene and amphibole of terrestrial rock in Tawmaw area, the geochemistry of such kind of rocks may have special conditions. Metasomatism between serpentinites and an albitite vein occurred during high

pressure-low temperature metamorphism and forming such kind of unsual rocks.

#### CHAPTER

#### VII

### VII. Conclusions and geological significance

#### 7.1. Origin of Jadeitite

The occurrence of pure jadeite in various metamorphic rocks is usually attributed to high pressure metamorphism (e.g., Holland, 1980, 1983; Tropper et al. 1999). Monomineralic jadeitite rocks, called jadeitite, within the serpentinite have been interpreted as formed by metasomatism at depth (Coleman, 1961, 1980; Harlow, 1994; Harlow and Sorensen, 2001, 2005; Shi et al. 2001). An important item for the discussion of jadeitite formation is the occurrence of rare clinopyroxene mineral kosmochlor. This mineral is well known as an accessory mineral in iron meteorites (Frondel and Klein, 1965; Couper et al. 1981; Laspeyers, 1987 and Zinovieva et al. 1999) or as kosmochlor-jadeite solid solution in carbonaceous chondrites (Baryshnikova et al. 1987; Greshake and Bischoff, 1996). In terrestrial rocks, kosmochlor rich clinopyroxene was reported from ultra-high pressure metamorphic rocks (Liu, et al. 1998), peridotite xenoliths (Sobolev et al. 1997), kimberlites (Sobolev et al. 1975) and metasediments (Reznitskii, 1999). Solid solutions of kosmochlor-jadeite also occur in jadeitite and associated rocks of Myanmar and Guatemala (Mével and Kiénast, 1980; Yang, 1984). Kosmochlor and associated chromian jadeite in Myanmar jadeitite area reveal replacement textures, indicating growth of kosmochlor at the expense of chromite during metamorphism (Yang, 1984; Mével and Kiénast, 1986; Harlow and Olds, 1987; Shi et al. 2005a) These Cr-rich clinopyroxene have wide range of composition ranging from 5 wt. % Cr<sub>2</sub>O<sub>3</sub> to 25 wt. % Cr<sub>2</sub>O<sub>3</sub> (Mével and Kiénast, 1986; Harlow and Olds, 1987; Htein and Naing, 1994, 1995; Yang, 1984, 2001), Recently 32 wt.% Cr<sub>2</sub>O<sub>3</sub> (Shi et al. 2005a). Yang (1984) and Mével and Kiénast (1986) suggested that there has a miscibility gap on the kosmochlorjadeite join. Present study of kosmochlor indicates that 26 wt. % Cr<sub>2</sub>O<sub>3</sub> in Tawmaw area.

In the Tawmaw area in Myanmar, jadeitite bodies appear as discordant veins or lens-shaped blocks within the serpentinized ultramafic bodies (Chhibber, 1934; Bender, 1983). Shi *et al.* 2003 suggested that amphibole fels layers (1 cm to 0.5 m thick) rimming jadeitite bodies are attributed to metasomatic reaction between jadeitite and depleted peridotite at high-P, low-T conditions. Kosmochloar and chromian jadeite occur mainly as disseminated aggregates of jadeitite and related rocks (Shi *et al.* 2003). Most of the rocks are strongly deformed which lead to intermingling of kosmochloar and chromian jadeitite blocks with Cr-poor jadeitite.

### 7.1.1. Igneous Origin

Analyses from 3-phases fluid inclusions in jadeite from the Pharkant-Tawmaw jadeite belt indicate that it is mainly composed of H<sub>2</sub>O (95%) and CH<sub>4</sub> (5%). Based on these results, it was suggested that Myanmar jadeitites may directly crystallize from jadeitic melt containing H<sub>2</sub>O and CH<sub>4</sub> (Shi *et al.* 2000). Experimental investigations show that, in a hydrous system, the lower limit of P-T conditions of L = Jd+V is P> 1.5 Gpa, T> 650°C (Boettcher, and Wyllie, 1968, 1969). Such conditions are very close to the geothermal gradient of subduction zone (Shi *et.al.*, 2000). Accordingly, jadeite would have been formed in lower crust to upper upper mantle, at depth > 50 km.

### 7.1.2. Metasomatic origin

A metasomatic and metamorphic origin for the formation of jadeitite was proposed by several authors (Yoder, 1950; Coleman, 1961, 1980; Mével and Kiénast, 1986; Goffé *et al.* 2000; Harlow and Sorensen, 2001, 2005). The processes involved could have been a direct crystallization in the presence of a fluid phase as proposed by (Chhibber, 1935), pressure solution and re-deposition in fractures (Harlow, 1994), or precipitation from the fluid phase (Shi *et al.* 2000).

Jadeitites from the Tawmaw area occurs in the same tectonic setting as in other localities. The core (jadeitite) is surrounded by albite and then by a thin zone of chlorite schist and/or actinolite schist, by amphibole felses and finally the serpentinized peridotite-dunite country rock containing a zonal pattern (Fig. 2.1-2.6). In some places, no jadeitite but only the other rock types appear. Some authors (e.g. Chhibber, 1934; Chihara, 1971) proposed a protolith of albitite composition for the jadeitite. But it is difficult to prove, because the alteration product of jadeitite is also albite.

For the direct crystallization model, the jadeitite forming fluid should be essentially composed of jadeitite composition. Two models may be considered:

- Na-metamorphism of a protolith with high Al/(Fe+Mg) (or interaction with fluids having high Na activity compared to K, Ca, etc.) or
- a fractionation process that extracts jadeitite components from some protoliths and crystallized them as bodies within the serpentinite (Harlow, 1994).

Coleman (1961) suggests that jadeitite can be form from the remobilization and metasomatism of quartz keratophyres (plagiogranite-like rocks). In the study area, the granitic rock exposed is just a small body and no report on plagiogranite is known. Coleman (1961) also suggested that jadeitites are silica depleted with respect to the acidic magmatic precursors and during jadeite crystallization, released silica is captured by the formation of serpentinite. For the chromium in jadeite, there is no doubt that supply comes from the destabilization of

chromite in the peridotite. It is also observed that chromite in Maw-sit-sit and amphibole felses were directly replaced by kosmochlor. The size of these kosmochlor grains mainly depends on the original chromite grain. Accordingly, it may be suggested that kosmochlor is formed at the contact between the host peridotite (serpentinized peridotite) and Na rich acidic dyke as a result of metasomatism. If the jadeitite was formed by interactions with a Na rich source, there must be a Na rich environment such as subduction channel environment. A specific tectonic environment in peridotite which offers the channel ways for the crystallization of jadeitite in the Tawmaw area could be TTF triple junction environment (Thin, 1991).

Other probable source for the Na metasomatism could be spilitic basalt (Dr. Maung Thein, personal communication; Sorensen *et al.* 2006) which may be associated with the peridotite in an ophiolite suite. Formation of jadeitite and association with high pressure glaucophane bearing schist suggest that these two rock associations are contemporaneously in an subduction environment. The occurrence of HP-LT rocks in this area under consideration and of LP-HT garnet-sillimanite rocks in the Mogok Metamorphic Belt exposed in more eastern region suggest the occurrence of pair metamorphic belt (Thein, 1983).

The late Cretaceous-Paleogene structural and tectonic events in western part of Myanmar are related to the collision of India-Asia. This process is supported by the presence of the late Cretaceous-Eocene ophiolite in Myanmar (Mitchell, 1993; Bertrand et al. 2001; Bertrand & Rangin, 2003; Morley, 2004). The presence of extensive S-type granite magmatism of the Cretaceous-Paleogene in Myanmar and Thailand has been used to confirm the synchrynous events of crustal thickening (Cobbing et al. 1986, 1992; Zaw 1990; Hutchison 1996). Previous work recognised the evolution of deformation events in Myanmar and the whole Asia region as related to transpression arising from an oblique subduction and approximately NE-SW directed collisions. These collisional events are represented by the Cretaceous-Paleogene Burma plate-ShanThai block collision, and the Eocene-Recent India-Burma plate-Shan-Thai block collision (Metcalf, 1998; Leloup, 2001; Morely, 2002; Huchon et al. 1994 and Morley, 2004) (Fig. 7.1). The peak of the deformation event in this region is characterized by the development of Mae Ping-Three-Pagoda transpressional belt. The main feature of this structure is development of high angle shear zone with main left lateral movement (Bertrand & Rangin 2003; Morley 2004). This last author suggest that a proto Sagaing fault zone probably formed the westerly boundary of the Mae Ping fault zone and inferred a sinistral transform plate boundary along which the Hpakant-Tawmaw jadeitite dyke were emplaced. This model suggests a sinistral movement of the Ma Ping and Three Pagoda fault zone related to escape tectonics of Himalayan Belt. This scenario is responsible for





regional NS uplift, and is related to northerly passage of the Himalayan syntaxis which generated the Sagaing fault zone (Bertrand & Rangin, 2002; Morely, 2004). Thus rare occurrence of jadeitite indicates that formation of jadeitite is unsual and limited condition.

Monazite occuring exclusively in garnet mica schists were analysed with the electron microprobe also for their U, Th, and Pb contents. Only 43 analyses of monazite were suitable for geochronology. The analyses yielded an age ranging between <15 and 120 Ma. Goffé *et al.* (2000) determined <sup>39</sup>Ar-<sup>40</sup>Ar ages of phengites from high-pressure rocks of the jade mine area. These ages were between 50 to 80 Ma and were related to the high-pressure metamorphic events resulting from the collision of India and Asia. Shi *et al.* (2008) recently reported on Ion Microprobe U-Pb ages of zircon grains from the Myanmar jadeitite. These authors related the age of 146.5  $\pm$  3.4 Ma to the formation of the Myanmar jadeitites, as well as to the subduction of the eastern Indian Oceanic plate. This assignment contradicts the here presented view that the formation of the jadeitite was a Tertiary event. It is therefore suggested that the Mesozoic ages are related to metamorphism of sedimentary protoliths (garnet mica schist) prior to high pressure conditions at lower crustal levels (6-8 kbar).

The formation of jadeitite requires the presence of fluids for the intensive transport of sodium and other mobile elements to form the wall-rock assemblage. These fluids found their pathways along the major strike-slip zone of the Sagaing fault to produce wall rocks at the contact of serpentinite and country rock. The corresponding high pressure during this event was the result of continent-continent collision. Previous authors related this collisional event to subduction of oceanic crust. But this subduction event was earlier leading to the tectonic mixing of oceanic crust (serpentinites) and continental crust. It is suggested that jadeitite experienced the same P-T history as the garnet-mica schist and glaucophane schist country rocks. As country rocks (garnet mica schist) show, they were also affected by high pressures corresponding to Earth's depths of ca. 50 km. Therefore, the continental crust was deeply buried by continent-continent collision, for instance, by underthrust of one plate under the other plate. This was probably the result of the early tectonic motions of the (pre) Sagaing fault in Tertiary times.

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# Metamorphic evolution of garnet- and glaucophane-bearing schists in the Tawmaw jade district, northern Myanmar

by

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#### Abstract

A detailed petrological investigation of garnet- and glaucophane bearing mica schists in the immediate vicinity of the serpentinite in Tawmaw area was undertaken. This detailed study led to the distinction of at least 3 metamorphic stages (I = early, related to the core of garnet in mica schists) at 470-540° C, 16-19 kb and 5.5-8.5 kbar, 570-630°C (III = late, rim composition of garnet, phengite rim). P-T conditions for each stage were calculated using thermodynamic methods, considering assemblages of coexisting minerals and their compositions to constrain the P-T path of the rocks. The path (1) explains the observed Ca, Mn and Mg zonation of garnet, (2) considers the change of Si contents in potassic white mica (e.g., late increase of Si p.f.u according). The P-T conditions estimated for glaucophane schists are similar to those of the garnet mica schist. For the core of the garnet, 470-490°C, 18-20 kbar are derived, and the P-T condition of rim compositions of garnet from the glaucophane schist result in 560-620°C, 7-12 kbar. Monazite exclusively occurs in garnet mica schists. 43 analyses of monazite were suitable for microprobe geochronology and yielded an age range between < 15 and 120 Ma which was related to the high-pressure metamorphic events resulting from the collision of India and Asia. This work is important to understand the formation and metamorphic history of jadeitite and jadeite-albite rocks in the Tawmaw area. It is suggested that jadeitite experienced the same P-T history as the garnetmica schist and glaucophane schist country rocks. The formation of jadeite may be attributed to (stage I) whereas albitite bodies cold have crystallized at (stage III). The derived high pressure conditions are interpreted as due to the continental crust was deeply buried by continent-continent collision, for instance, by underthrust of one plate under the other plate. This was probably the result of the early tectonic motions of the (pre) Sagaing fault in Tertiary times.

#### 1. Introduction

Tertiary tectonic events in SE Asia are poorly characterized but important for the understanding of the orogenesis which resulted from the collision of India and Asia (for plate motions see, e.g., Hall, 2002). For example, the Sagaing fault is a prominent major N-S trending dextral strike-slip fault (Fig.1) resulting from these colliding plates and the occurrence of the rigid Sundaland block (Mitchell, 1989). This still active fault in Myanmar (formerly Burma), extending nearly 900 km in north-south direction, cuts through the Tertiary



Fig. 1: Simplified tectonic map of Myanmar (after Bender, 1983; Mitchell *et al.,* 2006 and Socquet et al., 2002). Black quadrangle shows positions of the area of Fig. 2.



Fig. 2: Geological map of the Pharkant-Tawmaw Area, Kachin State, Myanmar (modified after Chhibber, 1934 and Tun, 1997). Black quadrangle indicates Study area. sedimentary units of the central Burma basin (Vigny *et al.*, 2003). Along this fault serpentinite and related jadeitite bodies occur in northern Myanmar. In addition, various medium-grade metamorphic rocks in contact to these bodies are exposed (Fig.2). The appearance of these rocks of the intermediate to lower crust and the observed structural features gave rise to the assumption that such crust was exhumed in a transtensional regime which is older than 10 Ma (Rangin *et al.* 2002).

One of the world's largest and best quality jade (jadeitite) including the rare mawsitsit, a unique emerald green gemstone and carving material of the Tawmaw (this village is also written Tawhmaw or Taw Maw) area which is mainly composed of kosmochlor (Colombo et al. 2000; Qi et al. 2003), is exposed in the Pharkant-Tawmaw jade belt, Myitkyina District, Northern Myanmar. The rocks of this belt were formed in Mesozoic presumably in Upper Cretaceous times (e.g., Mitchell, 1993). Major outcrops of the Pharkant-Tawmaw area, also called jade mine belt (Chhibber, 1934), are related to the ophiolite belt of the Indo-Burman Ranges which are bounded by the aforementioned Sagaing strike slip fault to the east (Fig. 1). The occurrences of jadeitite and associated blueschists, in fact, indicate that the area west of the Sagaing fault was object of high-pressure metamorphism but neither precise age nor extension of this type of metamorphism are known thus far. Furthermore, the relationships of high-pressure glaucophane bearing schist and jadeitite and albite-jadeite rocks are still unclear. For these reasons, a detailed petrological and geochemical study was started in the Tawmaw area because of 1) relatively good exposures due to the jade mining and 2) valuable information by previous studies (Chhibber, 1934; Mével and Kiénast, 1986; Goffé et al. 2000; Shi et al. 2001, 2003, 2005a, 2005b, 2008 and Sorensen et al. 2006). In an area southeast of Tawmaw (25°40'44.3" N, 96°18'04.6" E, see Fig. 2) a complexly arranged variety of rocks occurs among them are serpentinized peridotite (Chhibber, 1934) and its wall rocks albitite, jadeitite and albite-jadeite rock as well as diverse crystalline schists. The ordinary schists are garnet-mica schist but also epidote and glaucophane-bearing schists occur. These highpressure metamorphic rocks in the Tawmaw area were not yet studied in detail due to dense vegetation and also limited permission of the access since many years. To gain a better understanding of the high-pressure rocks in the Pharkant-Tawmaw Jade Mine area, geothermobarometric estimates were carried out, for instance, using phengite barometry. Furthermore, pseudosections, calculated for garnet-blueschist and garnet mica schists, were applied to derive a P-T path for the schists. Moreover, monazite ages were determined to produce a geochronological frame for the metamorphic processes. This study will provide useful constraints for the tectonic processes of the collision of India and Asia in the past.

#### 2. Geological Setting

The Tertiary geotectonic evolution of SE Asia is dominated by the collision of India and Asia. This process is responsible for the tectonic intercalation between accrectionary wedge complex, arc-related basin and marine to continental metasedimentary sequences of the basement. Recent research has recognized 4 main geotectonic units in the region of Myanmar and surrounding (Fig. 1).

The Shan Plateau in the eastern part of this region is composed of Paleozoic and continental Mesozoic low grade metasediments and sedimentary rocks intruded by Mesozoic calcalkaline granites (Mitchell, 1977; Mitchell et al. 2002; Morely, 2004). This association occurs in a relative pervasive thrust and fold belt trending NNW-SSE with parallel stretching lineation (Bertrand and Rangin, 2003). In the western part of the Shan Plateau the structures are truncated by a reverse fault known as Shan Scarp fault, which is a high angle transpressive shear zone (Bertrand and Rangin, 2003). West of the Shan Plateau occurs an elongated and narrow geotectonic unit called the Mogok Metamorphic Belt (MMB, see Chhibber, 1934, Searle and Haq, 1964). This belt is composed of micaschist, gneiss, ruby-bearing marble, rare quartzite, granulite and foliated intrusive rocks (Bender, 1983). Chhibber (1934) and Iyer (1953) regarded the ruby-bearing marble from the MMB as Pre-Cambrian, whereas Searle and Haq (1964) considered various ages from Pre-Cambrian to Jurassic. The latter ages were, however related to rocks of the Shan Plateau. Mid-Cretaceous limestones occur to the north and Jurassic sedimentary rocks to the south of the MMB (Clegg, 1941). Thein et al. (1988) correlated the gneisses and marbles from the MMB with the Ordivician and Silurian rocks from the Shan Plateau. Mitchell et al. (2007) and other workers correlated the rocks from the MMB with Permian limestones (Cobbing et al. 1992). The foliated intrusive rocks of the MMB are Upper Jurassic to Late Cretaceous in age (Searle and Haq 1964; Cobbing et al. 1992; Mitchell et al. 2007) and are highly foliated generally with E-W trend and gentle dip towards the north or the south. The foliation plane shows a stretching lineation trending in NNW-SSE direction. The sense of transport of the upper layers is towards the NNW or SSE (Bertrand and Rangin, 2003; Bertrand et al. 2001). There are two metamorphic events in these rocks with grades between greenschist and granulite facies (Bender, 1983; Mitchell, 2006). K/Ar and Ar/Ar ages range between 32 and  $16 \pm 4$  Ma (Bertrand *et al.* 1999, 2001; Bertrand and Rangin, 2003). The youngest intrusive rock, the undeformed Kabaing granite yielded 15.8  $\pm$  1.1 Ma postdating the ductile stretching of Mogok Metamorphic Belt (Bertrand and Rangin, 2003).

In the central part of Myanmar the N-S trending Central Burma Basin is located which is filled with Eocene to Plio-Quaternary sediments up to a thickness of 15 km and more especially in the western part of the basin (Curray *et al.* 1979; Pivnik *et al.* 1998). The sedimentary association is related to a fore-arc basin which resulted from northeastward subduction (to the east) of the Bengal oceanic crust beneath Myanmar (Swe, 1981; Bertrand and Rangin, 2003).

The Indo-Burman Ranges west of the Central Burma Basin are mainly composed of Cenozoic rocks representing an accretionary wedge formed by this subduction (Socquet et al. 2002). This accretionary wedge can be subdivided into an eastern narrow strip composed of metamorphic rocks, ophiolites, Triassic schists and Late Cretaceous sediments, which constitute the internal zone of the range, and a large western belt of Cenozoic sediments that formed more recently as accrectionary wedge (Socquet et al. 2002). Metamorphic rocks from the eastern strip of the Indo-Burman Ranges include metapelite, metagreywacke and metabasite. These rocks were affected by ductile deformation. It is possible to recognize two main foliations. They are imprinted by a S30°E stretching lineation and a top-to-the-southeast shear. The mineral assemblages in metapelite, metabasite and metagreywacke indicate a greenschist to blueschist transition to the peak of metamorphic conditions (Socquet et al. 2002). There were three major tectonic phases affecting the Indo-Burman Ranges. (1) an early compressive phase is related to the closure of the Meso-Tethys ocean in the late Cretaceous-Eocene and is responsible for the thrust of the ophiolites over the Mesozoic metamorphic wedge. (2) The subsequent extensive phase is related to ductile crustal thinning. This phase is coeval with the metamorphism along the Shan Scarp and the subsidence of the Central Burma Basin with earliest deposits being Eocene in age. (3) The final event was again a compressive type of deformation starting in the Pliocene. This event formed the present accretionary wedge. Therefore, the evolution of the Indo-Burman Ranges shows similarities with the construction of the Himalayas and, because of its location away from the frontal convergence, may have preserved high-pressure facies rocks (Socquet et al. 2002).

The Indo-Burman Ranges are limited by the Andaman Trench to the west. The Andaman Sea further to the west is an active back-arc basin which started to develop ca. 32 Ma ago (Curray, 2005). Northwest of the trench the Shilong Plateau occurs which is bounded by the Main Boundary Fault to the Himalayan sequences.

The study area is located in the northern part of the Central Burma Basin around 15 km northwest of the city of Pharkant. The ca. 2600 km<sup>2</sup> sized area is generally composed of crystalline schists of continental origin, mafic schists and serpentinized peridotite-dunite of

oceanic affinity and Tertiary sedimentary rocks. Minor granite intruded the crystalline schists. Tertiary rocks such as sandstones and the Uru Boulder Conglomerate of Pleistocene and younger age are cut by minor andesitic intrusions in the north-eastern part of the Pharkant-Tawmaw area.

Geological mapping of the area shows the dominance of crystalline rocks compared with the sedimentary association of the basin. The western and central part of the study area is dominated by the intercalation of pelitic, mafic and subordinate magnesian schists. The glaucophane schist is the most common rock in the eastern part of the Tawmaw area hosting peridotite and jadeite-bearing rocks. In the central part of the study area a larger ultramafic body occurs which is intercalated with this schist. This body has an elongated shape trending NNW-SSE and is part of the belt of late Cretaceous to early Eocene (dismembered) ophiolite bodies extending from the Assam-Burma region in the north to the Nicobar Islands in the south.

The eastern part of the study area is composed of sedimentary units from the Central Burma Basin with a small structural island of Permo-Carboniferous fossil-bearing limestone. This limestone is probably part of the Plateau Limestone Group of the Southern Shan States (Chhibber, 1934), are the oldest rocks in the study area. All the previously mentioned rock associations are covered in the central and southern part of the study area by the Pleistocene Uru Boulder Conglomerate.

#### 3. Sample Description

The studied rocks were separated into three groups: (1) garnet-bearing mica-schist (GM), (2) epidote schist (ES), and (3) glaucophane-bearing HP rocks (GS). Jadeitite, jadeite- albite rocks and serpentinized peridotite close to group (1) to (3) samples were, in fact, investigated as well but the results are not presented here.

The GM samples 017, 018 and 019 (for modal analyses see Table 1) were taken close to the western part of the serpentinized peridotite body. Megascopically, this GM rock is greyishbrown on the weathered surface and greyish white on the fresh surface glimmering by white micas. The size of garnet (8-12 vol%), forming highly fractured, euhedral porphyroblasts, ranges from 0.1 to 10 mm in diameter. The matrix is composed of fine-grained muscovite-phengite (30-40 %), quartz (25-35 %), chlorite (3-5 %), 2-10 % feldspar (albite, which is partially altered), epidote (1-3 %), magnetite (0.5-1 vol%), rutile (1 vol%), titanite (1 vol%) and the opaque and accessory phases (1-4 vol%) ilmenite, zircon, apatite and monazite. The latter mineral is particularly abundant in sample 017. In sample 019, monazite is intergrowth with other REE rich minerals, forming sponge-like aggregates, and, thus, difficult to analyse for age determinations. Minerals enclosed in garnet are phengite, apatite, rutile, zircon and chlorite, but mainly quartz. Mineral inclusions in quartz are epidote, phengite, apatite, zircon and rutile. Zircon, titanite and magnetite are included in white mica. Epidote is usually found in the matrix and sometimes surrounded by opaques. Intergrowths of quartz and white mica are common in garnet-mica schist.

The ES samples 030/05, 031/05, and 032/05 (Table 1) lack amphibole, but are rich in epidote. Megascopically, these rocks show a yellowish white weathered surface but are bluish white on the fresh surface. Sample 030/05 is composed of albite (40-45 vol%), quartz (20-25 vol%), white mica (10-12 vol%), epidote (8-10 vol%), chlorite (5-6 vol%), titanite, rutile and accessory magnetite, ilmenite, apatite and zircon. Albite grains range in size from 20-2000 µm with subhedral to anhedral outlines. These grains are fractured and curved discernible by their twinning. Quartz occurs as large anhedral grains and smaller secondary recrystallized grains. White micas often form small aggregates, which can be fan-shaped often showing kink bending. Potassic white mica (phengite) also occurs as isolated grains surrounded by quartz. Epidote forms up to 1 mm large prophyroblasts in the matrix but also smaller yellowishbrown grains. It is mostly spindle-shaped in basal sections as well as subhedral and anhedral. Epidote also appears as inclusions in albite and quartz. Zircon and apatite occur as accessory in the matrix and as inclusions in quartz. Chlorite often surrounds albite, epidote and white mica. Large rounded clusters of chlorite may probably be pseudomorphs after garnet although no relict of garnet was found. Sample 031/05 is composed of albitic feldspar (30-35 vol%), quartz (20-25 vol%), epidote (20-25 vol%), chlorite (7-10 vol%), white mica (1-2 vol%), titanite (1-2 vol%), opaques (2 vol%), rutile and other accessories (1 vol%). Albite shows subhedral to anhedral grains. Epidote, being as large as 1 mm, occurs as elongated porphyroblasts parallel to the direction of foliation. Some epidote grains are surrounded by chlorite. Quartz forms anhedral grains and secondary recrystallized grains with granular mosaic texture. It is also found as inclusion in albite and epidote.

Sample 032/05 is composed of albitic feldspar (30-40 vol%), quartz (20-25 vol%), epidote (15-20 vol%), chlorite (3-6 vol%), garnet (2-3 vol%), white mica (3-4 vol %), rutile, opaques and other accessories (1 vol%). Subhedral grains of albite are as large as 2.5 mm. Quartz exhibits subhedral to anhedral grains with granular mosaic texture. Epidote shows porphyroblasts, being as large as 1 mm, in the albite-quartz matrix. Relicts of garnet were found which originally formed grains ranging in size from 1-2 mm. Rutile occurs as inclusions in quartz, epidote and garnet.

| Rock Type  |       | GM    |       |        | ES     |        | GS     |        |        |        |  |
|------------|-------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--|
| Sample No. | 017   | 018   | 019   | 030/05 | 031/05 | 032/05 | 033/05 | 034/05 | 035/05 | 041/05 |  |
| Quartz     | 25-30 | 25-30 | 30-35 | 20-25  | 20-25  | 20-25  | 5-7    | 5-7    | 10-15  | 10-12  |  |
| Feldspar   | 2-3   | 5-10  | 3-4   | 35-45  | 30-35  | 30-40  | 15-18  | 25-30  | 20-25  | 10-12  |  |
| White Mica | 35-42 | 35-41 | 30-37 | 8-12   | 1-2    | 2-4    | 1      | 1-3    | 2      | 2      |  |
| Garnet     | 10-12 | 8-10  | 10-12 | -      | -      | 2-3    | -      | 2-3    | 2-3    | 2      |  |
| Amphibole  | -     | -     | -     | -      | -      | -      | 25-30  | 20-25  | 7-10   | 10-15  |  |
| Chlorite   | 4-5   | 3-5   | 3-5   | 5-6    | 7-10   | 3-6    | 15-18  | 15-18  | 10-15  | 10-15  |  |
| Titanite   | 1     | 1     | 1     | 1      | 1      | 1      | 1      | 1      | 1      | 1      |  |
| Epidote    | 1-2   | 2     | 2-3   | 8-10   | 20-25  | 15-20  | 15-20  | 10-12  | 25-30  | 35-40  |  |
| Rutile     | 1     | 1     | 1     | 1      | 1-2    | 1      | 3      | 1      | 1-3    | 2-3    |  |
| Opaque     | 2-4   | 1     | 2-3   | 1      | 2      | 1      | 2-3    | 1-2    | -      | 1-2    |  |

Table 1. Model composition of the studied garnet-mica schists (GM), epidote schists (ES) and glaucophane schists (GS).

The glaucophane-bearing schists (GS) occur in the eastern and south-eastern part of the study area where they are highly weathered and covered with dense vegetation. Thus, their relationships and contacts to other rock units are hardly to detect. Megascopically, these rocks are yellowish brown to brownish on the weathered surface and greenish blue to bluish on the fresh surface. The GS samples can be grouped in amphibole rich - epidote poor (type I) and amphibole poor - epidote rich (types II) (Table 1). The amphiboles are different in composition (sodic to calcic) discernible under the polarizing microscope by zonal differences in colour and birefringence especially in sample 034/05 and 041/05 (Fig. 3 a,b).

Type I samples 033/05 and 034/05 are composed of amphibole (20-30 vol%), albitic feldspar (15-30 vol%, garin size 10-300  $\mu$ m), epidote (10-20 vol%, 10-200  $\mu$ m), chlorite (15-18 vol%), quartz (5-7 vol%, up to 0.5 mm), white mica (1-3 vol%), rutile (1-3 vol%) and opaques and other accessories (1-3 vol%). In addition, relict garnet (2-3 vol%) occurs in sample 034/05 forming originally grains as large as 4 mm but are widely decomposed to chlorite. Zoned amphibole is mainly glaucophane forming subhedral to euhedral grains up to 0.4 mm in size. Type II samples 035/05 and 041/05 contain subhedral prismatic to anhedral rounded grains of epidote (25-40 vol%, 5-400  $\mu$ m in size). Feldspar (10-25 vol%) and quartz (10-15 vol%) grains are as large as 0.4 mm. Blue amphiboles (7-15 vol%) are prismatic to needle-like up to 0.3 mm in size. Generally, most of the amphibole is transformed to chlorite (total content 10-15 vol%) at the boundary. Some amphiboles are completely replaced by chlorite. The latter phase developed together with epidote, albite and quartz the foliation of the rock. Garnet (2-3 vol %) occurs as relict grains up to 2 mm in diameter. This phase is surrounded by amphibole, epidote and chlorite.

Moreover, chlorite, epidote, white mica (2 vol%) are incorporated in quartz and feldspar. Rutile (1-3 vol%), opaques and accessories (1-2 vol%) are additional phases in the GS samples of type II. In general in the GS samples, rutile is subhedral prismatic to rounded and occasionally spindle shaped. Some intergrowths of rutile with epidote and blue amphibole with sizes ranging from 1-200  $\mu$ m were observed. Magnetite, ilmenite, apatite, titanite and zircon are the accessories in GS samples, in general.

On the basis of the complexity of the rock textures developed during different stages of metamorphic evolution, we propose at least three stages for the metamorphic history of Tawmaw area. The mineral assemblage of the early metamorphic stage (Stage I = earliest stage) in the studied samples comprises garnet (core) and inclusions in the garnet core, which are phengite, rutile, epidote and quartz. Stage II metamorphism is characterized by the garnet



(a)



(b)

Fig. 3 a-b: Compositional zoning of amphiboles (glaucophane) in glaucophane schists (034/05) and (041/05), Polarised Light.

compositons. Stage I, probably representing the peak metamorphism, is characterized by the assemblage of garnet, blue amphiboles, phengite and rutile. These minerals occur as porphyroblasts especially concerning garnet in the matrix. The matrix was formed by recrystallization after a deformation process. Thus, the matrix mineral phases of stage III (white micas, chlorite, epidote, rutile and plagioclase) are texturally different to those of stages I and II. However, the grain sizes of the matrix phases are not always clearly distinguishable from those of the porphyroblasts (stage I). During stage III, garnet and amphibole were partially replaced by chlorite.

#### 4. Mineral Chemistry

#### 4.1. Analytical procedure

The compositions of minerals in the above samples were analyses using a Cameca SX100 electron microprobe with five wavelength-dispersive spectrometers to determine the concentration of Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn, Fe and Ba. The applied accelerationvoltage and electric current were 15 kV and 15 nA, respectively. The beam diameter was generally about 6  $\mu$ m, but was reduced to 3  $\mu$ m to also analyze small-sized minerals.

The following standards have been used: albite (Na), diopside (Ca, Mg, Si), garnet (Al, Si), synthetic corundum (Al), orthoclase (K), synthetic rutile (Ti), synthetic  $Cr_2O_3$  (Cr), rhodonite (Mn), hematite (Fe) and barite (Ba). Counting time for full analyses were 20 s on peak and background of each element. The PAP correction procedure provided by Cameca was applied. Concentration maps for major elements were prepared by step-wise movement (100 or 200 ms counting time per step) of the thin section under the electron beam of the microprobe and subsequent computer aided evaluation and processing. The energy-dispersive system of the microprobe served as mean of identification of phases during the selection of spots for full analyses.

Monazite analyses for U-Th-Pb dating have been performed with 20 kV and 150 or 200 nA beam current, focused beam. The applied standards for REE and Y were either synthetic phosphates or glass (Jarosewish, 1991). For U, U glass or U metal have been used, and for Th, Th glass or ThO<sub>2</sub>. Lead was calibrated with PbTe and P with LaPO<sub>4</sub>. To detect tiny monazite grains, BSE electron images have been used. It turned out that monazite are always the brightest phases in the BSE images.

#### 4.2. Garnet

Typically, garnet in all samples is chemically zoned (Fig. 4 a-d). In general, there is an increase of Mg and decrease of Mn from core to rim. Garnet core (stage I) in GM sample 017, 018 and 019 are characterized by content of 5-6, 7-9 and 4.5-5-5 mol% pyrope, 26-24, 27-25 and 26-24 mol% grossular, 65-67, 61-62 and 57-61 mol% almandine and 4-3, 5-3 and 12-9 mol% spessartine respectively. Inner rim (stage II) of these garnet show 6-11, 11-14 and 6-9 mol% pyrope, 24-19, 24-22 and 24-23 mol% grossular, 67-69, 63-64 and 64-67 mol% almandine and 3-1, 2-1 and 6-1 mol% spessartine. The outermost rim (stage III) of GM garnet exhibit 11-27, 14-17 and 9-27 mol% pyrope, 19-9, 23-22 and 23-16 grossular, 69-63, 62-60 and 67-56 mol% almandine and 0.3-1, 1-0.7 and 1-0.84 mol% spessartine. Within a single sample, core and rim compositions of garnet can best be distinguished by using the Mn contents. Most of the GM garnets show clear prograde compositional zoning from core to rim, with bell-shaped Mn profile decreasing from the inner to the outer part (Fig. 5 a,b,c and d and 4 a, b and c). Ca contents also decrease. In sample 017, Almandine content is decrease from stage II to stage III (inner rim to outermost rim) than other GM samples.

ES sample (032/05) show garnets with 7-8 mol% pyrope, 25-24 mol% grossular, 58-56 mol% almandine and 10-12 mol% spessartine in core (stage I). Inner rim (stage II) composition of ES garnet is characterized by 8-9 mol% pyrope, 26-25 mol% grossular, 56-55 mol% almandine and 9-11 mol% spessartine. Outermost rim (stage III) composition of ES garnet is composed of 10-11 mol% pyrope, 26-25 mol% grossular, 58-59 mol% almandine and 6-4 mol% spessartine. Garnet from ES samples also exhibit decrease the spessartine content and increase of the pyrope component from core to rim with bell-shaped profile.

Composition of garnet cores (stage I) in GS sample 034/05, 035/05 and 041/05 shows content of 13-12 mol% pyrope, 19-22 mol% grossular, 60-55 mol% almandine and 7-10 mol% spessartine respectively. Inner rim (stage II) of GS garnets are characterized by 15-14 mol% pyrope, 22-23 mol% grossular, 57-55 mol% almandine and 6-8 mol% spessartine. Outermost rim composition of garnet contain 15-16 mol% pyrope, 20-22 mol% grossular, 62-56 mol% almandine and 3-6 mol% spessartine. Garnets from the GS samples also show prograde compositional zoning from core to rim with decreasing Mn content from core to rim and Mg behaving opposite. Grossular content in GS garnets is lower than GM and ES garnet. Representative analyses of garnet are given in Table 2.









Fig: 5 a-c: Chemical zoning profile of garnet (rim to rim) from garnet-mica schist (GM) samples obtained with the EMP. The zonation is characterized by decrease on spessartine component and increase of pyrope component from core to rim.

3

4

5

2

Distance in mm

(c)

0.0

1

#### 4.3. Amphibole

Analysed amphiboles comprise Na and Na-Ca amphiboles. Ca amphibole (actinolite) was found only in sample 033/05. The Fe<sup>2+</sup> and Fe<sup>3+</sup> contents of these amphiboles were estimated on the assumption that the sum of tetrahedrally and octahedrally coordinated cations (Si+Al+Ti+Cr+Fe+Mn+Mg) is equal to13 and that all cations have a charge of 46+ (equivalent to 23 oxygens) in total. Representative amphibole analyses are listed in Tables 3 and 4. The compositional variation of amphiboles in the studied rocks is plotted in Figure 6, according to the nomenclature of amphiboles by Leake *et al.* (1997), with Si per formula unit (pfu) versus  $X_{Mg}=Mg/(Fe^{2+}+Mg)$ .

Na amphiboles from GS samples 033/05, 034/05, 035/05 and 041/05 are mainly glaucophane which formed as late phase in the matrix. Excepting 033/05 such amphiboles also show magnesioriebeckite, ferroglaucophane to riebeckite compositions.

The Si contents of Na amphiboles from GS samples 033/05, 034/05, 035/05 and 041/05 range between 7.72-7.99 pfu.  $X_{Mg}$  can be highly variable in single samples such as in sample 033/05 with  $X_{Mg} = 0.39$ -0.76 (Tables 3-4 and Fig. 6). Na-Ca amphiboles vary in composition from richterite, magnesiokatophorite, ferrorichterite, winchite to ferrowinchite (Fig. 6 b). Si contents in these amphiboles range from 7.25 to 7.84.  $X_{Mg}$  is again variable with highest values in Na-Ca amphibole from sample GS 041/05 ( $X_{Mg} = 0.70$ -0.99). Actinolite in GS 033/05 shows an  $X_{Mg}$  and Si pfu of 0.70-0.74 and 7.50-7.75, respectively.

#### 4.4. Mica

In all studied samples, white micas are present as paragonite and potassic white mica (muscovite, phengite). Paragonite commonly coexists with potassic white mica bordering phengite (Fig. 7a and b). Moreover, there are two generations of potassic white mica: (1) as inclusion in garnet and (2) in the matrix oriented parallel to the foliation as coexisting paragonite (Fig. 8). Representative analyses of muscovite, phengite and paragonite are listed in Table 6a and b.  $Fe^{3+}$  contents were calculated by normalization of the mica structural formula to 12.1 cations pfu (based on 22 O)+ interlayer cations. This arbitrary selected value of 12.1 is based on the slightly elevated octahedral occupanies (ideal value: 4.00 pfu) in phengitic micas (see Massonne and Schreyer, 1986) which should be relevant to those coexisting with Fe-Mg-bearing minerals (biotite, chlorite, garnet). The Si and Na contents of phengite of GM samples show a nearly linear trend from 6.20 to 6.97 Si pfu (in 017) and 6.19

|                                |        | 017Ex1_08 |        |        | 018_08 |        |        | 019_08 |        |
|--------------------------------|--------|-----------|--------|--------|--------|--------|--------|--------|--------|
| х                              | Rim    | Core      | Rim    | Rim    | Core   | Rim    | Rim    | Core   | Rim    |
|                                | #122   | #134      | #144   | #69    | #82    | #98    | #1     | #13    | #46    |
| SiO <sub>2</sub>               | 37.34  | 36.64     | 37.67  | 36.70  | 36.19  | 36.31  | 36.88  | 36.67  | 37.33  |
| TiO <sub>2</sub>               | 0.03   | 0.12      | 0.05   | 0.08   | 0.18   | 0.13   | 0.01   | 0.11   | 0.06   |
| Al <sub>2</sub> O <sub>3</sub> | 22.27  | 21.44     | 22.31  | 22.04  | 21.48  | 21.73  | 22.20  | 21.32  | 21.83  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.02   | 0.03      | 0.03   | 0.01   | 0.03   | 0.04   | 0.02   | 0.03   | 0.01   |
| Fe <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00      | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.39   | 0.07   |
| FeO                            | 29.56  | 28.88     | 29.79  | 27.22  | 27.58  | 27.93  | 25.56  | 26.72  | 26.25  |
| MnO                            | 0.15   | 3.24      | 0.31   | 0.37   | 2.32   | 0.26   | 0.37   | 5.50   | 0.35   |
| MgO                            | 6.64   | 2.48      | 6.56   | 4.31   | 1.83   | 3.43   | 6.83   | 1.26   | 6.68   |
| CaO                            | 3.06   | 6.29      | 3.07   | 7.84   | 8.64   | 8.01   | 5.49   | 8.60   | 6.02   |
| Na <sub>2</sub> O              | 0.03   | 0.02      | 0.02   | 0.00   | 0.01   | 0.00   | 0.02   | 0.03   | 0.02   |
| Total                          | 99.10  | 99.14     | 99.79  | 98.58  | 98.27  | 97.84  | 97.39  | 100.62 | 98.60  |
|                                |        |           |        |        |        |        |        |        |        |
| Si                             | 5.8030 | 5.8463    | 5.8323 | 5.7447 | 5.8009 | 5.7712 | 5.7644 | 5.7667 | 5.7909 |
| Ті                             | 0.0037 | 0.0140    | 0.0062 | 0.0096 | 0.0213 | 0.0154 | 0.0016 | 0.0132 | 0.0066 |
| sum4                           | 5.8067 | 5.8604    | 5.8385 | 5.7543 | 5.8222 | 5.7866 | 5.7660 | 5.7799 | 5.7975 |
| AI                             | 4.0802 | 4.0325    | 4.0706 | 4.0663 | 4.0577 | 4.0703 | 4.0898 | 3.9511 | 3.9912 |
| Cr                             | 0.0020 | 0.0039    | 0.0034 | 0.0009 | 0.0039 | 0.0051 | 0.0020 | 0.0033 | 0.0011 |
| Fe <sup>3</sup>                | 0.0000 | 0.0000    | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0456 | 0.0078 |
| sum6                           | 4.0821 | 4.0364    | 4.0740 | 4.0672 | 4.0616 | 4.0754 | 4.0918 | 4.0000 | 4.0000 |
| Fe <sup>2</sup>                | 3.8417 | 3.8539    | 3.8577 | 3.5632 | 3.6968 | 3.7122 | 3.3406 | 3.5142 | 3.4050 |
| Mg                             | 1.5384 | 0.5909    | 1.5147 | 1.0048 | 0.4382 | 0.8129 | 1.5922 | 0.2963 | 1.5439 |
| Са                             | 0.5103 | 1.0752    | 0.5086 | 1.3151 | 1.4845 | 1.3649 | 0.9192 | 1.4488 | 1.0005 |
| Mn                             | 0.0194 | 0.4373    | 0.0401 | 0.0496 | 0.3143 | 0.0346 | 0.0496 | 0.7325 | 0.0458 |
| Na                             | 0.0081 | 0.0063    | 0.0049 | 0.0000 | 0.0046 | 0.0000 | 0.0065 | 0.0082 | 0.0049 |
| sum8                           | 5.9179 | 5.9636    | 5.9260 | 5.9328 | 5.9384 | 5.9246 | 5.9082 | 6.0000 | 6.0000 |
| components                     |        |           |        |        |        |        |        |        |        |
| grossular                      | 0.0862 | 0.1803    | 0.0858 | 0.2217 | 0.2500 | 0.2304 | 0.1556 | 0.2415 | 0.1667 |
| pyrope                         | 0.2600 | 0.0991    | 0.2556 | 0.1694 | 0.0738 | 0.1372 | 0.2695 | 0.0494 | 0.2573 |
| almandine                      | 0.6492 | 0.6462    | 0.6510 | 0.6006 | 0.6225 | 0.6266 | 0.5654 | 0.5857 | 0.5675 |
| spessartine                    | 0.0033 | 0.0733    | 0.0068 | 0.0084 | 0.0529 | 0.0058 | 0.0084 | 0.1221 | 0.0076 |
| xAl                            | 0.9995 | 0.9990    | 0.9992 | 0.9998 | 0.9990 | 0.9987 | 0.9995 | 0.9878 | 0.9978 |

Table 2. Representative analyses of garnet in GM.

|                                |         | ES      |         | GS     |        |        |        |        |        |  |  |  |  |
|--------------------------------|---------|---------|---------|--------|--------|--------|--------|--------|--------|--|--|--|--|
|                                |         | 032/05  |         |        | 034/05 |        |        | 035/05 |        |  |  |  |  |
| х                              | Rim     | Core    | Rim     | Rim    | Core   | Rim    | Rim    | Core   | Rim    |  |  |  |  |
|                                | #33     | #40     | #49     | #15    | #60    | #31    | #1     | #14    | #25    |  |  |  |  |
| SiO <sub>2</sub>               | 39.2055 | 36.8030 | 37.2052 | 36.76  | 36.95  | 36.51  | 37.35  | 37.53  | 36.68  |  |  |  |  |
| TiO <sub>2</sub>               | 0.0434  | 0.1051  | 0.0133  | 0.14   | 0.16   | 0.08   | 0.08   | 0.21   | 0.09   |  |  |  |  |
| Al <sub>2</sub> O <sub>3</sub> | 20.1228 | 20.5196 | 20.7803 | 20.53  | 20.47  | 20.5   | 21.93  | 21.48  | 21.61  |  |  |  |  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.0015  | 0.0058  | 0.0000  | 0.0100 | 0.0000 | 0.0100 | 0.0000 | 0.0100 | 0.0000 |  |  |  |  |
| Fe <sub>2</sub> O <sub>3</sub> | 0.9711  | 0.9552  | 0.8558  | 1.0100 | 1.1100 | 0.98   | 0.0000 | 0.19   | 0.05   |  |  |  |  |
| FeO                            | 25.8324 | 25.5289 | 26.9691 | 28.93  | 25.22  | 28.87  | 24.46  | 25.18  | 25.71  |  |  |  |  |
| MnO                            | 3.1428  | 4.2378  | 2.3733  | 1.6    | 5.24   | 1.56   | 2.49   | 4.73   | 3.27   |  |  |  |  |
| MgO                            | 2.6151  | 2.2254  | 2.8357  | 2.56   | 2.07   | 2.53   | 3.55   | 3.46   | 3.86   |  |  |  |  |
| CaO                            | 7.9237  | 8.4190  | 8.2511  | 7.43   | 8.01   | 7.5    | 9.91   | 7.39   | 7.62   |  |  |  |  |
| Na <sub>2</sub> O              | 0.0094  | 0.0431  | 0.0364  | 0.06   | 0.13   | 0.04   | 0.07   | 0.03   | 0.04   |  |  |  |  |
| Total                          | 99.8676 | 98.8430 | 99.3203 | 99.03  | 99.38  | 98.58  | 99.84  | 100.2  | 98.93  |  |  |  |  |
|                                |         |         |         |        |        |        |        |        |        |  |  |  |  |
| Si                             | 6.4145  | 5.9104  | 5.9208  | 5.8901 | 5.9195 | 5.8643 | 5.7951 | 5.8948 | 5.7513 |  |  |  |  |
| Ti                             | 0.0053  | 0.0127  | 0.0016  | 0.0165 | 0.0193 | 0.0097 | 0.0088 | 0.0248 | 0.0108 |  |  |  |  |
| sum4                           | 6.4198  | 5.9231  | 5.9224  | 5.9066 | 5.9388 | 5.874  | 5.8039 | 5.9196 | 5.7621 |  |  |  |  |
| AI                             | 3.8803  | 3.8838  | 3.8975  | 3.8764 | 3.8653 | 3.8804 | 4.0101 | 3.9769 | 3.9938 |  |  |  |  |
| Cr                             | 0.0002  | 0.0007  | 0.0000  | 0.0019 | 0.0004 | 0.0011 | 0.0000 | 0.0007 | 0.0005 |  |  |  |  |
| Fe <sup>3</sup>                | 0.1196  | 0.1154  | 0.1025  | 0.1218 | 0.1344 | 0.1185 | 0.0000 | 0.0223 | 0.0057 |  |  |  |  |
| sum6                           | 4.0000  | 4.0000  | 4.0000  | 4.0000 | 4.0000 | 4.0000 | 4.0101 | 4.0000 | 4.0000 |  |  |  |  |
| Fe <sup>2</sup>                | 3.5346  | 3.4287  | 3.5892  | 3.8766 | 3.3785 | 3.8785 | 3.1732 | 3.3077 | 3.371  |  |  |  |  |
| Mg                             | 0.6378  | 0.5328  | 0.6727  | 0.6124 | 0.4946 | 0.6056 | 0.8215 | 0.8097 | 0.9032 |  |  |  |  |
| Са                             | 1.3891  | 1.4487  | 1.4069  | 1.2751 | 1.3746 | 1.2915 | 1.6481 | 1.2441 | 1.281  |  |  |  |  |
| Mn                             | 0.4355  | 0.5765  | 0.3199  | 0.2171 | 0.7113 | 0.2119 | 0.3271 | 0.6295 | 0.4337 |  |  |  |  |
| Na                             | 0.0030  | 0.0134  | 0.0112  | 0.0188 | 0.041  | 0.0126 | 0.0199 | 0.009  | 0.0111 |  |  |  |  |
| sum8                           | 6.0000  | 6.0000  | 6.0000  | 6.0000 | 6.0000 | 6.0000 | 5.9899 | 6.0000 | 6.0000 |  |  |  |  |
| components                     |         |         |         |        |        |        |        |        |        |  |  |  |  |
| grossular                      | 0.2315  | 0.2414  | 0.2345  | 0.2125 | 0.2291 | 0.2152 | 0.2752 | 0.2074 | 0.2135 |  |  |  |  |
| pyrope                         | 0.1063  | 0.0888  | 0.1121  | 0.1021 | 0.0824 | 0.1009 | 0.1372 | 0.1349 | 0.1505 |  |  |  |  |
| almandine                      | 0.5891  | 0.5714  | 0.5982  | 0.6461 | 0.5631 | 0.6464 | 0.5298 | 0.5513 | 0.5618 |  |  |  |  |
| spessartine                    | 0.0726  | 0.0961  | 0.0533  | 0.0362 | 0.1185 | 0.0353 | 0.0546 | 0.1049 | 0.0723 |  |  |  |  |
| xAl                            | 0.9701  | 0.9710  | 0.9744  | 0.9691 | 0.9663 | 0.9701 | 1.0000 | 0.9942 | 0.9984 |  |  |  |  |

Table 2. (Continued) Representative Analyses of Garnet in ES and GS.

| ×                                |                 | #03305              |               |                  |                            |                 | #03405                 |               |                |                     |                  | #03505        |                          |
|----------------------------------|-----------------|---------------------|---------------|------------------|----------------------------|-----------------|------------------------|---------------|----------------|---------------------|------------------|---------------|--------------------------|
| Х                                | #32             | #35                 | #42           | #50              | #78                        | #35             | #41                    | #44           | #2             | #19                 | #27              | #28           | #40                      |
| SiO <sub>2</sub>                 | 53.31           | 49.84               | 50.62         | 56.17            | 56.29                      | 54.15           | 54.17                  | 51.80         | 50.91          | 50.44               | 56.56            | 51.93         | 51.29                    |
| TiO <sub>2</sub>                 | 0.01            | 0.06                | 0.01          | 0.01             | 0.05                       | 0.03            | 0.04                   | 0.04          | 0.08           | 0.14                | 0.06             | 0.06          | 0.09                     |
| $AI_2O_3$                        | 1.78            | 4.95                | 3.11          | 9.16             | 10.40                      | 3.99            | 3.47                   | 4.24          | 5.30           | 4.72                | 9.61             | 4.10          | 4.22                     |
| Cr <sub>2</sub> O <sub>3</sub>   | 0.01            | 0.02                | 0.00          | 0.01             | 0.00                       | 0.01            | 0.00                   | 0.01          | 0.01           | 0.02                | 0.01             | 0.01          | 0.00                     |
| Fe <sub>2</sub> O <sub>3</sub> * | 4.61            | 9.76                | 7.26          | 4.30             | 2.19                       | 11.20           | 12.15                  | 10.60         | 9.47           | 9.38                | 4.15             | 7.48          | 7.21                     |
| FeO*                             | 9.46            | 9.67                | 10.37         | 12.76            | 13.14                      | 13.27           | 12.37                  | 11.14         | 12.50          | 11.87               | 7.93             | 9.08          | 9.38                     |
| MnO                              | 0.43            | 0.44                | 0.31          | 0.13             | 0.26                       | 0.23            | 0.23                   | 0.46          | 0.36           | 0.41                | 0.17             | 0.39          | 0.43                     |
| MgO                              | 14.92           | 11.17               | 12.77         | 7.43             | 7.24                       | 6.87            | 7.57                   | 9.80          | 8.92           | 10.02               | 10.45            | 13.06         | 12.78                    |
| CaO                              | 10.42           | 6.87                | 9.06          | 0.57             | 0.15                       | 0.77            | 1.46                   | 5.56          | 5.07           | 6.92                | 1.15             | 8.78          | 8.68                     |
| BaO                              | 0.00            | 0.00                | 0.00          | 0.00             | 0.00                       | 0.00            | 0.00                   | 0.00          | 0.00           | 0.02                | 0.00             | 0.00          | 0.00                     |
| Na <sub>2</sub> O                | 1.49            | 3.97                | 2.53          | 7.22             | 7.74                       | 6.99            | 6.45                   | 4.32          | 4.94           | 3.69                | 6.98             | 2.49          | 2.63                     |
| K <sub>2</sub> O                 | 0.10            | 0.23                | 0.20          | 0.04             | 0.01                       | 0.02            | 0.05                   | 0.15          | 0.20           | 0.20                | 0.05             | 0.12          | 0.13                     |
| H <sub>2</sub> O*                | 2.06            | 2.03                | 2.02          | 2.12             | 2.13                       | 2.05            | 2.06                   | 2.06          | 2.04           | 2.04                | 2.15             | 2.07          | 2.05                     |
| Σ                                | 98.59           | 99.01               | 98.27         | 99.91            | 99.59                      | 99.57           | 100.02                 | 100.15        | 99.80          | 99.86               | 99.27            | 99.55         | 98.89                    |
| Si                               | 7.75            | 7.35                | 7.50          | 7.93             | 7.93                       | 7.92            | 7.89                   | 7.56          | 7.49           | 7.42                | 7.87             | 7.52          | 7.49                     |
| Alt                              | 0.25            | 0.65                | 0.50          | 0.07             | 0.07                       | 0.08            | 0.11                   | 0.44          | 0.51           | 0.58                | 0.13             | 0.48          | 0.51                     |
| ΣΤ                               | 8.0000          | 8.0000              | 8.0000        | 8.0000           | 8.0000                     | 8.0000          | 8.0000                 | 8.0000        | 8.0000         | 8.0000              | 8.0000           | 8.0000        | 8.0000                   |
| Alo                              | 0.0561          | 0.2066              | 0.0435        | 1.4545           | 1.6616                     | 0.6111          | 0.4852                 | 0.2849        | 0.4049         | 0.2361              | 1.4473           | 0.2142        | 0.2164                   |
| Fe <sup>3+</sup>                 | 0.5039          | 1.0825              | 0.8096        | 0.4569           | 0.2319                     | 1.2335          | 1.3313                 | 1.1631        | 1.0478         | 1.0379              | 0.4341           | 0.8144        | 0.7926                   |
| Cr                               | 0.0007          | 0.0021              | 0.0001        | 0.0013           | 0.0000                     | 0.0008          | 0.0001                 | 0.0008        | 0.0014         | 0.0023              | 0.0010           | 0.0007        | 0.0000                   |
| Ti                               | 0.0011          | 0.0069              | 0.0011        | 0.0011           | 0.0051                     | 0.0030          | 0.0041                 | 0.0044        | 0.0085         | 0.0157              | 0.0061           | 0.0068        | 0.0093                   |
| Mg                               | 3.2351          | 2.4547              | 2.8217        | 1.5640           | 1.5218                     | 1.4992          | 1.6441                 | 2.1312        | 1.9549         | 2.1968              | 2.1688           | 2.8178        | 2.7830                   |
| Fe <sup>2+</sup>                 | 1.1498          | 1.1928              | 1.2856        | 1.5068           | 1.5490                     | 1.6243          | 1.5069                 | 1.3593        | 1.5374         | 1.4604              | 0.9227           | 1.0987        | 1.1458                   |
| Mn                               | 0.0533          | 0.0544              | 0.0384        | 0.0153           | 0.0306                     | 0.0281          | 0.0282                 | 0.0563        | 0.0451         | 0.0508              | 0.0200           | 0.0474        | 0.0528                   |
| Σ <b>M</b> 1-3                   | 5.0000          | 5.0000              | 5.0000        | 5.0000           | 5.0000                     | 5.0000          | 5.0000                 | 5.0000        | 5.0000         | 5.0000              | 5.0000           | 5.0000        | 5.0000                   |
| Mn <sub>M4</sub>                 | 0.0000          | 0.0000              | 0.0000        | 0.0000           | 0.0000                     | 0.0000          | 0.0000                 | 0.0000        | 0.0000         | 0.0000              | 0.0000           | 0.0000        | 0.0000                   |
| Fe <sub>M4</sub>                 | 0.0000          | 0.0000              | 0.0000        | 0.0000           | 0.0000                     | 0.0000          | 0.0000                 | 0.0000        | 0.0000         | 0.0000              | 0.0000           | 0.0000        | 0.0000                   |
| Ca                               | 1.6235          | 1.0856              | 1.4388        | 0.0858           | 0.0228                     | 0.1202          | 0.2274                 | 0.8694        | 0.7986         | 1.0910              | 0.1715           | 1.3610        | 1.3574                   |
| Na <sub>M4</sub>                 | 0.3765          | 0.9144              | 0.5612        | 1.9142           | 1.9772                     | 1.8798          | 1.7726                 | 1.1306        | 1.2014         | 0.9090              | 1.8285           | 0.6390        | 0.6426                   |
| $\Sigma M_4$                     | 2.0000          | 2.0000              | 2.0000        | 2.0000           | 2.0000                     | 2.0000          | 2.0000                 | 2.0000        | 2.0000         | 2.0000              | 2.0000           | 2.0000        | 2.0000                   |
| Na <sub>A</sub>                  | 0.0441          | 0.2192              | 0.1666        | 0.0626           | 0.1370                     | 0.1020          | 0.0495                 | 0.0901        | 0.2059         | 0.1436              | 0.0552           | 0.0589        | 0.1011                   |
| К                                | 0.0178          | 0.0431              | 0.0382        | 0.0065           | 0.0025                     | 0.0034          | 0.0085                 | 0.0270        | 0.0383         | 0.0372              | 0.0080           | 0.0214        | 0.0240                   |
| Ва                               | 0.0000          | 0.0001              | 0.0000        | 0.0000           | 0.0000                     | 0.0000          | 0.0000                 | 0.0000        | 0.0000         | 0.0010              | 0.0000           | 0.0001        | 0.0001                   |
| ΣΑ                               | 0.0619          | 0.2623              | 0.2048        | 0.0691           | 0.1395                     | 0.1054          | 0.0581                 | 0.1171        | 0.2442         | 0.1817              | 0.0632           | 0.0804        | 0.1252                   |
| ОН                               | 2.0000          | 2.0000              | 2.0000        | 2.0000           | 2.0000                     | 2.0000          | 2.0000                 | 2.0000        | 2.0000         | 2.0000              | 2.0000           | 2.0000        | 2.0000                   |
|                                  | Actino-<br>lite | Ferri-<br>barrosite | Win-<br>chite | Glauco-<br>phane | Ferro-<br>Glauco-<br>phane | Riebe-<br>ckite | Magnesio<br>riebeckite | Win-<br>chite | Barro-<br>site | Ferri-<br>barrosite | Glauco-<br>phane | Win-<br>chite | Ferri-<br>barro-<br>site |

Table 3. Representative analyses of amphiboles in (GS)(033/05, 034/05 and 035/05).

| Х                                | #16         | #29                     | #144     | #27            | #167       | #168                     |
|----------------------------------|-------------|-------------------------|----------|----------------|------------|--------------------------|
| SiO <sub>2</sub>                 | 56.88       | 55.84                   | 52.31    | 51.14          | 56.34      | 52.33                    |
| TiO <sub>2</sub>                 | 0.01        | 0.02                    | 0.08     | 0.07           | 0.24       | 0.12                     |
| Al <sub>2</sub> O <sub>3</sub>   | 9.52        | 3.39                    | 4.05     | 4.61           | 3.04       | 6.08                     |
| Cr <sub>2</sub> O <sub>3</sub>   | 0.02        | 0.01                    | 0.00     | 0.01           | 0.02       | 0.01                     |
| Fe <sub>2</sub> O <sub>3</sub> * | 7.02        | 11.87                   | 8.84     | 9.24           | 2.16       | 2.06                     |
| FeO*                             | 7.08        | 7.87                    | 7.91     | 8.40           | 0.57       | 0.85                     |
| MnO                              | 0.11        | 0.15                    | 0.36     | 0.28           | 0.18       | 0.11                     |
| MgO                              | 10.08       | 10.63                   | 13.05    | 12.78          | 20.91      | 20.95                    |
| ZnO                              | 0.28        | 0.12                    | 0.28     | 0.16           | 0.00       | 0.11                     |
| CaO                              | 0.59        | 1.67                    | 7.55     | 8.39           | 3.72       | 8.67                     |
| BaO                              | 0.00        | 0.00                    | 0.00     | 0.00           | 0.00       | 0.00                     |
| Na <sub>2</sub> O                | 7.23        | 6.40                    | 3.39     | 2.84           | 8.91       | 5.66                     |
| K <sub>2</sub> O                 | 0.02        | 0.01                    | 0.11     | 0.17           | 0.32       | 0.27                     |
| H <sub>2</sub> O*                | 2.18        | 2.11                    | 2.08     | 2.08           | 2.16       | 2.15                     |
| Σ                                | 101.02      | 100.08                  | 100.01   | 100.16         | 98.56      | 99.35                    |
| Si                               | 7.8129      | 7.9403                  | 7.5242   | 7.3866         | 7.8298     | 7.2958                   |
| Alt                              | 0.1871      | 0.0597                  | 0.4758   | 0.6134         | 0.1702     | 0.7042                   |
| Fe <sup>3+</sup>                 | 0.0000      | 0.0000                  | 0.0000   | 0.0000         | 0.0000     | 0.0000                   |
| ΣΤ                               | 8.0000      | 8.0000                  | 8.0000   | 8.0000         | 8.0000     | 8.0000                   |
| Al <sub>o</sub>                  | 1.3535      | 0.5087                  | 0.2112   | 0.1704         | 0.3280     | 0.2952                   |
| Fe <sup>3+</sup>                 | 0.7260      | 1.2704                  | 0.9564   | 1.0042         | 0.2261     | 0.2157                   |
| Cr                               | 0.0020      | 0.0007                  | 0.0000   | 0.0010         | 0.0020     | 0.0010                   |
| Ti                               | 0.0010      | 0.0025                  | 0.0081   | 0.0071         | 0.0248     | 0.0121                   |
| Zn                               | 0.0279      | 0.0123                  | 0.0302   | 0.0168         | 0.0000     | 0.0110                   |
| Mg                               | 2.0637      | 2.2523                  | 2.7983   | 2.7512         | 4.3319     | 4.3537                   |
| Fe <sup>2+</sup>                 | 0.8128      | 0.9357                  | 0.9521   | 1.0145         | 0.0659     | 0.0988                   |
| Mn                               | 0.0133      | 0.0175                  | 0.0437   | 0.0347         | 0.0213     | 0.0125                   |
| Σ <b>Μ</b> <sub>1-3</sub>        | 5.0000      | 5.0000                  | 5.0000   | 5.0000         | 5.0000     | 5.0000                   |
| Mg <sub>M4</sub>                 | 0.0000      | 0.0000                  | 0.0000   | 0.0000         | 0.0000     | 0.0000                   |
| Mn <sub>M4</sub>                 | 0.0000      | 0.0000                  | 0.0000   | 0.0000         | 0.0000     | 0.0000                   |
| Fe <sub>M4</sub>                 | 0.0000      | 0.0000                  | 0.0000   | 0.0000         | 0.0000     | 0.0000                   |
| Са                               | 0.0867      | 0.2546                  | 1.1630   | 1.2980         | 0.5542     | 1.2950                   |
| Na <sub>M4</sub>                 | 1.9133      | 1.7454                  | 0.8370   | 0.7020         | 1.4458     | 0.7050                   |
| $\Sigma M_4$                     | 2.0000      | 2.0000                  | 2.0000   | 2.0000         | 2.0000     | 2.0000                   |
| Na <sub>A</sub>                  | 0.0131      | 0.0189                  | 0.1086   | 0.0941         | 0.9538     | 0.8252                   |
| К                                | 0.0039      | 0.0015                  | 0.0204   | 0.0315         | 0.0566     | 0.0480                   |
| Ва                               | 0.0000      | 0.0000                  | 0.0000   | 0.0000         | 0.0000     | 0.0000                   |
| ΣΑ                               | 0.0169      | 0.0204                  | 0.1290   | 0.1256         | 1.0103     | 0.8732                   |
| OH                               | 2.0000      | 2.0000                  | 2.0000   | 2.0000         | 2.0000     | 2.0000                   |
|                                  | Glaucophane | Magnesio-<br>riebeckite | Winchite | Ferribarrosite | Richterite | Magnesio-<br>katophorite |

Table 4. Representative analyses of amphiboles in GS (041/05).



to 7.03 Si pfu in (019) and  $X_{Na}$  = (Na/(Na+K)) from 0.01 to 0.24 (in 017) and 0.01 to 0.23 (in 019)( Table 5a and Fig. 9 a-d).

Phengites in GS and ES samples lack strong compositional zoning but show the following compositional ranges: Si pfu = 6.17-6.76 in sample 030/05 and 6.34-6.86 in samples 034/05 and 041/05;  $X_{Na} = 0.01$  to 0.15 in ES samples and 0.02 to 0.12 in GS samples (Table 5b and Fig. 9 e-h). The total Al contents in phengite of all samples (GM, ES and GS) show a good negative correlation with increasing Si contents due to Tschermak's substitution, but  $X_{Fe}$  ( $X_{Fe}$ =Fe<sup>2+</sup>/(Mg+Fe<sup>2+</sup>)) does not show a simple linear correlation except in sample 019 and 034/05 where a positive linear correlation of increasing  $X_{Fe}$  with increasing Si contents is discernible (Fig. 9 d and h). Highest  $X_{Fe}$  in phengite could be noted for GM samples. Lowest  $X_{Fe}$  values were found in phengite of GS samples. The Si and Na contents of paragonite in GM and ES samples range between 5.91-6.03 and 1.61-1.70 and 5.99-6-01 and 1.80-1.91 pfu, respectively (Table 5 a,b).

#### 4.5. Other minerals

Analyses of epidote from the studied samples were plotted in Figures 10 a-f. Representative epidote analyses are given in Table 6. Iron was assumed to be  $Fe^{3+}$ . The clinozoisite/zoisite component in terms of Al# = (100·Al/(Fe<sup>3+</sup>+Al)) in epidote of GM, ES and GS samples ranges between 86-100, 70-80 and 63-87, respectively. Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> relation in GM, ES and GS samples show clear negative correlations.

Rutile is virtually a pure phase and ilmenite occurs with minor amount of pyrophanite component.

The compositions of chlorite are variable depending on the rock type (Table 7). Chlorite in GS samples is generally somewhat more magnesian ( $X_{Mg}$ = 0.44-0.61) than chlorite in ES ( $X_{Mg}$  = 0.48-0.57). Chlorite in GM samples shows a wider compositional range ( $X_{Mg}$ =0.26-0.72) than those in ES and GS samples.

Plagioclase in all studied samples is albite ( $Ab_{99}$  to  $Ab_{100}$  in GS and ES). Only in GM samples oligoclase compositions were also found ( $Ab_{84}$  to  $Ab_{100}$  in GM, see Table 7).

#### 4.6. Monazite

Monazite occurred exclusively in garnet mica schists but was often not large enough to be analyzed because most grains are smaller than 1  $\mu$ m in diameter. In addition, monazite in sample 019 is intergrown with other REE-rich minerals such as thorite forming sponge-like aggregates. These features additionally complicated the analysis. More than 400 grains of



(a)



(b)

Fig. 7 a-b: Element distribution maps for K in potassic white mica (sample 017, garnetmica schist). K-rich outermost zone is phengite whereas inner portion is relatively Na-rich muscovite.



Fig. 8: BSE image showing the replacement of muscovite by paragonite and phengite (Sample 019, garnet-mica schist).

Table 5a. Representative analyses of Muscovite, Phengite and Paragonite in GM.

|                                |        |        |        | Muscovit | e-Phengi | te     |        |        |        | Paragonite |        |        |  |
|--------------------------------|--------|--------|--------|----------|----------|--------|--------|--------|--------|------------|--------|--------|--|
| x                              | 017    | 017    | 017    | #017     | 019      | 019    | 019    | 019-   | 017    | 019        | 019    | 017    |  |
| ~                              | Ex6    | ext    | Exa    | #011     | Ex2      | Ex2    | Ex2    | Phe    | Ex2    | Ex1        | Ex1    | Ex1a   |  |
|                                | #6     | #11    | #43    | #56      | #53      | #138   | #137   | #110   | #89    | #47        | #72    | #38    |  |
| SiO <sub>2</sub>               | 45.90  | 46.79  | 53.49  | 52.43    | 53.67    | 45.99  | 46.35  | 49.57  | 45.69  | 47.07      | 47.20  | 46.75  |  |
| TiO <sub>2</sub>               | 0.86   | 1.19   | 0.35   | 0.07     | 0.10     | 0.85   | 0.88   | 0.17   | 0.14   | 0.17       | 0.02   | 0.08   |  |
| Al <sub>2</sub> O <sub>3</sub> | 34.25  | 33.69  | 23.49  | 27.49    | 25.32    | 33.35  | 33.55  | 23.67  | 37.82  | 39.49      | 38.99  | 40.74  |  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00   | 0.05   | 0.00   | 0.00     | 0.00     | 0.02   | 0.01   | 0.02   | 0.01   | 0.00       | 0.00   | 0.00   |  |
| FeO                            | 1.03   | 1.24   | 1.74   | 2.83     | 2.76     | 1.04   | 0.96   | 4.11   | 0.61   | 0.24       | 0.66   | 0.34   |  |
| Fe <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00   | 1.74   | 0.00     | 0.00     | 0.00   | 0.00   | 3.20   | 0.00   | 0.00       | 0.00   | 0.00   |  |
| MnO                            | 0.01   | 0.02   | 0.00   | 0.02     | 0.00     | 0.00   | 0.02   | 0.05   | 0.02   | 0.00       | 0.03   | 0.00   |  |
| MgO                            | 1.72   | 1.66   | 5.78   | 2.94     | 3.90     | 1.94   | 1.85   | 3.16   | 0.11   | 0.15       | 0.27   | 0.16   |  |
| CaO                            | 0.02   | 0.00   | 0.04   | 0.00     | 0.01     | 0.03   | 0.01   | 0.03   | 0.57   | 0.43       | 0.38   | 0.87   |  |
| Na <sub>2</sub> O              | 1.72   | 1.88   | 0.17   | 0.10     | 0.18     | 1.58   | 1.75   | 0.08   | 6.30   | 7.16       | 6.80   | 6.94   |  |
| K2O                            | 9.13   | 9.03   | 10.37  | 10.35    | 10.50    | 9.09   | 9.02   | 10.83  | 1.01   | 0.93       | 1.24   | 0.66   |  |
| BaO                            | 0.17   | 0.18   | 0.01   | 0.00     | 0.02     | 0.23   | 0.19   | 0.00   | 0.00   | 0.01       | 0.00   | 0.00   |  |
| H <sub>2</sub> O               | 4.49   | 4.53   | 4.60   | 4.58     | 4.58     | 4.45   | 4.48   | 4.37   | 4.54   | 4.70       | 4.69   | 4.74   |  |
| Total                          | 99.31  | 100.26 | 101.79 | 100.79   | 101.03   | 98.56  | 99.06  | 99.25  | 96.82  | 100.34     | 100.27 | 101.28 |  |
| Total_corr.                    | 99.31  | 100.26 | 101.79 | 100.79   | 101.03   | 98.56  | 99.06  | 99.25  | 96.82  | 100.34     | 100.27 | 101.28 |  |
|                                |        |        |        |          |          |        |        |        |        |            |        |        |  |
| Si                             | 6.1359 | 6.1978 | 6.9731 | 6.8675   | 7.0280   | 6.1911 | 6.2025 | 6.8011 | 6.0289 | 6.0046     | 6.0314 | 5.9082 |  |
| AI_T                           | 1.8641 | 1.8022 | 1.0269 | 1.1325   | 0.9720   | 1.8089 | 1.7975 | 1.1989 | 1.9711 | 1.9954     | 1.9686 | 2.0918 |  |
| sum4                           | 8.0000 | 8.0000 | 8.0000 | 8.0000   | 8.0000   | 8.0000 | 8.0000 | 8.0000 | 8.0000 | 8.0000     | 8.0000 | 8.0000 |  |
| AI_O                           | 3.5317 | 3.4577 | 2.5813 | 3.1113   | 2.9356   | 3.4831 | 3.4938 | 2.6275 | 3.9099 | 3.9409     | 3.9043 | 3.9767 |  |
| Ti                             | 0.0869 | 0.1190 | 0.0342 | 0.0067   | 0.0099   | 0.0858 | 0.0887 | 0.0177 | 0.0139 | 0.0162     | 0.0016 | 0.0073 |  |
| Cr                             | 0.0003 | 0.0054 | 0.0000 | 0.0000   | 0.0000   | 0.0019 | 0.0011 | 0.0019 | 0.0008 | 0.0000     | 0.0000 | 0.0000 |  |
| Fe <sup>2</sup>                | 0.1156 | 0.1375 | 0.1893 | 0.3095   | 0.3018   | 0.1169 | 0.1078 | 0.4716 | 0.0670 | 0.0257     | 0.0701 | 0.0364 |  |
| Fe <sup>3</sup>                | 0.0000 | 0.0000 | 0.1709 | 0.0000   | 0.0000   | 0.0000 | 0.0000 | 0.3299 | 0.0000 | 0.0000     | 0.0000 | 0.0000 |  |
| Mn                             | 0.0009 | 0.0022 | 0.0004 | 0.0019   | 0.0000   | 0.0000 | 0.0020 | 0.0060 | 0.0026 | 0.0003     | 0.0034 | 0.0001 |  |
| Mg                             | 0.3437 | 0.3288 | 1.1240 | 0.5745   | 0.7611   | 0.3884 | 0.3692 | 0.6454 | 0.0222 | 0.0281     | 0.0512 | 0.0297 |  |
| sum6                           | 4.0792 | 4.0506 | 4.1000 | 4.0038   | 4.0083   | 4.0761 | 4.0626 | 4.1000 | 4.0163 | 4.0111     | 4.0306 | 4.0503 |  |
| Са                             | 0.0030 | 0.0000 | 0.0057 | 0.0000   | 0.0020   | 0.0044 | 0.0008 | 0.0041 | 0.0805 | 0.0583     | 0.0519 | 0.1175 |  |
| Ва                             | 0.0091 | 0.0093 | 0.0007 | 0.0000   | 0.0011   | 0.0119 | 0.0098 | 0.0000 | 0.0000 | 0.0006     | 0.0000 | 0.0000 |  |
| Na                             | 0.4469 | 0.4819 | 0.0426 | 0.0250   | 0.0448   | 0.4131 | 0.4547 | 0.0204 | 1.6125 | 1.7696     | 1.6840 | 1.7015 |  |
| К                              | 1.5564 | 1.5260 | 1.7252 | 1.7290   | 1.7536   | 1.5615 | 1.5395 | 1.8959 | 0.1693 | 0.1506     | 0.2025 | 0.1057 |  |
| sum8                           | 2.0154 | 2.0171 | 1.7741 | 1.7540   | 1.8015   | 1.9909 | 2.0048 | 1.9205 | 1.8623 | 1.9791     | 1.9384 | 1.9246 |  |
| н                              | 4.0000 | 4.0000 | 4.0000 | 4.0000   | 4.0000   | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000     | 4.0000 | 4.0000 |  |
| Components                     |        |        |        |          |          |        |        |        |        |            |        |        |  |
| MUSCOVITE                      | 0.6152 | 0.5669 | 0.3724 | 0.5467   | 0.4486   | 0.5991 | 0.5855 | 0.4427 | 0.0179 | 0.0304     | 0.0459 | 0.0110 |  |
| WM PHLOGOPITE                  | 0.0396 | 0.0253 | 0.0500 | 0.0019   | 0.0042   | 0.0381 | 0.0313 | 0.0500 | 0.0082 | 0.0055     | 0.0153 | 0.0251 |  |
| AL CELADONITE                  | 0.0553 | 0.0730 | 0.4195 | 0.2819   | 0.3693   | 0.0798 | 0.0824 | 0.2327 | 0.0143 | 0.0167     | 0.0179 | 0.0068 |  |
| FE AL CELADONITE               | 0.0186 | 0.0305 | 0.0706 | 0.1519   | 0.1464   | 0.0240 | 0.0241 | 0.1700 | 0.0433 | 0.0153     | 0.0246 | 0.0083 |  |
| PARAGONITE                     | 0.2217 | 0.2389 | 0.0240 | 0.0142   | 0.0249   | 0.2075 | 0.2268 | 0.0106 | 0.8659 | 0.8941     | 0.8688 | 0.8841 |  |
| TI MN CA WM                    | 0.0495 | 0.0654 | 0.0634 | 0.0034   | 0.0066   | 0.0516 | 0.0499 | 0.0940 | 0.0504 | 0.0379     | 0.0276 | 0.0647 |  |
| ХОН                            | 1.0000 | 1.0000 | 1.0000 | 1.0000   | 1.0000   | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000     | 1.0000 | 1.0000 |  |
| TI_MN_CA_WM<br>XOH             | 0.0495 | 0.0654 | 0.0634 | 0.0034   | 0.0066   | 0.0516 | 0.0499 | 0.0940 | 0.0504 | 0.0379     | 0.0276 | 0.0647 |  |

|                                |        |        |        | Phengite | Э      |        |        |        | Paragonite |        |
|--------------------------------|--------|--------|--------|----------|--------|--------|--------|--------|------------|--------|
|                                | ES     |        |        |          | GS     |        |        |        | E          | S      |
| Х                              | #03005 | #3405  | #03405 | #03405   | 04105  | 04105  | 04105  | 04105  | 03005a     | 03005a |
|                                | #4     | #96    | #38    | #42      | #10    | #48    | #49    | #50    | #172       | #177   |
| SiO <sub>2</sub>               | 49.45  | 51.40  | 49.07  | 49.23    | 49.51  | 45.91  | 46.81  | 46.80  | 47.06      | 46.11  |
| TiO <sub>2</sub>               | 0.08   | 0.17   | 0.08   | 0.11     | 0.17   | 0.07   | 0.07   | 0.05   | 0.11       | 0.11   |
| Al <sub>2</sub> O <sub>3</sub> | 26.90  | 24.79  | 26.76  | 26.23    | 24.06  | 30.08  | 29.79  | 29.39  | 38.34      | 38.50  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00   | 0.00   | 0.01     | 0.00   | 0.01   | 0.01   | 0.00   | 0.00       | 0.00   |
| FeO                            | 3.39   | 5.05   | 4.48   | 3.89     | 3.23   | 2.01   | 2.56   | 2.42   | 1.10       | 1.09   |
| Fe <sub>2</sub> O <sub>3</sub> | 0.00   | 1.24   | 0.00   | 1.00     | 3.11   | 1.78   | 1.26   | 1.46   | 0.00       | 0.00   |
| MnO                            | 0.00   | 0.05   | 0.01   | 0.03     | 0.02   | 0.03   | 0.03   | 0.01   | 0.00       | 0.00   |
| MgO                            | 2.90   | 3.18   | 2.52   | 2.94     | 3.59   | 2.07   | 2.13   | 2.28   | 0.12       | 0.10   |
| CaO                            | 0.00   | 0.06   | 0.00   | 0.02     | 0.02   | 0.00   | 0.01   | 0.00   | 0.16       | 0.12   |
| Na <sub>2</sub> O              | 0.11   | 0.16   | 0.91   | 0.35     | 0.24   | 0.59   | 0.50   | 0.51   | 7.64       | 7.13   |
| K <sub>2</sub> O               | 10.78  | 10.52  | 10.22  | 10.94    | 10.33  | 10.30  | 10.87  | 10.73  | 0.73       | 0.66   |
| BaO                            | 0.06   | 0.35   | 0.30   | 0.19     | 0.10   | 0.18   | 0.18   | 0.15   | 0.01       | 0.03   |
| H <sub>2</sub> O               | 4.39   | 4.49   | 4.37   | 4.39     | 4.38   | 4.34   | 4.38   | 4.36   | 4.66       | 4.61   |
| Total                          | 98.06  | 101.46 | 98.71  | 99.32    | 98.76  | 97.39  | 98.60  | 98.18  | 99.94      | 98.48  |
| Total corr.                    | 98.06  | 101.46 | 98.71  | 99.32    | 98.76  | 97.39  | 98.60  | 98.18  | 99.94      | 98.48  |
|                                |        |        |        |          |        |        |        |        |            |        |
| Si                             | 6.7556 | 6.8579 | 6.7320 | 6.7209   | 6.7772 | 6.3446 | 6.4158 | 6.4339 | 6.0564     | 5.9952 |
| AI_T                           | 1.2444 | 1.1421 | 1.2680 | 1.2791   | 1.2228 | 1.6554 | 1.5842 | 1.5661 | 1.9436     | 2.0048 |
| Sum4                           | 8.0000 | 8.0000 | 8.0000 | 8.0000   | 8.0000 | 8.0000 | 8.0000 | 8.0000 | 8.0000     | 8.0000 |
| AI_O                           | 3.0861 | 2.7563 | 3.0595 | 2.9406   | 2.6588 | 3.2437 | 3.2284 | 3.1961 | 3.8725     | 3.8944 |
| Ti                             | 0.0081 | 0.0172 | 0.0077 | 0.0108   | 0.0177 | 0.0076 | 0.0067 | 0.0048 | 0.0105     | 0.0109 |
| Cr                             | 0.0000 | 0.0002 | 0.0000 | 0.0013   | 0.0000 | 0.0014 | 0.0016 | 0.0003 | 0.0000     | 0.0000 |
| Fe <sup>2</sup>                | 0.3873 | 0.5635 | 0.5135 | 0.4436   | 0.3701 | 0.2327 | 0.2936 | 0.2783 | 0.1182     | 0.1190 |
| Fe <sup>3</sup>                | 0.0000 | 0.1244 | 0.0000 | 0.1028   | 0.3200 | 0.1851 | 0.1302 | 0.1515 | 0.0000     | 0.0000 |
| Mn                             | 0.0000 | 0.0060 | 0.0014 | 0.0033   | 0.0019 | 0.0032 | 0.0037 | 0.0011 | 0.0003     | 0.0000 |
| Mg                             | 0.5897 | 0.6323 | 0.5145 | 0.5977   | 0.7315 | 0.4263 | 0.4357 | 0.4679 | 0.0235     | 0.0199 |
| Sum6                           | 4.0711 | 4.1000 | 4.0965 | 4.1000   | 4.1000 | 4.1000 | 4.1000 | 4.1000 | 4.0251     | 4.0443 |
| Са                             | 0.0006 | 0.0084 | 0.0000 | 0.0027   | 0.0031 | 0.0000 | 0.0010 | 0.0004 | 0.0222     | 0.0170 |
| Ва                             | 0.0033 | 0.0183 | 0.0160 | 0.0102   | 0.0056 | 0.0100 | 0.0095 | 0.0082 | 0.0005     | 0.0015 |
| Na                             | 0.0289 | 0.0412 | 0.2427 | 0.0924   | 0.0626 | 0.1593 | 0.1336 | 0.1354 | 1.9071     | 1.7986 |
| К                              | 1.8785 | 1.7909 | 1.7885 | 1.9059   | 1.8041 | 1.8156 | 1.9001 | 1.8818 | 0.1201     | 0.1091 |
| Sum8                           | 1.9114 | 1.8588 | 2.0472 | 2.0112   | 1.8753 | 1.9848 | 2.0442 | 2.0258 | 2.0498     | 1.9262 |
| Н                              | 4.0000 | 4.0000 | 4.0000 | 4.0000   | 4.0000 | 4.0000 | 4.0000 | 4.0000 | 4.0000     | 4.0000 |
| Components                     |        |        |        |          |        |        |        |        |            |        |
| MUSCOVITE                      | 0.5634 | 0.4304 | 0.4477 | 0.4994   | 0.4300 | 0.6370 | 0.6301 | 0.6174 | 0.0016     | 0.0218 |
| WM_PHLOGOPITE                  | 0.0356 | 0.0500 | 0.0483 | 0.0500   | 0.0500 | 0.0500 | 0.0500 | 0.0500 | 0.0125     | 0.0221 |
| AL_CELADONITE                  | 0.2293 | 0.2344 | 0.1871 | 0.2106   | 0.2611 | 0.1147 | 0.1273 | 0.1387 | 0.0065     | 0.0010 |
| FE_AL_CELADONITE               | 0.1506 | 0.2089 | 0.1867 | 0.1563   | 0.1321 | 0.0626 | 0.0858 | 0.0825 | 0.0327     | 0.0062 |
| PARAGONITE                     | 0.0151 | 0.0221 | 0.1186 | 0.0459   | 0.0334 | 0.0802 | 0.0654 | 0.0669 | 0.9304     | 0.9338 |
| TI_MN_CA_WM                    | 0.0061 | 0.0541 | 0.0117 | 0.0378   | 0.0935 | 0.0555 | 0.0414 | 0.0446 | 0.0163     | 0.0151 |
| ХОН                            | 1.0000 | 1.0000 | 1.0000 | 1.0000   | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000     | 1.0000 |

Table 5b. Representative analyses of Phengite and Paragonite in ES and GS.









Si p.f.u versus Al tot, Na/(Na+K) and Fe<sup>2+</sup>/(Fe<sup>2+</sup>+Mg) p.f.u.

monazite from samples 017 were finally analysed. Among these analyses, 43 analyses of monazite (other analyses gave totals only between 80 to 95 wt.%) were used for geochronology. For the garnet-mica schist the resulting ages range between < 15 and 120 Ma (Table 8, Fig. 11 a,b). The content of Y was found to be 0.001-0.040 pfu but a correlation with age and other chemical parameters failed.

#### 5. Pressure-Temperature Evolution

Mineralogical compositions and textural evidence led to the distinction of at least 3 metamorphic stages. P-T conditions of each stage were calculated using thermodynamic methods, considering the above outlined specific (coexisting) mineral assemblages and compositions, to constrain the P-T path of the rocks. This P-T path also leads to the understanding of the formation of jadeitite and jadeite-albite rocks in the Tawmaw area.

#### 5.1. Methods for deriving P-T conditions of mineral equilibria

Thermodynamic calculations of selected mineral equilibria were achieved with the computer program PTGIBBS (Brandelik and Massonne, 2004) applying the following solid solution models and end-member data: garnetmas, Ti-muscovite and WhiteMica, NEW-ALMANDINE, PHLOGOPITE, NEW-PYROPE, NEW-ANNITE-B, NEW-TI-MUSCOVITE, QUARTZ-ALPHA, NEW-MG-AL-CELADONITE and NEW-FE-AL-CELADONITE B (see, e.g., Massonne, 2006). The mineral equilibria taken into account are subsequently given by end-member components in corresponding phases:

1) 1 Almandine + 1 Phlogopite = 1 Annite + 1 Pyrope

2) 3 MgAlCeladonite + 1 Almandine = 1 Muscovite + 1 Annite + 1 Phlogopite+ 6 Quartz

3) 1 Almandine + 3 MgAlCeladonite = 3 FeAlCeladonite + 1 Pyrope

4) 2 Rutile + 1 Muscovite = 2 Quartz + 1 Ti-Muscovite

Quartz and rutile were considered as pure phases.

In addition, P-T pseudosections, considering the chemical bulk rock compositions of GS and GM samples (see XRF analyses in Table 9), were calculated with the computer program package PERPLE\_X (Connolly, 2005). H<sub>2</sub>O was assumed to be present as excess phase. We used the thermodynamic data and solid solution models and successive modifications by Holland and Powell (1998). The calculations involve biotite, amphibole, paragonite, phengite, plagioclase, epidote, staurolite, garnet, omphacite, chloritoid, and chlorite as solid solutions (labelled in the newest\_format\_solut.dat file of the PERPLE\_X package as Bio(HP), GlTrTsPg, Pa, Pheng(HP), AbFsp(C1), Ep(HP), St(HP), Gt(HP), Omph(HP), Ctd(HP), and

|                                | G      | М      |         | ES       |          |          | G        | S        |          |
|--------------------------------|--------|--------|---------|----------|----------|----------|----------|----------|----------|
| х                              | 017Ex2 | 019Ex2 | 03005Ep | 03105Epi | 03205Epi | 03305Epi | 03405Epi | 03505Epi | 04105Epi |
|                                | #137   | #33    | #27     | #10      | #1       | #7       | #87      | #29      | #43      |
| SiO <sub>2</sub>               | 38.41  | 38.9   | 38.48   | 38.19    | 37.99    | 38.31    | 37.68    | 37.70    | 38.38    |
| TiO <sub>2</sub>               | 0.46   | 0.24   | 0.10    | 0.1      | 0.11     | 0.03     | 0.03     | 0.04     | 0.11     |
| Al <sub>2</sub> O <sub>3</sub> | 29.9   | 27.81  | 24.70   | 24.08    | 25.39    | 21.12    | 23.58    | 23.30    | 26.65    |
| Cr <sub>2</sub> O <sub>3</sub> | 0.02   | 0.00   | 0.01    | 0.00     | 0.00     | 0.01     | 0.01     | 0.01     | 0.00     |
| Fe <sub>2</sub> O <sub>3</sub> | 4.12   | 7.33   | 12.00   | 12.67    | 10.95    | 15.47    | 13.44    | 13.72    | 9.33     |
| Mn <sub>2</sub> O <sub>3</sub> | 0.000  | 0.11   | 0.16    | 0.14     | 0.13     | 0.30     | 0.25     | 0.42     | 0.01     |
| MgO                            | 0.24   | 0.06   | 0.07    | 0.05     | 0.05     | 0.00     | 0.01     | 0.00     | 0.12     |
| CaO                            | 23.82  | 23.4   | 22.80   | 23.3     | 23.17    | 22.61    | 23.71    | 23.18    | 23.71    |
| Na <sub>2</sub> O              | 0.00   | 0.00   | 0.02    | 0.03     | 0.11     | 0.03     | 0.02     | 0.03     | 0.03     |
| H <sub>2</sub> O               | 1.93   | 1.93   | 1.91    | 1.9      | 1.90     | 1.87     | 1.89     | 1.89     | 1.92     |
| Total                          | 98.89  | 99.78  | 100.26  | 100.45   | 99.80    | 99.75    | 100.62   | 100.30   | 100.26   |
| Total_corr.                    | 98.89  | 99.78  | 100.26  | 100.45   | 99.80    | 99.75    | 100.62   | 100.30   | 100.26   |
|                                |        |        |         |          |          |          |          |          |          |
| Si                             | 2.98   | 3.02   | 3.02    | 3.01     | 3.00     | 3.07     | 2.98     | 2.99     | 3.00     |
| Ti                             | 0.03   | 0.01   | 0.01    | 0.01     | 0.01     | 0.00     | 0.00     | 0.00     | 0.01     |
| AI                             | 2.74   | 2.55   | 2.29    | 2.24     | 2.36     | 1.99     | 2.20     | 2.18     | 2.45     |
| Cr                             | 0.00   | 0.00   | 0.00    | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     |
| Fe <sup>3</sup>                | 0.24   | 0.43   | 0.71    | 0.75     | 0.65     | 0.93     | 0.80     | 0.82     | 0.55     |
| Mn <sup>3</sup>                | 0.00   | 0.01   | 0.01    | 0.01     | 0.01     | 0.02     | 0.02     | 0.03     | 0.00     |
| Mg                             | 0.03   | 0.01   | 0.01    | 0.01     | 0.01     | 0.00     | 0.00     | 0.00     | 0.01     |
| sum6                           | 3.03   | 3.00   | 3.02    | 3.01     | 3.03     | 2.95     | 3.02     | 3.03     | 3.02     |
| Са                             | 1.98   | 1.95   | 1.92    | 1.97     | 1.96     | 1.94     | 2.01     | 1.97     | 1.98     |
| Na                             | 0.00   | 0.00   | 0.00    | 0.00     | 0.02     | 0.01     | 0.00     | 0.00     | 0.00     |
| sum8                           | 1.98   | 1.95   | 1.92    | 1.97     | 1.97     | 1.95     | 2.01     | 1.98     | 1.99     |
| Н                              | 1.00   | 1.00   | 1.00    | 1.00     | 1.00     | 1.00     | 1.00     | 1.00     | 1.00     |

Table 6. Representative analyses of Epidotes in GM, ES and GS.


Fig. 10 a-f: Variation diagrans of selected chemical parameters for epidote in garnet-mica schist (GM) a-b, epidote schist (ES) c-d) and glaucophane schist (GS) e-f showing  $Al_2O_3$  (wt %) versu  $Fe_2O_3$  (wt %) and MgO (wt %).

|                                | Chlorite (GN | /I, ES) |         | Feldspar (GM and GS)           |        |        |         |         |  |  |  |  |
|--------------------------------|--------------|---------|---------|--------------------------------|--------|--------|---------|---------|--|--|--|--|
|                                | 017Ex2       | 019Ex1  | 03005a  |                                | 017Ex6 | 017Ex  | 03405Ex | 03405Ex |  |  |  |  |
| Х                              | #8           | #253    | #178    | Х                              | #13    | #28    | #97     | #27     |  |  |  |  |
| SiO <sub>2</sub>               | 26.25        | 31.13   | 25.91   | SiO <sub>2</sub>               | 63.62  | 70     | 67.84   | 67.81   |  |  |  |  |
| TiO <sub>2</sub>               | 6.16         | 0.04    | 0.06    | TiO <sub>2</sub>               | 0.01   | 0.01   | 0.00    | 0.00    |  |  |  |  |
| Al <sub>2</sub> O <sub>3</sub> | 16.83        | 22.04   | 19.78   | Al <sub>2</sub> O <sub>3</sub> | 22.8   | 18.83  | 19.92   | 19.85   |  |  |  |  |
| Cr <sub>2</sub> O <sub>3</sub> | 0.31         | 0.00    | 0       | Cr <sub>2</sub> O <sub>3</sub> | 0.00   | 0.00   | 0.00    | 0.00    |  |  |  |  |
| FeO                            | 28.13        | 19.4    | 23.03   | Fe <sub>2</sub> O <sub>3</sub> | 0      | 0.02   | 0.16    | 0.00    |  |  |  |  |
| MnO                            | 0.15         | 0.11    | 0.2     | Mn <sub>2</sub> O <sub>3</sub> | 0.04   | 0.00   | 0.00    | 0.02    |  |  |  |  |
| MgO                            | 11.4         | 15.19   | 16.61   | MgO                            | 0.00   | 0.00   | 0.00    | 0.00    |  |  |  |  |
| H <sub>2</sub> O               | 11.35        | 12.01   | 11.23   | CaO                            | 3.22   | 0      | 0.02    | 0.05    |  |  |  |  |
| Total                          | 100.59       | 99.93   | 96.81   | Na <sub>2</sub> O              | 9.7    | 12.07  | 11.89   | 12.01   |  |  |  |  |
| Total_corr.                    | 100.59       | 99.93   | 96.81   | K <sub>2</sub> O               | 0.05   | 0.03   | 0.09    | 0.04    |  |  |  |  |
|                                |              |         |         | BaO                            | 0.01   | 0.00   | 0.00    | 0.00    |  |  |  |  |
| Si                             | 5.5459       | 6.2155  | 5.5358  | Total                          | 99.44  | 100.96 | 99.92   | 99.79   |  |  |  |  |
| AI_T                           | 2.4541       | 1.7845  | 2.4642  |                                |        |        |         |         |  |  |  |  |
| sum4                           | 8.0000       | 8.0000  | 8.0000  | Si                             | 2.8200 | 3.0261 | 2.9707  | 2.9730  |  |  |  |  |
| AI_O                           | 1.7354       | 3.4005  | 2.5160  | AI                             | 1.1910 | 0.9596 | 1.0281  | 1.0259  |  |  |  |  |
| Cr                             | 0.0512       | 0.0000  | 0.0000  | Fe <sup>3</sup>                | 0.0000 | 0.0007 | 0.0054  | 0.0000  |  |  |  |  |
| Ti                             | 0.9794       | 0.0065  | 0.0089  | Mn <sup>3</sup>                | 0.0014 | 0.0000 | 0.0000  | 0.0007  |  |  |  |  |
| Fe                             | 4.9703       | 3.2388  | 4.1154  | Cr                             | 0.0000 | 0.0000 | 0.0001  | 0.0001  |  |  |  |  |
| Mn                             | 0.0275       | 0.0193  | 0.0358  | Ti                             | 0.0002 | 0.0003 | 0.0000  | 0.0000  |  |  |  |  |
| Mg                             | 3.5907       | 4.5204  | 5.2893  | su1                            | 4.0124 | 3.9867 | 4.0043  | 3.9996  |  |  |  |  |
| sum6                           | 11.3544      | 11.1855 | 11.9653 | Ва                             | 0.0001 | 0.0000 | 0.0000  | 0.0000  |  |  |  |  |
| Н                              | 16.0000      | 16.0000 | 16.0000 | Са                             | 0.1529 | 0.0002 | 0.0009  | 0.0025  |  |  |  |  |
| Compositions                   |              |         |         | Na                             | 0.8336 | 1.0113 | 1.0099  | 1.0208  |  |  |  |  |
| xSi                            | 0.7730       | 1.1077  | 0.7679  | К                              | 0.0029 | 0.0017 | 0.0048  | 0.0023  |  |  |  |  |
| xMg                            | 0.4181       | 0.5811  | 0.5603  | su2                            | 0.9895 | 1.0132 | 1.0156  | 1.0256  |  |  |  |  |
| xFe                            | 0.5787       | 0.4164  | 0.4359  | Components                     |        |        |         |         |  |  |  |  |
|                                |              |         |         | ANORTHITE                      | 0.1546 | 0.0002 | 0.0008  | 0.0024  |  |  |  |  |
|                                |              |         |         | H_ALBITE                       | 0.8425 | 0.9982 | 0.9944  | 0.9953  |  |  |  |  |
|                                |              |         |         | K_FELDSPAR                     | 0.0029 | 0.0016 | 0.0048  | 0.0022  |  |  |  |  |

Table 7. Representative analyses of chlorite and feldspar from GM, ES and GS.

|                                | 017Ext9 | 017Ext6 | 017Ext5 | 017Ext9 | 017Ext6 | 017Ext5 | 017Ext9 | 017Ext6 | 017Ext10 | 017Ext6 |
|--------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|----------|---------|
| х                              | #103    | #49     | #42     | #30     | #56     | #27     | #8      | #57     | #14      | #81     |
| P <sub>2</sub> O <sub>5</sub>  | 29.66   | 29.14   | 28.41   | 29.13   | 29.51   | 29.59   | 29.02   | 29.82   | 29.62    | 29.56   |
| SiO <sub>2</sub>               | 0.23    | 0.27    | 0.29    | 0.19    | 0.21    | 0.41    | 0.17    | 0.19    | 0.29     | 0.29    |
| SO <sub>3</sub>                | 0.05    | 0.04    | 0.02    | 0.02    | 0.04    | 0.04    | 0.02    | 0.02    | 0.05     | 0.84    |
| CaO                            | 1.16    | 1.17    | 1.15    | 1.01    | 1.18    | 1.24    | 1.70    | 1.26    | 1.19     | 4.48    |
| PbO                            | bdl     | bdl     | 0.01    | 0.01    | 0.01    | 0.02    | 0.02    | 0.02    | 0.03     | 0.03    |
| ThO <sub>2</sub>               | 5.32    | 4.90    | 4.78    | 4.99    | 5.09    | 5.52    | 5.85    | 5.32    | 5.59     | 4.33    |
| UO <sub>2</sub>                | 0.93    | 0.80    | 0.66    | 0.53    | 0.75    | 1.06    | 1.04    | 0.78    | 1.38     | 0.52    |
| Y <sub>2</sub> O <sub>3</sub>  | 0.36    | 0.34    | 0.07    | 0.71    | 0.44    | 0.43    | 0.56    | 0.51    | 1.52     | 1.77    |
| La <sub>2</sub> O <sub>3</sub> | 14.27   | 13.85   | 14.97   | 14.07   | 14.54   | 13.91   | 14.36   | 14.58   | 13.33    | 13.82   |
| Ce <sub>2</sub> O <sub>3</sub> | 29.37   | 29.06   | 29.34   | 28.96   | 29.04   | 28.73   | 28.34   | 29.07   | 27.17    | 25.72   |
| Pr <sub>2</sub> O <sub>3</sub> | 3.21    | 3.23    | 3.20    | 3.19    | 2.98    | 3.11    | 3.01    | 3.08    | 3.10     | 2.58    |
| $Nd_2O_3$                      | 11.98   | 12.53   | 12.14   | 12.28   | 11.81   | 12.14   | 11.50   | 11.80   | 11.97    | 10.64   |
| Sm <sub>2</sub> O <sub>3</sub> | 2.05    | 2.52    | 2.19    | 2.03    | 2.11    | 2.24    | 1.93    | 2.15    | 2.13     | 2.07    |
| EuO                            | 0.01    | 0.08    | 0.00    | 0.30    | 0.04    | 0.03    | 0.24    | 0.04    | 0.21     | 0.12    |
| Gd <sub>2</sub> O <sub>3</sub> | 0.96    | 1.18    | 0.92    | 1.15    | 0.98    | 0.97    | 0.97    | 0.96    | 1.41     | 0.98    |
| Dy <sub>2</sub> O <sub>3</sub> | 0.34    | 0.30    | 0.17    | 0.34    | 0.29    | 0.23    | 0.30    | 0.27    | 0.57     | 0.46    |
| Total                          | 99.91   | 99.42   | 98.33   | 98.89   | 99.03   | 99.66   | 99.05   | 99.88   | 99.56    | 98.20   |
|                                |         |         |         |         |         |         |         |         |          |         |
| Р                              | 0.9885  | 0.9811  | 0.9732  | 0.9852  | 0.9902  | 0.9859  | 0.9803  | 0.9915  | 0.9874   | 0.9612  |
| Si                             | 0.0090  | 0.0107  | 0.0119  | 0.0075  | 0.0085  | 0.0161  | 0.0068  | 0.0075  | 0.0114   | 0.0111  |
| S                              | 0.0014  | 0.0013  | 0.0006  | 0.0005  | 0.0011  | 0.0013  | 0.0007  | 0.0007  | 0.0015   | 0.0242  |
| Са                             | 0.0490  | 0.0499  | 0.0500  | 0.0432  | 0.0501  | 0.0522  | 0.0728  | 0.0531  | 0.0502   | 0.1842  |
| Pb                             | 0.0000  | 0.0000  | 0.0001  | 0.0006  | 0.0001  | 0.0002  | 0.0002  | 0.0002  | 0.0003   | 0.0003  |
| Th                             | 0.0477  | 0.0444  | 0.0441  | 0.0453  | 0.0459  | 0.0494  | 0.0531  | 0.0475  | 0.0501   | 0.0379  |
| U                              | 0.0081  | 0.0071  | 0.0059  | 0.0047  | 0.0066  | 0.0093  | 0.0093  | 0.0068  | 0.0121   | 0.0045  |
| Y                              | 0.0076  | 0.0072  | 0.0016  | 0.0151  | 0.0092  | 0.0091  | 0.0120  | 0.0106  | 0.0319   | 0.0362  |
| La                             | 0.2071  | 0.2032  | 0.2234  | 0.2074  | 0.2126  | 0.2019  | 0.2113  | 0.2112  | 0.1936   | 0.1957  |
| Ce                             | 0.4233  | 0.4230  | 0.4347  | 0.4237  | 0.4214  | 0.4139  | 0.4141  | 0.4180  | 0.3916   | 0.3616  |
| Pr                             | 0.0461  | 0.0469  | 0.0472  | 0.0465  | 0.0431  | 0.0446  | 0.0438  | 0.0441  | 0.0444   | 0.0360  |
| Nd                             | 0.1684  | 0.1778  | 0.1755  | 0.1752  | 0.1672  | 0.1706  | 0.1639  | 0.1655  | 0.1684   | 0.1460  |
| Sm                             | 0.0278  | 0.0345  | 0.0306  | 0.0279  | 0.0288  | 0.0304  | 0.0265  | 0.0290  | 0.0289   | 0.0274  |
| Eu                             | 0.0001  | 0.0012  | 0.0000  | 0.0043  | 0.0006  | 0.0004  | 0.0035  | 0.0006  | 0.0029   | 0.0016  |
| Gd                             | 0.0126  | 0.0155  | 0.0123  | 0.0152  | 0.0129  | 0.0127  | 0.0129  | 0.0126  | 0.0183   | 0.0124  |
| Dy                             | 0.0043  | 0.0038  | 0.0023  | 0.0044  | 0.0037  | 0.0029  | 0.0039  | 0.0035  | 0.0072   | 0.0057  |
| SumKat                         | 2.0010  | 2.0076  | 2.0133  | 2.0061  | 2.0020  | 2.0007  | 2.0149  | 2.0024  | 2.0002   | 2.0459  |
| Age                            | <15 Ma  | < 15 Ma | 29.7829 | 19.2014 | 34.3087 | 40.3763 | 58.5958 | 65.5526 | 74.1940  | 119.268 |

Table 8. Representative analyse of monazite for age determination in GM. (bdl = below detection limit).



<sup>(</sup>a)



Fig. 11 a-b. Age determination by monazite from garnet-mica schist 017 (GM).

Chl(HP)) and the pure phases magnetite, hematite, ilmenite, quartz and water. The P-T pseudosections obtained with PERPLE\_X were manually redrawn also to smooth the reaction curves (see Connolly, 2005). In addition, P-T maps showing the contents of grossular, almandine and spessartine in garnet and Si pfu in phengite were produced with the subprogram 'werami' in PERPLE\_X. The corresponding curves were manually smoothed as well. Although it could not be avoided to undertake this in an arbitrary manner, the phase relations of the P-T pseudosections were considered for this smoothing process (e.g., different dP/dT-slope of smoothed curves in P-T fields of distinct mineral assemblages).

For reconstructing the P-T path with the PERPLE\_X results the following criteria were considered: The path should (1) explain the observed Ca, Mn and Mg zonation of garnet, (2) consider the change of Si contents in potassic white mica (e.g., late increase of Si pfu according to phengite rims of potassic white mica grains), and (3) be compatible with the observed mineral assemblages of the various metamorphic stages.

#### 5.2. Geothermobarometric results

The application of the garnet-biotite-phengite thermobarometry (equilibria 1 to 3) and equilibrium (4) are applied to garnet-mica schist GM 017 and 019 as shown in (Table 10) and (Figure 12 and 14). In the calculation of PTGIBBS, the activity for biotite is assuming as the relict chlorite in the garnet-mica schist.

The P-T phase diagrams obtained with PERPLE\_X are shown for garnet-mica schists GM 017 and GM 019 in (Figures 13 and 15), respectively. For glaucophane schist GS 034/05 the corresponding result is given in (Figure 16). The compatibility of the results obtained with PERPLE X and possible P-T paths are outlined subsequently.

#### 5.3. P-T paths

#### Garnet-mica schist GM 017

The matrix assemblage is garnet + white mica + chlorite + albite-rich plagioclase + rutile + epidote + magnetite + quartz. In the matrix, the biotite is formed as relict after chlorite and assumes to use for PTGIBBS calculation. The calculation for earliest stage with PERPLE\_X yielded a P-T field between about 16-19 kbar and 470-540°C (Fig. 13b) (Si p.f.u = 3.4). This P-T field is nearly compatible with the corresponding PTGIBBS results ranging about 16-19 kbar and 469-557°C (Table 10, Fig. 12). The intermediate stage calculated with phengite rim in the garnet and inner rim zone of garnet with PERPLE\_X indicating about 525-570°C and 11-14 kbar (Si pfu = 3.21-3-23). The calculated result of PTGIBBS for this stage with garnet

| x                              | G      | M     | E      | S      | GS     |        |        |  |  |  |  |
|--------------------------------|--------|-------|--------|--------|--------|--------|--------|--|--|--|--|
| ^                              | 017    | 019   | 030/05 | 031/05 | 034/05 | 035/05 | 041/05 |  |  |  |  |
| SiO <sub>2</sub>               | 63.84  | 64.93 | 73.60  | 65.80  | 60.35  | 53.44  | 53.45  |  |  |  |  |
| Al <sub>2</sub> O <sub>3</sub> | 16.91  | 17.29 | 12.71  | 13.62  | 14.87  | 17.79  | 15.85  |  |  |  |  |
| MnO                            | 0.07   | 0.14  | 0.03   | 0.08   | 0.13   | 0.16   | 0.17   |  |  |  |  |
| MgO                            | 1.92   | 1.43  | 0.65   | 1.47   | 2.34   | 3.25   | 3.01   |  |  |  |  |
| CaO                            | 1.02   | 1.41  | 2.28   | 4.65   | 2.41   | 7.00   | 9.55   |  |  |  |  |
| Na <sub>2</sub> O              | 1.24   | 1.19  | 3.39   | 3.50   | 7.29   | 4.70   | 1.85   |  |  |  |  |
| K <sub>2</sub> O               | 1.88   | 2.00  | 0.47   | 0.02   | 0.21   | 0.03   | 0.07   |  |  |  |  |
| TiO <sub>2</sub>               | 0.81   | 0.66  | 0.40   | 0.73   | 0.82   | 1.19   | 1.23   |  |  |  |  |
| $P_2O_5$                       | 0.13   | 0.08  | 0.04   | 0.16   | 0.07   | 0.11   | 0.13   |  |  |  |  |
| FeO (total)                    | 6.44   | 5.38  | 2.61   | 5.63   | 7.85   | 7.42   | 9.23   |  |  |  |  |
| H <sub>2</sub> O               | 3.06   | 1.29  | 0.16   | 0.16   | 0.10   | 0.14   | 0.20   |  |  |  |  |
| CO <sub>2</sub>                | 2.70   | 3.37  | 1.78   | 2.06   | 1.49   | 2.50   | 2.93   |  |  |  |  |
| Trace                          | 0.14   | 0.12  | 0.05   | 0.05   | 0.07   | 0.08   | 0.07   |  |  |  |  |
| Total                          | 100.14 | 99.29 | 98.17  | 97.93  | 97.98  | 97.81  | 97.74  |  |  |  |  |

Table 9: Chemical analyses of GM, ES and GS.

Table 10. Selected Results of Applied Geothermobarometery of garnet-mica schist.

| Sample No.                 |       |      |                     |   |                   |                  |                   |                     |     |        |      |
|----------------------------|-------|------|---------------------|---|-------------------|------------------|-------------------|---------------------|-----|--------|------|
|                            | Stage |      | Garnet              |   |                   | Ph               | nengite           | Equilibrium         | T°C | P kbar |      |
|                            |       | Core | Intermediate<br>Rim | Outermost<br>Rim  | Core in<br>Garnet | Rim in<br>Garnet | Core in Foliation | Rim in<br>Foliation |     |        |      |
|                            |       | #40  |                     |   | #16               |                  |                   |                     | 1+2 | 479    | 19   |
| Sample No.<br>#017<br>#019 |       |      |                     |   |                   |                  |                   |                     | 2+3 | 557    | 19   |
|                            | · ·   | #135 |                     |   | #5                |                  |                   |                     | 1+2 | 470    | 16.7 |
|                            |       | #135 |                     |   | #8                |                  |                   |                     | 1+4 | 469    | 16   |
|                            |       | #53  |                     |   |                   | #56              |                   |                     | 1+2 | 395    | 16   |
|                            |       |      |                     |   |                   |                  |                   |                     | 2+3 | 470    | 17   |
|                            |       |      | #130                |   |                   |                  | #39               |                     | 1+3 | 522    | 14   |
|                            |       |      | #126                |   |                   |                  | #43               |                     | 1+3 | 583    | 11   |
|                            |       |      |                     | #146  |                   |                  |                   | #71                 | 1+3 | 591    | 11   |
|                            |       |      |                     | #64   |                   |                  |                   | #71                 | 1+3 | 621    | 8    |
|                            |       | #8   |                     |   | #53               |                  |                   |                     | 2+3 | 440    | 18.7 |
|                            |       | #11  |                     | Garnet         Phengite         Equilibrium         T°C         P kbar           mediate<br>Rim         Outermost<br>Rim         Core in<br>Garnet         Rim in<br>Garnet         Core in<br>Foliation         Rim in<br>Foliation         T°C         P kbar           Image: Stress of the stress | 18                |                  |                   |                     |     |        |      |
| #019                       | п     |      | #28                 |   |                   | #51              |                   |                     | 1+4 | 446    | 11   |
| #015                       |       |      | #36                 |   |                   | #51              |                   |                     | 1+4 | 395    | 9.2  |
|                            |       |      |                     | #22   |                   |                  |                   | #53                 | 1+3 | 592    | 8    |
|                            |       |      |                     | #143  |                   |                  |                   | #8                  | 1+3 | 646    | 7    |



Fig. 12: P-T estimate of garnet-mica schist (017) using the phengite, Ti muscovite composition and coexisting garnet.



Fig. 13: Pseudosections calculated for garnet-mica schist. a. Sample 017, from western part of the Tawmaw area. P-Tfield assemblage is Gt + Qtz + Wm + Chl + Ab + Phen + Rt + Ep + Mt. b. Isopleths are drawn by Ca, Mg and Mn composition in garnet and Si p.f.u in phengite. Grey quadrangel indicate the estimated P-T field for GM.

core and phengite rim in the garnet indicating that  $395-470^{\circ}$ C, 16-17 kbar which is quite far from the calculated P-T field with PERPLE\_X (equilibrium 1+2 and 2+3) but calculation with intermediate rim of garnet and rim of phengite gives 522-585 °C at 11-14 kbar (equilibrium 1+3) which is nearly compatible with result of PERPLE X.

The late P-T path of this rock indicating about 8-11 kbar and 591-621°C calculated by PTGIBBS (equilibrium 1+3) were reached confirmed by phengite rims in the matrix (Si pfu = 3.15-3.05). The result of PERPLE\_X for this stage is nearly the same range showing 6-8.5 kbar, 570-630°C (Fig. 15 b).

#### Garnet-mica schist GM 019

Inclusions in garnet provide the pre-matrix mineral assemblage information such as Quartz + Chlorite + Paragonite + Albite + Phengite (Si = 3.35) + Rutile. The matrix assemblage is Quartz + Chlorite + Albite + Phengite (Si = 3.10) + Rutile + Epidote + Magnetite + Rutile + Epidote. Relict biotite after chlorite is used for the PTGIBBS calculation.

The P-T field for the core assemblage is about 18-18.7 kbar, 426-440°C by calculating with PTGIBBS (equilibrium 2+3) (Table 10, Fig. 14). This P-T field is slightly different in temperature range with the result from PERPLE\_X which indicate about 16-18.5 kbar, 480-510°C. The pressure of this stage is confirmed by the Si content of phengite in garnet (Si pfu = 3.35). The intermediate stage is calculated by PTGIBBS with equilibrium (1+4) indicating the range of 395-446°C, 9-11 kbar (Ti pfu 0.0312) (garnet intermediate zone and Ti-rich white mica in garnet intermediate zone). The result of PERPLE\_X for this stage is quite different indicating 525-480 °C, 12-14 kbar. The pressure condition for this stage is confirmed by the Si content of Ti mica in the garnet (Si = 3.20).

The later P-T path is characterized by the outermost rim composition of garnet and rim composition of phengite in foliation (Si pfu = 3.05-3.10) with PTGIBBS showing about 592-646 °C, 7-8 kbar. This P-T condition is nearly compatible with the result of PERPLE\_X calculation 570-620 °C, 5.5-7.5 kbar (Fig. 15 b).

#### Glaucophane schist GS 034/05

This sample is characterized as glaucophane schist because glaucophane is the dominant amphibole. The matrix assemblage is Quartz + Albite + Glucophane + Epidote + Chlorite + White mica (Phengite) + Garnet + Rutile + Magnetite. The P-T field for this assemblage is 560-620°C at 7-12 kbar (Fig. 16 a-b) calculated by the PERPLE\_X. These conditions are compatible with the relict garnet rim compositon. The P-T path for core composition of relict



Fig. 14. P-T estimate of garnet-mica schist (019) using the phengite, Ti muscovite composition and coexisting garnet.





Fig. 15: Pseudosections calculated for garnet-mica schist. a. Sample 019m from western part of the Tawmaw area. The matrix assemblage is Qtz + Wm + Chl + Ab + Phen + Rt + Ep + Mt. b. Isopleths are drawn by Ca, Mg and Mn composition in garnet and Si p.f.u in phengite. Grey quadrangel indicate the estimated P-T field for GM.



Fig. 16: Pseudosections calculated for garnet- bearing glaucophane schist. a. Sample 034/05, from southeastern part of the Tawmaw area. P-T field assemblage is Qtz + Ab + Gl + Ep + Chl + Wm + Gt + Phen + Rt + Mt. b. Isopleths are constructed by Ca, Mg and Mn composition of relict garnet and Si p.f.u in phengite.

garnet is estimated about 18-20 kbar and 470-490°C confirmed by PERPLE\_X using and garnet core composition and phengite in the relict garnet (Si pfu = 3.43).

## 6. Discussion and Conclusions

Tectonometamorphic history of the garnet-mica schists, epidote schists and blue schists from Tawmaw area

The metamorphic rocks exposed in the Tawmaw area, garnet-mica schit, which include the phengite in the garnet core and also in the matrix, and zonation pattern in garnet (e.g. low-Mn, high-Mg rims on garnet) indicate that prograde metamorphism. The presence of phengite, epidote and glaucophane in glaucophane schist (GS) indicates that these rocks have been suffered under high-P condition.

These rocks had been undergone metamorphism during the subduction at different structural levels and depth before exhumation. Moreover, different structural level and depth also control for their grade of metamorphism.

The selection of specific representative compositions of the coexisting minerals in the analysed samples, were use for calculation of P-T path. Core compositions of garnet from GM rocks were use to estimate the P-T condition of stage I which range from 470-540° C and 16-19 kbar and the rim composition of garnet from GM rock of stage III were estimate as 570-620 °C, 5.5-8.5 kbar. Relict core composition of garnet from the GS rocks were use to estimate the P-T conditions as 470-490 °C, 18-20 kbar. The P-T condition of relict rim composition of garnet from the GS rocks were estimate as 560-620°C, 7-12 kbar. Si composition of phengite inclusion in garnet from GM (Si pfu = 3.35) and GS (Si p.f.u = 3.43) show that these phengite was formed under HP-LT condition ranging from 16-20 kbar and 470-540° C.

The intersect of garnet core compositon in GS rocks with calculated isopleths indicating that Mg is off equilibrium in GS sample which is shift to the right side. The probable reason for this garnet is during the subduction conduction, the original composition of the rock sheared in the garnet which causes the deformation of garnet and the quick diffusion of Mg is replaced by Fe.

The here derived P-T evolution of the glaucophane schist and garnet mica schist is different to previous interpretions of other authors. Shi *et al.* (2003) assumed P-T condition for the amphibole felses of > 10 kbar and 250-370°C. Shi *et al.* (2001) also mentioned the P-T condition of blueschists from the Tawmaw area as to be higher than 8-10 kbar with an average T of 582°C. Goffé *et al.* (2000) estimated P-T conditions for four stages of

crystallization in the surrounding rocks of the jadeitite. These authors proposed that the jadeitite crystallization based on the textural evidence occurred at 14-16 GPa at temperature of 450-500°C. Their estimation is similar to the here presented results. Moreover, Mével and Kiéneast also estimated the conditions of adjacent glaucophane schists by comparison with high-pressure rocks from the Western Alps to be 10-15 kbar at temperature of 300-500 °C.

Monazite occurs exclusively in garnet mica schists and only 43 analyses of monazite were suitable for geochronology yielded an age range between < 15 and 120 Ma. Goffé *et al.* (2000) determined <sup>39</sup>Ar-<sup>40</sup>Ar ages of phengites from high-pressure rocks of the jade mine area. These ages were between 50 to 80 Ma and were related to the high-pressure metamorphic events resulting from the collision of India and Asia. Recently, Ion Microprobe U-Pb ages of zircon grains from the Myanmar jadeitite were reported by Shi *et al.* (2008). These authors related the age of  $146.5 \pm 3.4$  Ma to the formation of the Myanmar jadeitites, as well as to the subduction of the eastern Indian Oceanic plate. This assignment contradicts the here presented view that the formation of the jadeitite was a Tertiary event. The Mesozoic ages are related here to metamorphism of sedimentary protoliths (garnet mica schist) at lower crustal levels (6-8 kbar). As country rocks (garnet mica schist) show, they were affected also by high pressures corresponding to Earth's depths of c. 50 km. Therefore, the continental crust was deeply buried by continent-continent collision, for instance, by underthrust of one plate under the other plate. This was probably the result of the early tectonic motions of the (pre) Sagaing fault in Tertiary times.

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# Na-rich vesuvianite in jadeitite of the Tawmaw jade district, northern Myanmar

by

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## running title: Na-rich vesuvianite in northern Myanmar

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## Abstract

In general, vesuvianite occurs in low-pressure environments such as contact aureoles, rodingite/metarodingite, and skarns. We describe a new occurrence of vesuvianite in a high-pressure metamorphic jadeitite, characterized by a P-T loop from 570-620 °C and 5.5-8.5 kbar to 470-540° C and 16-19 kbar. The mineral assemblage of vesuvianite + end-member jadeite does not show any indication for non-equilibrium.

The composition of this vesuvianite is characterized by up to  $1.5 \text{ wt.}\% \text{ Na}_2\text{O}$  that is higher than for vesuvianite described from elsewhere. A major mechanism to incorporate Na into vesuvianite is the charge balance keeping substitution Ca + Al = Na + Ti. Detailed measurements with the electron microprobe reveal that the composition of this vesuvianite is not homogeneous, but characterized by a relatively Na-Ti rich core. This core grades, at a sharp hiatus, into Na-Ti poor vesuvianite which is getting again continuously richer in Na and Ti towards the outer rim.

The petrological significance of this zoning is discussed in chemical potential diagrams. It is assumed that, in the general case during the formation of jadeitite or albitite, chemical potentials of all components in the fluid phase are externally controlled and the paragenesis only consisted of jadeite or albite. Local heterogeneities could have been caused by slow dissolution of precursor minerals such as titanite resulting in locally higher chemical potentials of TiO<sub>2</sub> and CaO. In such an environment, vesuvianite possibly has been formed. The zoning in vesuvianite may result from dilution of components released from precursor minerals into the "normal" fluid phase. Alternatively, it can speculated that the formation of vesuvianite is just the result of temporal and spatial variation in the composition of the fluid phase.

## 1. Introduction

Myanmar is famous for its wealth of high quality jadeitite which is a rock almost exclusively composed of Na-pyroxene such as jadeite. Jade is the trade term for rocks mainly composed of either jadeite or amphibole (nephrite). These (nearly) monomineralic rocks have typically been formed close to tectonically emplaced ultrabasic bodies by rock-fluid interaction (so-called wall-rock formation). In Myanmar, jadeitite deposits are generally associated with major strike-slip fault systems and found in serpentinite hosted blueschist or eclogite terrains related to subduction or transpression (Shi *et al.* 2008). In the present paper, vesuvianite,

found in a peculiar high pressure metamorphic jadeitite from Myanmar, is characterized and its formation discussed.

Vesuvianite is previously known to occur exclusively in relatively low pressure formations such as contact aureoles, rodingite/metarodingite, skarns, zeolite to granulite facies metamorphic calcsilicate rocks (e.g., Gnos & Armbruster 2006, Bogoch *et al.* 1997), or as late formation in igneous rocks such as nephelin syenites (e.g., Fitzgerald *et al.* 1987). The occurrence of this mineral in blueschist or eclogite facies rocks has never been reported before. A further peculiarity of the vesuvianite in the Myanmar jadeitite is high sodium content, higher than in vesuvianite from elsewhere.

## 2. Geological setting

The study area is located in the western part of the Sagaing fault zone within the Central Burma Basin in the Pharkant (Hpakan or Hparkant)-Tawmaw area, Kachin state, Northern Myanmar. It is bounded by Indo-Burman Ranges at the west and the Sagaing fault at the east. The Sagaing fault is a major active tectonic feature of Myanmar extending about more than 1200 km, with the Andaman spreading being its southern termination. The occurrence of ophiolite and tectonic slices of glaucophane bearing high-pressure metamorphic rocks in the Central Burma Basin and Indo-Burman Range results from collision and subduction processes between India and Asia (Mitchell, 1993; Shi *et al.* 2008).

In serpentinized peridotite of some of the ophiolites, jadeitite is found as veins or dyke-like bodies (Chhibber, 1934). The size of the jadeitite bodies range from about 1-10 m in width and about 10-20 m in length. The boundaries of these bodies to the host serpentinized peridotite are marked by chlorite and/or actinolite schist (Shi *et al.* 2003). The jadeitite partly shows a transition to albitite bodies. The occurrence of kosmochlor within the jadeite and albitite also indicate that these rocks have been formed in a specific chemical environment.

Shi *et al.* (2008) performed zircon U-Pb dating on zircons from the Myanmar jadeitite. Zircons with oscillatory zoning and inclusions of Mg rich minerals with an age cluster of  $163.2 \pm 3.3$  Ma are interpreted to be related to the formation of oceanic crust and/or hydrothermal overprint (serpentinization, rodingitization). A second group of zircon with a mean age of  $146.5 \pm 3.4$  Ma has inclusions of jadeite/sodic pyroxene, indicating the formation of the jadeitites at high-pressure conditions possibly related to subduction of the eastern Indian oceanic plate. Group III zircons with average age of  $122.2 \pm 4.8$  Ma may reflect the later thermal event.

Vesuvianite has been detected in just one (sample MJ11) of the studied jadeitites samples. This jadeitite body belongs in the Tawmaw ophiolite. The studied sample was collected close the jade mine in the city of Tawmaw in the Myitkyina district, Myanmar.

P-T conditions of a garnet-bearing mica schist, representing the country rock close to the jadeitite bodies, were derived from thermodynamic calculations using the computer programs PTGIBBS (Brandelik & Massonne 2004) and PERPLE\_X (Connolly 2005), the later for constructing P-T pseudosections. In garnet-mica schist, the P-T conditions for an early stage were 570-630 °C and 5.5-8.5 kbar followed by an overprint at 470-540° C and 16-19 kbar. The later P-T conditions could be also verified for a glaucophane schist sampled close to a jadeitite body (Nyunt & Massonne, in prep.).

## 3. Petrography

The vesuvianite-bearing jadeitite sample MJ11 belongs to the "monomineralic" jade variety. The rock contains about 97 % of jadeite showing medium to fine grained granoblastic texture with grain sizes ranging from 0.05 to 0.7 mm in width and about 0.1 to 3 mm in length. This heterogeneous grain size distribution reflects deformation localized along shear planes and subsequent fine grained recrystallization of stressed crystals forming a mortar structure. Uneven extinction observed under the microscope with crossed polarisers is common in most of the larger grains.

Vesuvianite occurs as accessory mineral in sample MJ11, amounting to about 1 % of the rock volume. It forms almost monomineralic aggregates up to 1 mm in diameter (Fig. 1). The shape of the aggregates is roundish. Individual columnar crystals of vesuvianite are up to 0.5 mm in length. The spatial orientation of the crystals is heterogeneous. Only a few jadeite inclusions occur in such aggregates. No indication for non-equilibrium between vesuvianite and adjacent jadeite was observed.

Most vesuvianite is heavily or even completely altered along cracks and grain boundaries (Fig. 2b). Brownish alteration products are composed of smectite-like sheet silicates and limonite. The alteration products amount to 2 % of the rock.



Fig. 1a: Roundish aggregate of vesuvianite crystals embedded in a colourless matrix of jadeite. The vesuvianite is partly replaced by yellowish smectite and brownish/black limonite. The arrow points to an inclusion of jadeite in the vesuvianite aggregate. The rectangle indicates the position of the micrograph in Fig. 2b. Sample MJ11, plane polarized light.



Fig. 1b: Back-scattered electron image of a vesuvianite aggregate (lower left of Fig. 1a). Vesuvianite is characterized by bright colours. Matrix jadeite and smectite show an intermediate grey. Black: resin.



Fig. 2a: Distribution of Ti in a vesuvianite aggregate. A core zone is characterized by a relatively high Ti content. An overgrowth on this core starts with Ti poor compositions grading into Ti rich at the outer rim. Line A - B indicates the measured profile of Fig. 4.



Fig. 2b: Micrograph of the lower right portion of the Ti distribution image of Fig. 2a. The dots from A to B indicate the positions of the chemical analyses presented in Fig. 4.

## Mineral chemistry and spectroscopic investigation

### 4.1. Analytical Methods

Because of the unusual occurrence of vesuvianite in a high-pressure environment, we verified the identity of this mineral by micro Raman spectroscopy using a high resolution Witec CRM200 spectrometer. This spectrometer was equipped with a frequency doubled Nd-YAG laser (523 nm). Scattered Raman light was collected in 180° backscattering geometry, and dispersed with a grading of 600 groves/mm. A 100x objective lens with a numerical aperture of 0.9 was used.

The chemical compositions of minerals in sample MJ11 was analysed using a Cameca SX100 electron microprobe equipped with five wavelength-dispersive spectrometers. The applied acceleration voltage and beam current were 15 kV and 15 or 20 nA, respectively. The beam diameter was normally set to 6 µm, but in case of small grains reduced to 1 µm. For vesuvianite, the concentrations of Si, Al, Ti, Mg, Mn, Fe, Ce, Ca, and Na were quantitatively measured, using the following standards: albite (Na), wollastonite (Ca, Si), periclase (Mg), synthetic corundum (Al), rutile (Ti), CePO<sub>4</sub> (Ce), rhodonite (Mn), and hematite (Fe). Counting times for full analyses were 20 s on peak and background of each element except Ce (40 s counting time). The PAP correction procedure provided by Cameca was applied. With these analytical conditions, the following elements analysed on several grains were found to be below the detection limit: Cl (detection limit: 0.04 wt.%), F (0.4), K (0.06), Sr (0.3), Ba (0.05), Cr (0.04), Zr (0.26), Nb (0.15), V (0.10), Cu (0.11), Pb (0.10), Th (0.19) and U (0.08). Boron was not quantitatively analysed. WDS scans performed with the PC2 and PC3 diffraction crystals of the microprobe, however, showed no discernable peak at the B Ka position. It was concluded that boron, if at all, is only present in subordinate amounts. The same major elements as in vesuvianite were also analysed in jadeite (except Ce).

Concentration maps for major elements were prepared by step-wise movement (100 or 200 ms counting time per step) of the thin section under the electron beam of the microprobe. The energy-dispersive system of the microprobe served as mean of identification of phases during the selection of spots for full analyses.

#### 4.2. Verification of vesuvianite by Raman spectrometry

Raman spectra of the phase under consideration have been acquired from several grains of sample MJ11. All collected spectra of this phase show the same peak positions and intensities. A sample spectrum is shown in (Fig. 3a).

The peak positions of the acquired Raman spectra were compared with a reference vesuvianite spectrum (No. R060170 provided by the RRUFF<sup>TM</sup> Project, <u>http://rruff.info</u>). It can be seen that the coincidence of the peak positions with this reference spectrum is very good, indicating that the investigated mineral in sample MJ11 is indeed vesuvianite (Fig. 3b).

#### 4.3. Vesuvianite composition

Representative mineral analyses of the measured vesuvianite of sample MJ11 are given in Table 1. Concerning the major elements, the MJ11 vesuvianite corresponds to analyses of this mineral from elsewhere (e.g., Gnos & Armbruster 2006). However, the high Na<sub>2</sub>O content of up to 1.5 wt.% is a peculiar feature of the vesuvianite from the high-pressure jadeitete from Myanmar. To the author's knowledge, this is actually the highest Na content in vesuvianite ever reported.

A common end-member formula of vesuvianite is  $Ca_{19}Mg_2Al_{11}Si_{18}O_{68}(O)(OH)_9$ . More generally, the formula can be written as  $X_{19}Y_{13}T_5Z_{18}O_{68}(W)_{10}$ , with the most common cations being X = (Ca,Na), Y = (Al,Fe,Mn,Ti), Z = (Si), W = (OH,O,F,Cl). The additional T-site is vacant in common vesuvianite, but may occasionally contain some Al, Fe<sup>3+</sup>, and B (Groat *et al.* 1994).

For the calculation of the structural formulae, it is generally proposed to normalize vesuvianite analyses to 50 cations (e.g., Groat *et al.* 1992, Gnos & Armbruster 2006), not considering partial occupancy of the T-site. For our vesuvianite, this procedure results in average Z-site and X-site occupancies of 17.75 and 18.73 cations, respectively, being below the ideal values of 18 and 19. In contrast, the Y-site cations are above the ideal value of 13, showing a mean value of 13.32 cations. It is therefore obvious that the T-site is partially filled, as it is the case for other high-grade metamorphic vesuvianite ("Excess-Y"; Groat *et al.* 1994; Gnos & Armbruster 2006). Accordingly, we adopted the procedure to normalize Si to 18 cations as proposed by Gnos & Armbruster (2006). The assumption to restrict the Z site to Si as sole cation may be particular appropriate for vesuvianite from a high pressure metamorphic environment at elevated temperature.

The resulting cation total of the X-site is 18.89 as mean value, close to ideal with only a slight deficiency. Assuming that the Y-site contains 13 cations in total, an average value of



Fig. 3a: Raman spectrum (raw data) of the vesuvianite of the jadeitite sample MJ11.



Fig. 3b: The peak positions of the Raman spectrum of the MJ11 vesuvianite in comparison with a vesuvianite reference spectrum (No. R060170, provided by the RRUFF<sup>TM</sup> Project, <u>http://rruff.info</u>). The reference spectrum is corrected for background intensity.

Table 1. Representative analyses of vesuvianite normalized to 18 Si. The H<sub>2</sub> O content is calculated from stoichiometry.

bld = below detection limit

| ge)   | #5   | 36.69   | 1.29    | 20.36     | 1.82 | 0.16 | 0.41 | bdl       | 33.69 | 1.40    | 2.39   | 98.21 | • •   | 18.00 | 0.48            | 18.00<br>0.48<br>11.77  | 18.00<br>0.48<br>11.77<br>0.75  | 18.00<br>0.48<br>11.77<br>0.75<br>0.07                                  | 18.00<br>0.48<br>11.77<br>0.75<br>0.07<br>0.30  | 18.00<br>0.48<br>11.77<br>0.75<br>0.07<br>0.30<br>13.36                                | 18.00<br>0.48<br>0.75<br>0.75<br>0.07<br>0.07<br>0.00<br>0.00   | 18.00           0.48           0.48           0.75           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.07           0.00           0.00  | 18.00<br>0.48<br>0.75<br>0.75<br>0.07<br>0.30<br>0.30<br>0.30<br>0.30<br>13.36<br>1.3.36<br>1.3.34   | $\begin{array}{c} 18.00\\ 0.48\\ 0.177\\ 0.07\\ 0.30\\ 0.30\\ 0.00\\ 0.00\\ 117.71\\ 1.34\\ 1.34\\ 1.9.07\\ 19.07\\ \end{array}$   |
|---|------|---------|---------|-----------|------|------|------|-----------|-------|---------|--------|-------|-------|-------|-----------------|---|---|---|---|--|---|---|--|--|
| n BSE imi   | #4   | 37.01   | 1.41    | 20.51     | 1.81 | 0.21 | 0.26 | lbd       | 33.72 | 1.44    | 2.51   | 98.88 |       | 18.00 | $18.00 \\ 0.52$ | $     \begin{array}{r}       18.00 \\       0.52 \\       11.76     \end{array} $ | $   \begin{array}{r}     18.00 \\     0.52 \\     11.76 \\     0.74   \end{array} $ | 18.00<br>0.52<br>11.76<br>0.74<br>0.09                                  | $ \begin{array}{c} 18.00 \\ 0.52 \\ 0.52 \\ 11.76 \\ 0.74 \\ 0.09 \\ 0.19 \\ \end{array} $  | 18.00<br>0.52<br>11.76<br>0.74<br>0.09<br>0.19<br>13.29                                | 18.00<br>0.52<br>11.76<br>0.74<br>0.09<br>0.19<br>13.29<br>0.00   | $\begin{array}{c} 18.00\\ \hline 0.52\\ 11.76\\ 0.74\\ 0.09\\ 0.19\\ 13.29\\ 13.29\\ 17.57\\ 17.57\\ \end{array}$   | $\begin{array}{c} 18.00\\ \hline 0.52\\ 11.76\\ 0.74\\ 0.09\\ 0.19\\ 13.29\\ 13.29\\ 17.57\\ 1.36\end{array}$  | 18.00           0.52           0.52           11.76           0.74           0.09           0.19           13.29           0.00           17.57           1.36           1.36           1.8.96   |
| es (dark i  | #2   | 36.79   | 1.48    | 20.31     | 1.82 | 0.22 | 0.31 | lbd       | 33.45 | 1.49    | 2.47   | 98.35 | 0001  | 18.00 | 18.00           | 18.00<br>0.55<br>11.71  | 18.00<br>0.55<br>11.71<br>0.74  | 18.00<br>0.55<br>11.71<br>0.74<br>0.09                                  | 18.00<br>0.55<br>11.71<br>0.74<br>0.09<br>0.22  | 18.00<br>0.55<br>11.71<br>0.74<br>0.09<br>0.22<br>13.32                                | 18.00<br>0.55<br>11.71<br>0.74<br>0.09<br>0.09<br>13.32<br>13.32<br>0.00  | 18.00<br>0.55<br>11.71<br>0.74<br>0.09<br>0.09<br>0.22<br>13.32<br>13.32<br>0.00  | 18.00<br>0.55<br>11.71<br>0.74<br>0.09<br>0.22<br>13.32<br>13.32<br>0.00<br>0.00<br>1.7.54<br>1.41   | 18.00<br>0.55<br>11.71<br>0.74<br>0.09<br>0.22<br>13.32<br>13.32<br>0.00<br>17.54<br>1.41<br>1.8.96  |
| Relic cor   | #1   | 36.90   | 1.53    | 20.25     | 1.74 | 0.15 | 0.28 | lbdl      | 33.70 | 1.45    | 2.54   | 98.55 |       | 18.00 | 18.00<br>0.56   | $\frac{18.00}{0.56}$<br>11.64   | 18.00<br>0.56<br>11.64<br>0.71  | 18.00<br>0.56<br>11.64<br>0.71<br>0.06                                  | 18.00<br>0.56<br>0.56<br>11.64<br>0.71<br>0.71<br>0.06  | 18.00<br>0.56<br>0.71<br>0.71<br>0.06<br>0.20<br>13.18                                 | 18.00<br>0.56<br>0.71<br>0.71<br>0.71<br>0.06<br>0.20<br>0.00<br>0.00   | 18.00           0.56           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.71           0.70           0.70           0.00           0.00 | 18.00           0.56           0.56           0.71           0.71           0.71           0.06           0.06           0.13.18           13.18           17.61           17.61           17.61 | 18.00           0.56           0.71           0.71           0.06           0.06           0.20           0.13.18           0.00           13.18           0.00           13.18           13.18           13.18           13.18           19.00           19.00  |
| Profile rim (A) -> core (B) [Relic cores (dark in BSE image)] | #26  | 36.57   | 2.74    | 19.31     | 1.71 | 0.13 | 0.60 | 0.15      | 33.71 | 1.33    | 2.14   | 98.38 | 000   | 18.00 | 18.00           | $\frac{18.00}{1.01}$<br>11.21   | 18.00<br>1.01<br>11.21<br>0.70  | 18.00<br>1.01<br>11.21<br>0.70<br>0.06                                  | 18.00<br>1.01<br>11.21<br>0.70<br>0.06<br>0.44  | 18:00<br>1.01<br>11.21<br>0.70<br>0.06<br>0.44<br>13.41                                | 18:00<br>1.01<br>11.21<br>11.21<br>0.70<br>0.06<br>0.44<br>13.41<br>13.41<br>0.03   | 18:00<br>1.01<br>11.21<br>0.70<br>0.06<br>0.44<br>13.41<br>13.41<br>0.03<br>0.03  | $\begin{array}{c} 18.00\\ 1.01\\ 11.21\\ 0.70\\ 0.06\\ 0.44\\ 13.41\\ 13.41\\ 1.3.41\\ 1.778\\ 1.778\\ 1.27\end{array}$  | 18:00<br>1.01<br>11.21<br>0.70<br>0.44<br>0.44<br>13.41<br>0.03<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.78<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.71<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77<br>17.77 |
|   | #20  | 36.70   | 3.13    | 19.03     | 1.81 | 0.12 | 0.68 | 0.17      | 33.88 | 1.28    | 2.10   | 98.91 | 10.00 | 18.00 | 1.16            | 18.00<br>1.16<br>11.00  | 18.00<br>1.16<br>11.00<br>0.74  | 18.00<br>1.16<br>11.00<br>0.74<br>0.05                                  | 18.00<br>1.16<br>11.00<br>0.74<br>0.74<br>0.05  | 18.00<br>1.16<br>11.00<br>0.74<br>0.74<br>0.05<br>0.05<br>13.45                        | 18:00           1.16           11:00           0.74           0.50           13:45           13:45           0.03   | 18.00           1.16           11.00           0.74           0.75           0.05           0.50           0.50           13.45           0.03           17.81  | $\begin{array}{c} 18.00 \\ 1.16 \\ 11.00 \\ 0.74 \\ 0.05 \\ 0.05 \\ 0.03 \\ 13.45 \\ 13.45 \\ 17.81 \\ 1.21 \end{array}$   | 18.00           1.16           11.00           11.00           0.74           0.05           0.50           13.45           0.03           17.81           1.21           19.07  |
|   | #19  | 36.59   | 3.17    | 18.99     | 1.73 | 0.10 | 0.67 | 0.07      | 33.79 | 1.26    | 2.11   | 98.49 | ~~~~  | 18.00 | 18.00<br>1.17   | $\frac{18.00}{1.17}$ 11.01  | 18.00<br>1.17<br>11.01<br>0.71  | 18.00<br>1.17<br>11.01<br>0.71<br>0.04                                  | $\begin{array}{c} 18.00\\ 1.17\\ 1.17\\ 11.01\\ 0.71\\ 0.04\\ 0.49 \end{array}$   | 18.00<br>1.17<br>11.01<br>0.71<br>0.49<br>0.49<br>13.43                                | 18.00           1.17           11.01           0.71           0.71           0.49           13.43           13.43           0.01                            | 18.00           1.17           1.17           1.101           0.71           0.71           0.749           0.49           13.43           0.01           17.81   | 18.00           1.17           1.17           11.01           0.71           0.71           0.49           13.43           13.43           13.43           13.43           13.43           1.20  | 18.00           1.17           11.01           11.01           0.71           0.71           0.049           0.499           13.43           0.01           17.81           17.81           1.20           1.20  |
|   | #17  | 37.22   | 3.07    | 19.17     | 1.84 | 0.15 | 0.66 | 0.11      | 33.38 | 1.31    | 2.57   | 99.48 |       | 18.00 | 1.12            | $\frac{18.00}{1.12}$<br>10.93   | $   \begin{array}{r}     18.00 \\     1.12 \\     10.93 \\     0.75   \end{array} $ | 18.00<br>1.12<br>10.93<br>0.75<br>0.06                                  | $     \begin{array}{r}       18.00 \\       1.12 \\       10.93 \\       0.75 \\       0.06 \\       0.48 \\       0.48   \end{array} $ | 18.00<br>1.12<br>10.93<br>0.75<br>0.75<br>0.06<br>0.48<br>0.48<br>13.33                | $\begin{array}{c} 18.00\\ 1.12\\ 1.12\\ 10.93\\ 0.75\\ 0.75\\ 0.48\\ 0.48\\ 13.33\\ 13.33\\ 0.02\end{array}$  | $\begin{array}{c} 18.00\\ 1.12\\ 1.12\\ 0.75\\ 0.75\\ 0.48\\ 13.33\\ 13.33\\ 0.02\\ 17.30\\ \end{array}$  | $\begin{array}{c} 18.00\\ \hline 1.12\\ 10.93\\ 0.75\\ 0.75\\ 0.06\\ 0.06\\ 0.08\\ 13.33\\ 13.33\\ 13.33\\ 13.33\\ 17.30\\ 1.23\end{array}$  | $\begin{array}{c} 18.00\\ \hline 1.12\\ 10.93\\ 0.75\\ 0.75\\ 0.06\\ 0.48\\ 13.33\\ 13.33\\ 13.33\\ 0.02\\ 17.30\\ 17.30\\ 18.60\\ 18.60\\ \end{array}$  |
| <b>•</b>  | #15  | 37.05   | 1.23    | 20.41     | 1.90 | 0.15 | 0.60 | lbdl      | 34.96 | 1.09    | 2.21   | 99.62 | 10.00 | 18.00 | 0.45            | 18.00<br>0.45<br>11.69  | 18.00<br>0.45<br>11.69<br>0.77  | 18.00<br>0.45<br>11.69<br>0.77<br>0.06                                  | 18.00<br>0.45<br>11.69<br>0.77<br>0.06<br>0.44  | 18.00<br>0.45<br>11.69<br>0.77<br>0.77<br>0.66<br>0.44<br>13.40                        | $\begin{array}{c} 18.00\\ 0.45\\ 11.69\\ 0.77\\ 0.77\\ 0.44\\ 0.44\\ 13.40\\ 0.00\\ 0.00\\ \end{array}$   | $\begin{array}{c} 18.00\\ 0.45\\ 11.69\\ 0.77\\ 0.06\\ 0.44\\ 13.40\\ 13.40\\ 18.20\\ 18.20\\ \end{array}$  | $\begin{array}{c} 18.00\\ 0.45\\ 11.69\\ 0.77\\ 0.06\\ 0.44\\ 13.40\\ 13.40\\ 18.20\\ 1.03\\ 1.03\end{array}$  | $\begin{array}{c} 18.00\\ 0.45\\ 0.45\\ 11.69\\ 0.77\\ 0.06\\ 0.44\\ 13.40\\ 0.00\\ 18.20\\ 1.03\\ 1.03\\ 19.27\end{array}$  |
| core (B   | #13  | 37.00   | 1.26    | 20.37     | 1.77 | 0.21 | 0.56 | lbdl      | 34.59 | 1.15    | 2.33   | 99.22 |       | 18.00 | 18.00<br>0.46   | $   \frac{18.00}{0.46}   $ $   11.68 $  | 18.00<br>0.46<br>11.68<br>0.72  | $ \begin{array}{c} 18.00 \\ 0.46 \\ 11.68 \\ 0.72 \\ 0.09 \end{array} $ | $ \begin{array}{c} 18.00 \\ 0.46 \\ 11.68 \\ 0.72 \\ 0.72 \\ 0.09 \\ 0.41 \end{array} $   | 18.00<br>0.46<br>11.68<br>0.72<br>0.72<br>0.09<br>0.41<br>13.35                        | $\begin{array}{c} 18.00 \\ 0.46 \\ 0.46 \\ 0.72 \\ 0.09 \\ 0.01 \\ 0.00 \\ 0.00 \end{array}$  | $\begin{array}{c} 18.00\\ 0.46\\ 11.68\\ 0.72\\ 0.09\\ 0.41\\ 13.35\\ 13.35\\ 18.03\\ 18.03\end{array}$   | $\begin{array}{c} 18.00\\ 0.46\\ 11.68\\ 0.72\\ 0.09\\ 0.41\\ 13.35\\ 13.35\\ 18.03\\ 1.08\\ 1.08\end{array}$  | $\begin{array}{c} 18.00\\ 0.46\\ 11.68\\ 0.72\\ 0.09\\ 0.41\\ 13.35\\ 13.35\\ 13.35\\ 13.35\\ 13.35\\ 19.04\\ 19.14\end{array}$  |
| (Y)   | #12  | 36.94   | 1.33    | 20.43     | 1.85 | 0.17 | 0.56 | lbdl      | 34.71 | 1.12    | 2.17   | 99.32 |       | 18.00 | 18.00<br>0.49   | $     \begin{array}{r}       18.00 \\       0.49 \\       11.73     \end{array} $ | 18.00<br>0.49<br>11.73<br>0.75  | 18.00<br>0.49<br>11.73<br>0.75<br>0.07                                  | 18.00<br>0.49<br>11.73<br>0.75<br>0.07<br>0.41  | $\begin{array}{c} 18.00\\ 0.49\\ 11.73\\ 0.75\\ 0.75\\ 0.07\\ 0.41\\ 13.45\end{array}$ | $\begin{array}{c} 18.00 \\ 0.49 \\ 11.73 \\ 0.75 \\ 0.07 \\ 0.01 \\ 0.01 \\ 13.45 \\ 0.01 \end{array}$  | $\begin{array}{c} 18.00\\ 0.49\\ 11.73\\ 0.75\\ 0.07\\ 0.41\\ 13.45\\ 13.45\\ 18.13\\ 18.13\end{array}$   | $\begin{array}{c} 18.00\\ 0.49\\ 0.49\\ 0.75\\ 0.75\\ 0.07\\ 0.41\\ 13.45\\ 13.45\\ 1.06\\ 1.06\end{array}$  | $\begin{array}{c} 18.00\\ 0.49\\ 0.49\\ 11.73\\ 0.75\\ 0.07\\ 0.41\\ 13.45\\ 13.45\\ 13.45\\ 13.13\\ 18.13\\ 1.06\\ 19.22\end{array}$  |
| rofile rim  | #10  | 36.94   | 1.81    | 20.04     | 1.96 | 0.19 | 0.56 | lbdl      | 34.36 | 1.14    | 2.24   | 99.30 | 10.00 | 18.00 | 0.66            | 0.66<br>0.66<br>11.51   | 0.66<br>0.66<br>11.51<br>0.80   | 0.66<br>0.66<br>11.51<br>0.80<br>0.08                                   | 0.66<br>0.66<br>11.51<br>0.80<br>0.08<br>0.08   | 18.00<br>0.66<br>0.66<br>0.80<br>0.80<br>0.08<br>0.41<br>13.46                         | 18.00           0.66           0.80           0.80           0.80           0.81           0.93           0.41           0.41           0.41           0.01 | $\begin{array}{c} 18.00\\ 0.66\\ 0.66\\ 0.80\\ 0.80\\ 0.41\\ 13.46\\ 13.46\\ 17.94\\ 17.94\end{array}$  | $\begin{array}{c} 18.00\\ 0.66\\ 0.80\\ 0.80\\ 0.41\\ 13.46\\ 13.46\\ 1.08\\ 1.08\\ 1.08\\ 1.08\\ \end{array}$   | $\begin{array}{c} 18.00\\ 0.66\\ 11.51\\ 0.80\\ 0.08\\ 0.08\\ 0.01\\ 13.46\\ 13.46\\ 1.08\\ 1.08\\ 1.08\\ 19.06\end{array}$  |
| Ъ   | 8#   | 37.01   | 2.45    | 19.50     | 1.88 | 0.17 | 0.58 | lbdl      | 34.28 | 1.28    | 2.29   | 99.46 | 18 00 | 0000  | 0.90            | 0.90  | 0.90<br>11.18<br>0.77   | 0.90<br>0.90<br>0.77<br>0.07  | 0.90<br>0.77<br>0.77<br>0.07<br>0.42  | $\begin{array}{c} 0.90\\ 0.90\\ 0.77\\ 0.77\\ 0.07\\ 0.42\\ 13.33\end{array}$          | $\begin{array}{c} \begin{array}{c} 0.90\\ 11.18\\ 0.77\\ 0.07\\ 13.33\\ 13.33\\ 0.00\\ 0.00\\ \end{array}$  | $\begin{array}{c} 0.90\\ 0.90\\ 11.18\\ 0.77\\ 0.77\\ 0.42\\ 13.33\\ 13.33\\ 17.86\\ 17.86\end{array}$  | $\begin{array}{c} 0.90\\ 0.90\\ 11.18\\ 0.77\\ 0.77\\ 0.42\\ 13.33\\ 13.33\\ 13.33\\ 0.00\\ 17.86\\ 1.21\\ 1.21\end{array}$  | $\begin{array}{c} 0.900\\ 0.97\\ 0.77\\ 0.77\\ 0.07\\ 0.42\\ 13.33\\ 0.00\\ 0.00\\ 1.7.86\\ 1.21\\ 1.21\\ 1.21\\ 19.10\end{array}$   |
|   | L#   | 36.95   | 2.38    | 19.89     | 1.77 | 0.17 | 0.51 | lbdl      | 34.16 | 1.30    | 2.16   | 99.29 | 18.00 |       | 0.87            | 0.87<br>11.42   | 0.87<br>11.42<br>0.72   | 0.87<br>11.42<br>0.72<br>0.07   | $\begin{array}{c} 0.87 \\ 0.87 \\ 11.42 \\ 0.72 \\ 0.07 \\ 0.37 \end{array}$  | 0.87<br>11.42<br>0.72<br>0.07<br>0.37<br>13.45   | 0.87<br>11.42<br>0.72<br>0.07<br>0.37<br>13.45<br>13.45<br>0.00   | 0.87<br>11.42<br>0.72<br>0.07<br>0.37<br>13.45<br>13.45<br>13.45<br>0.00  | $\begin{array}{c} 0.87\\ 11.42\\ 0.72\\ 0.07\\ 0.37\\ 13.45\\ 13.45\\ 0.00\\ 17.83\\ 1.23\end{array}$  | 0.87<br>11.42<br>0.72<br>0.07<br>0.07<br>0.37<br>13.45<br>13.45<br>13.45<br>13.45<br>17.83<br>17.83<br>17.83<br>17.83  |
|   | #5   | 36.88   | 2.64    | 19.65     | 1.88 | 0.19 | 0.57 | lbdl      | 34.13 | 1.28    | 2.09   | 99.31 | 18.00 |       | 0.97            | 0.97<br>11.30   | 0.97<br>11.30<br>0.77   | 0.97<br>11.30<br>0.77<br>0.08   | 0.97<br>11.30<br>0.77<br>0.08<br>0.41   | 0.97<br>11.30<br>0.77<br>0.08<br>0.41<br>13.52   | $\begin{array}{c} 0.97\\ 11.30\\ 0.77\\ 0.08\\ 0.41\\ 13.52\\ 0.00\\ 0.00\\ \end{array}$  | 0.97<br>11.30<br>0.77<br>0.77<br>0.41<br>13.52<br>13.52<br>0.00   | 0.97<br>11.30<br>0.77<br>0.77<br>0.41<br>13.52<br>0.00<br>17.84<br>1.21  | 0.97<br>11.30<br>0.77<br>0.77<br>0.08<br>0.08<br>13.52<br>13.52<br>0.00<br>17.84<br>17.84<br>17.84<br>17.84<br>17.84   |
|   | #3   | 36.55   | 2.65    | 19.48     | 1.90 | 0.16 | 0.56 | lbdl      | 34.09 | 1.20    | 1.98   | 98.57 | 18.00 |       | 0.98            | 0.98<br>11.31   | 0.98<br>11.31<br>0.78   | 0.98<br>11.31<br>0.78<br>0.07   | 0.98<br>11.31<br>0.78<br>0.07<br>0.41   | 0.98<br>11.31<br>0.78<br>0.07<br>0.41<br>13.55   | 0.98<br>11.31<br>0.78<br>0.07<br>0.41<br>13.55<br>0.00  | 0.98<br>11.31<br>0.78<br>0.78<br>0.07<br>0.41<br>13.55<br>13.55<br>0.00<br>0.00   | 0.98<br>11.31<br>0.78<br>0.07<br>0.41<br>13.55<br>0.00<br>17.99<br>1.15  | 0.98<br>11.31<br>0.78<br>0.07<br>0.07<br>0.41<br>13.55<br>13.55<br>0.00<br>17.99<br>17.99<br>17.99   |
|   | #1   | 36.87   | 2.81    | 19.45     | 1.73 | 0.15 | 0.59 | lbdl      | 33.89 | 1.25    | 2.23   | 99.01 | 18.00 |       | 1.03            | 1.03<br>11.19   | 1.03<br>11.19<br>0.71   | 1.03<br>11.19<br>0.71<br>0.06   | 1.03<br>11.19<br>0.71<br>0.06<br>0.43   | 1.03<br>11.19<br>0.71<br>0.06<br>0.43<br>13.41   | 1.03<br>11.19<br>0.71<br>0.06<br>0.43<br>13.41<br>13.41<br>0.01   | 1.03<br>11.19<br>0.71<br>0.06<br>0.43<br>13.41<br>13.41<br>0.01<br>0.01   | $\begin{array}{c} 1.03\\11.19\\0.71\\0.71\\0.06\\0.43\\13.41\\13.41\\0.01\\17.73\\1.73\end{array}$   | 1.03<br>11.19<br>0.71<br>0.71<br>0.71<br>0.71<br>13.41<br>13.41<br>0.01<br>17.73<br>1.773<br>1.19<br>18.96   |
| /0 ***  | W1.% | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | FeO  | MnO  | MgO  | $Ce_2O_3$ | CaO   | $Na_2O$ | $H_2O$ | Total | Si    |       | Ξ               | Ti<br>Al  | $\frac{\mathrm{Ti}}{\mathrm{Fe}^{2+}}$  | Ti<br>Al<br>Fe <sup>2+</sup><br>Mn                                      | Ti<br>Al<br>Fe <sup>2+</sup><br>Mn<br>Mg  | $\begin{array}{c} Ti\\ Al\\ Fe^{2+}\\ Mn\\ Mg\\ \Sigma  Y+T \end{array}$               | $\begin{array}{c c} Ti \\ AI \\ AI \\ Mn \\ Mg \\ Mg \\ Mg \\ V+T \\ Ce \end{array}$  | $\begin{array}{c c} Ti \\ AI \\ Fe^{2^+} \\ Mn \\ Mn \\ Mg \\ Mg \\ Mg \\ Ce \\ Ce \\ Ca \\ Ca \\ Ca \\ Ca \\ Ca \\ Ca$   | $\begin{array}{c c} Ti & \\ AI & \\ Fe^{2^+} \\ \hline Mn & \\ Mm & \\ Mg & \\ Mg \\ Mg \\ Ce & \\ Ca & \\ Ca & \\ Na & \\ Na \end{array}$   | $\begin{array}{c c} Ti \\ Al \\ Fe^{2^+} \\ \hline Mn \\ Mn \\ Mg \\ Mg \\ Mg \\ Ce \\ Ca \\ Ca \\ Na \\ Na \\ \Sigma \\ X \end{array}$  |

0.26 cations can be assessed to the T-site. Because we did not find boron, it is assumed that the T-site cations mainly consist of Al. The OH content is calculated from charge balancing (H = 156 - F - Cl - valencies of cations). The resulting mean value of 7.6 is relatively low compared to the ideal value of 9. As discussed by Allen and Burnham (1992), crystalchemical reasons may preclude such a OH-poor member because of too low Pauling bond strength sum at O(10) although such OH-poor compositions are known from several localities.

A peculiar feature of MJ11 vesuvianite is a relatively high content of Na ranging up to about 1.5 wt.% of Na<sub>2</sub>O, whereas in most of published analyses of vesuvianite from elsewhere the content of this element is below 0.4 wt.%, or even below detection limit. In contrast, compared to common vesuvianite, FeO and MgO are present only in low concentrations of 2.2 and 0.7 wt.'%, respectively, in average. The analysed TiO<sub>2</sub> content of 1.0 to 3.3 wt.% is in the range of vesuvianite from elsewhere.

#### 4.4. Chemical zoning in vesuvianite

Chemical mapping with the microprobe was applied to detect chemical zonation. The most obvious zoning concerns the Ti content (Fig. 2a). A core zone of a vesuvianite aggregate is characterized by a relatively high and constant Ti content. This zone is overgrown by a second generation of this mineral, which started to crystallize with low Ti content continuously increasing towards the outer rim. On the basis of the Ti distribution image, a profile was selected perpendicular to the zoning (line A-B in Fig. 2). Along the profile (Fig. 4), the strong Ti zoning is visible as in the distribution map: a high and relatively constant Ti content in the core is dropping at a sharp hiatus from about 1.1 to 0.4 cations p.f.u.. The sodium zoning is roughly parallel to Ti, but not as strong. Particularly Al and to a lesser degree Ca show a opposite zoning compared to Ti. Iron and magnesium are almost constant along the profile. Whereas the rim is devoid of Ce, this element is present in minor amounts in the core of the vesuvianite aggregate. The described zoning pattern concerns an aggregate of several individual vesuvianite crystals. It can obviously be interpreted as a growth zoning.

In addition, there is also an intra-crystalline zoning present. In the BSE image (Fig. 5), there is occasionally a relic core composition in individual crystals discernable. In contrast to the aforementioned zoning pattern, this zoning seems to be due to a replacement process. Actually, if plotted in a diagram Ti vs. Na (Fig. 6), it can be recognized that the few relic compositions analyzed follow a different trend compared to all other analyses. These relic vesuvianite compositions are characterized by relatively low Ti and by high Na content.



Fig. 4: Profile from rim (A) to core (B) in vesuvianite. The location of the profile is indicated in Fig. 2.



Fig. 5: BSE image of vesuvianite, sample MJ11. Occasionally, in columnar vesuvianite crystals dark cores are visible in the BSE image. These cores are interpreted as relic of a precursor vesuvianite. Black: Alteration phases.


Fig. 6: Element correlation in vesuvianite. Oblique lines have a slope of 1 or -1. Jadeitite sample MJ11.

#### 4.5. Cation substitution mechanism in vesuvianite

The major cation in the X site of vesuvianite is Ca, and Al in the Y site, respectively. Replacing of Al by Ti,  $Fe^{2+}$  and Mg, and of Ca by Na and Ce (and further rare earth elements) requires charge balance considerations. A mechanism commonly proposed for the incorporation of Ti into vesuvianite is the coupled substitution (see Hoisch 1985; Fitzgerald *et al.* 1992; Groat *et al.* 1992; Groas & Armbruster 2006)

(1) 
$$Ti + (Mg, Fe^{2+}, Mn^{2+}) = 2 Al$$

However, in sample MJ11, the amount of  $Mg + Fe^{2+} + Mn^{2+}$  is almost constant at a value of c. 1.3 cations p.f.u. except in the relic cores which contain c. 1.0. Accordingly, substitution mechanism (1) can be ruled out as well. However, substitution of Al by Ti is strongly suggested by a good negative Al-Ti correlation with a slope of -1. The required charge balance can be provided by Na-Ca substitution (Groat *et al.* 1992):

(2) 
$$Ti + Na = Al + Ca.$$

Actually, a significant cluster of compositions have equal amount of Na + Ti of about 1.2 cations p.f.u. (Fig. 6). However, in case of Ti poorer compositions, the amount of Na remains too high to be completely explained by substitution mechanism (2). This is particularly true for the relic core compositions. A further mechanism is required to account for the high Na content.

A possible substitution to keep charge balance despite Na incorporation is

$$(3) \qquad Na + O = Ca + OH.$$

A plot of Na versus OH, however, shows that no correlation exists, ruling out mechanism (3) for our vesuvianite.

A plot of Na versus Fe + Mg + Mn shows, despite some scatter, a correlation with a slope of -

1, suggesting the substitution

(4) Na + Al = Ca + (Fe+Mg+Mn)

to be of importance.

Vacancies of T sites may also be considered for the charge balance, such as:

(5) Na + 0.33 Al<sub>T-site</sub> = Ca + 0.33  $_{T-site}$ 

However, a negative correlation exits between the total (Y + T) sites and Na, ruling out this substitution for Na incorporation.

Summarizing, an important substitution to incorporate Na and Ti into vesuvianite is (2), but also(4) is important for Na in vesuvianite. The negative correlation of Na with the total of the (Y+T) sites is not consistent with Na incorporation into vesuvianite but seems to counteract it.

### 4.6. Alteration of vesuvianite

The studied vesuvianite is always partially or completely altered along the rims and cracks. The alteration phases are limonite and a brownish sheet silicate. Microprobe analyses reveal that this mineral has the chemical composition and anhydrous total typical for smectite (Table 2). Obviously, the formation of limonite and smectite is a low temperature alteration not related to high-pressure conditions.

#### 4.7. Composition of jadeite

The jadeite analyses have been normalized to 4 cations and 6 oxygen. The resulting cation distribution corresponds to almost pure jadeite, with jadeite component ranging from  $Jd_{100}$  to  $Jd_{98}$  (Table 2).

# 5. Discussion and Conclusions

### 5.1. Petrological significance of vesuvianite in jadeitite jade

The vesuvianite from the Myanmar jadeitite contains a high amount of Na reflecting the Na rich environment consisting almost entirely of jadeite. The largest chemical variation in this mineral, however, concerns Ti. It can therefore be speculated that this element may be of importance for the formation of vesuvianite as it can be introduced in jadeite only to a limited amount (see also Table 2). In addition, it has to be considered that this mineral contains Ca, in contrast to jadeite. A further constraint is the distribution of vesuvianite crystals, which only occur in roundish aggregates and is not evenly spread as single crystals in the jadeite matrix.

Based on these observations, it can be speculated that the formation of vesuvianite is, on a millimetre scale, a local phenomena, characterized by a special chemical environment. Such a special environment may be the former presence of a Ca and/or Ti rich precursor mineral such as titanite. This mineral may have been replaced be vesuvianite according to a reaction that obviously cannot be isochemical but involved components of the fluid phase. Considering the ideal composition of vesuvianite, such a reaction may be:

$$(R1) \quad \text{titanite} + 18(\text{CaO})_{\text{fluid}} + 2(\text{MgO})_{\text{fluid}} + 18(\text{SiO}_2)_{\text{fluid}} + 11(\text{AlO}_{1.5})_{\text{fluid}} + 4.5(\text{H}_2\text{O})_{\text{fluid}}$$
$$= \text{vesuvianite} + (\text{TiO}_2)_{\text{fluid}} .$$

| Wt.%  | Jadeite |       |       | Smectite |       |
|-------|---------|-------|-------|----------|-------|
| SiO2  | 58.52   | 58.79 | 58.74 | 49.02    | 49.05 |
| TiO2  | bdl     | bdl   | bdl   | 0.30     | 0.57  |
| A12O3 | 25.30   | 25.53 | 25.10 | 12.86    | 12.37 |
| Cr2O3 | bdl     | bdl   | bdl   | bdl      | bdl   |
| FeO   | 0.06    | 0.05  | 0.07  | 7.34     | 10.55 |
| MnO   | bdl     | bdl   | bdl   | 0.09     | 0.10  |
| MgO   | 0.07    | 0.08  | 0.21  | 12.43    | 11.75 |
| CaO   | 0.20    | 0.07  | 0.30  | 0.81     | 0.72  |
| Na2O  | 15.00   | 15.09 | 14.96 | 0.23     | 0.24  |
| K2O   | bdl     | bdl   | bdl   | 0.66     | 0.72  |
| Total | 99.14   | 99.60 | 99.37 | 83.08    | 85.34 |
|       |         |       |       |          |       |
| Si    | 1.987   | 1.986 | 1.990 | 3.656    | 3.628 |
| Al    | 0.013   | 0.014 | 0.010 | 0.344    | 0.372 |
| S     | 2.000   | 2.000 | 2.000 | 4.000    | 4.000 |
| Al    | 1.000   | 1.003 | 0.993 | 0.787    | 0.706 |
| Ti    | 0.000   | 0.000 | 0.000 | 0.017    | 0.032 |
| Cr    | 0.000   | 0.000 | 0.000 | 0.000    | 0.000 |
| Fe3+  | 0.000   | 0.000 | 0.000 | 0.000    | 0.000 |
| Fe2   | 0.001   | 0.001 | 0.002 | 0.458    | 0.653 |
| Mn    | 0.000   | 0.001 | 0.000 | 0.006    | 0.006 |
| Mg    | 0.004   | 0.004 | 0.011 | 1.382    | 1.296 |
| Ca    | 0.007   | 0.003 | 0.011 | 0.064    | 0.057 |
| Na    | 0.987   | 0.988 | 0.982 | 0.033    | 0.034 |
| К     | 0.000   | 0.001 | 0.001 | 0.062    | 0.068 |
| S     | 2.000   | 2.000 | 2.000 | 2.809    | 2.852 |

Table 2. Representative analyses of jadeite and smectite.bld = below detection limit.

Reaction R1 can be considerably simplified with the following assumptions: Rocks influenced by strong hydrothermal infiltration are usually characterized by a few minerals or even a single phase, reflecting that chemical variables (chemical potentials or activities) of most or all components are externally controlled by the fluid phase in the sense of Korzhinskii (1959). In the rock under consideration, this was probably the case for all fluid components except CaO and TiO<sub>2</sub> which are locally controlled by the solids (i.e., titanite or vesuvianite). With the assumptions of the presence of such an externally controlled fluid phase, R1 can be re-written as:

(R1a) titanite +  $18(CaO)_{fluid}$  = vesuvianite +  $(TiO_2)_{fluid}$ .

Such an equilibrium involving components of the fluid phase can be presented in a chemical potential diagram with the chemical potentials of CaO and  $TiO_2$  as axes. In addition to the phases in (R1a), jadeite and rutile are considered for the construction of the phase boundaries in the chemical potential diagram (Fig. 7).

On the base of Fig. 7, it can be assumed that local control of relatively high chemical potentials of  $TiO_2$  and CaO was active during dissolution of a Ti mineral such as titanite. Dilution with the externally controlled fluid phase led to a decrease of the chemical potentials of  $TiO_2$  and CaO, and vesuvianite was formed. In case of complete equilibrium with the externally controlled fluid phase, a monomineralic rock (jadeitite) would be expected at the end. However, a further parameter to be considered is the vesuvianite solid solution. A decrease of the activity of this mineral by variable incorporation of Ti (and Na for charge balance) would enlarge its stability field. Probably, the vesuvianite composition has been buffered to the composition of the two phase boundary vesuvianite/jadeite (Fig. 7) shifting continuously with increasing Ti content. Because the highest Ti content occurs in the rim of vesuvianite, it can be assumed that, in the course of vesuvianite growth, the fluid was getting poorer in Ti. This behaviour can be expected, because it corresponds to a dilution of Ti (liberated by the destabilization) of a precursor Ti mineral in the (Ti-poorer) fluid phase.

Additional parameters to be considered are the solid state cation diffusion rates. As obvious from the preserved zoning in vesuvianite, these rates must be slow during the process under consideration. Therefore, it can be possible that the Ti rich rim of vesuvianite is in chemical equilibrium with jadeite (and the once present fluid phase), but not the core anymore. The Ti rich rim shielded the vesuvianite aggregate from getting dissolved in the fluid.

Alternatively, it can be speculated that the formation of vesuvianite and the zoning in this mineral is just the result of temporal and spatial variation in the composition of the fluid



Fig. 7: Schematic chemical potential diagram at constant P and T. The chemical potentials of the other components in the phases considered are externally controlled. 1 is the stability limit for end-member vesuvianite, 2 for low Ti vesuvianite , and 3 for high Ti vesuvianite.

phase. In particular, the relic cores in vesuvianite were possibly formed at different P-T conditions compared to those responsible for the formation of the bulk of vesuvianite.

A more quantitative calculation is not possible because of the poor knowledge of the thermodynamic properties of vesuvianite. This particularly concerns the activity coefficients for the incorporation of Na and Ti into this mineral. These coefficients are expected to strongly deviate from ideal because of the complex charge balance constraints. There are also only a few data on the P-T stability of this mineral (Plyusnina *et al.* 1994; Hochella *et al.* 1982). However, all experiments have been performed at low pressure, and no data are available for high-P conditions.

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