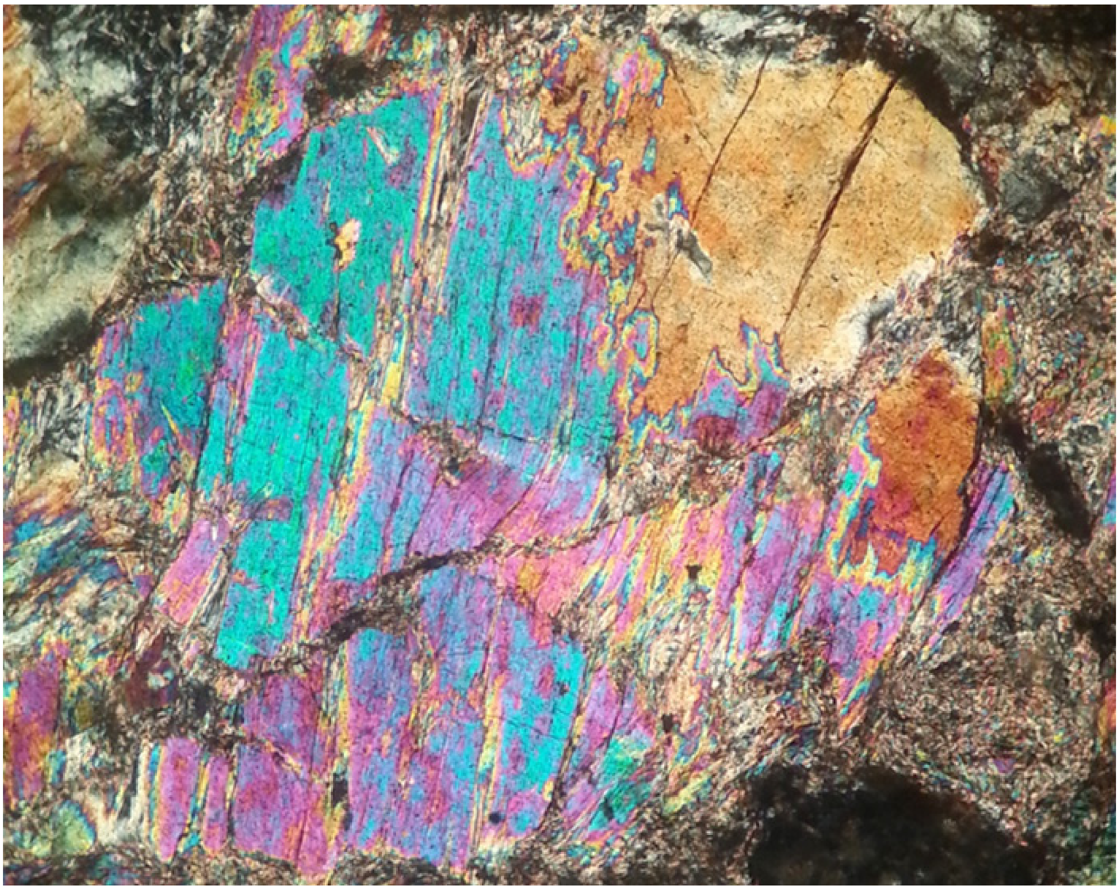
Stockholm University

Bachelor Thesis

Degree Project in Geology 15 hp

Optical Analyses of Devonian Metavolcanic Rocks, Brooks Range, Alaska

Niklas Strandberg



Stockholm 2016

Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

Abstract

The Brooks Range is a broadly Cretaceous orogenic belt in northern Alaska that trends east – west over about 1000 km. The range is traditionally divided into zones from north to south and includes the Endicott Mountains allochthon, the Central Belt, the Schist Belt, and the Angayucham terrane. This study focuses on the transition from the Central Belt to the Schist Belt which represents two distinct metamorphic histories. Investigation of mineral paragenesis by optical microscope analysis indicates greenschist and amphibolite facies metamorphic conditions are present in the Central Belt, greenschist and possibly blueschist conditions present in the Schist Belt. Together with ductile and overprinting brittle deformation fabrics, these results are interpreted to reflect: i) Two metamorphic events having occurred, one under ductile conditions and a later one under brittle conditions, ii) units with relict amphibolite facies and ductile textures have been uplifted from higher temperatures; iii) regional greenschist facies metamorphism then occurred; and iv) some of these metamorphic events are associated with compression and must pre-date Late Cretaceous extension, while others may reflect Late Cretaceous extension.

AIMS

The microscopic investigation of minerals in rocks by transmitted and/or reflected light remains an indispensable method for mineral analysis in geology today. Polarized-light microscopy provides a non-destructive way to identify minerals with relatively high spatial resolution within their textural framework. Advanced microscopic techniques that enable determination of, for example, mineral optic axis interference figures or 2V can refine our understanding of mineral paragenesis because these optical parameters are a function of crystal structure and composition. In igneous rocks, they directly reflect the environment related to mineral formation and can provides clues to the history of mineral formation. This project focuses on the petrographic evaluation of igneous rocks from the Brooks Range of Alaska with the specific aims of i) developing advanced optical microscopy skills, ii) assessing the metamorphic history associated to these samples, and iii) testing the hypothesis that metamorphism pre-dates late Cretaceous extension in the Brooks Range.

INTRODUCTION

The Brooks Range is a broadly Cretaceous orogenic belt in northern Alaska that trends east – west over about 1000 km (Fig. 1). The geological complexities of this large and remote region have not been fully investigated, consequently there is ongoing debate regarding the dominance of extension versus compression associated with the evolution of this belt (Hoiland et al., *in press*). Early on, the range was strictly perceived as a fold and trust belt developed in response to arc collision during Cretaceous subduction, with little to no extension recognized cross the range (Aleinikoff et al, 1993 and references therein). Miller and Hudson (1991) argued that extension played a major role in the formation of the belt, and their model suggested that crustal thickening drove later extension (post-orogenic collapse). The southern Brooks Range is traditionally divided into different zones (Fig. 1) that include, from north to south, the Endicott Mountains allochthon, the Central Belt, the Schist Belt, and the Angayucham terrane (Aleinikoff et al, 1993). These zones preserve different degrees of metamorphism, with the metamorphic grade increasing to the south. The Central Belt contains mostly metaclastic, metavolcanic and carbonate rocks recrystallized under greenschist facies conditions (Aleinikoff et al, 1993, and references therein).

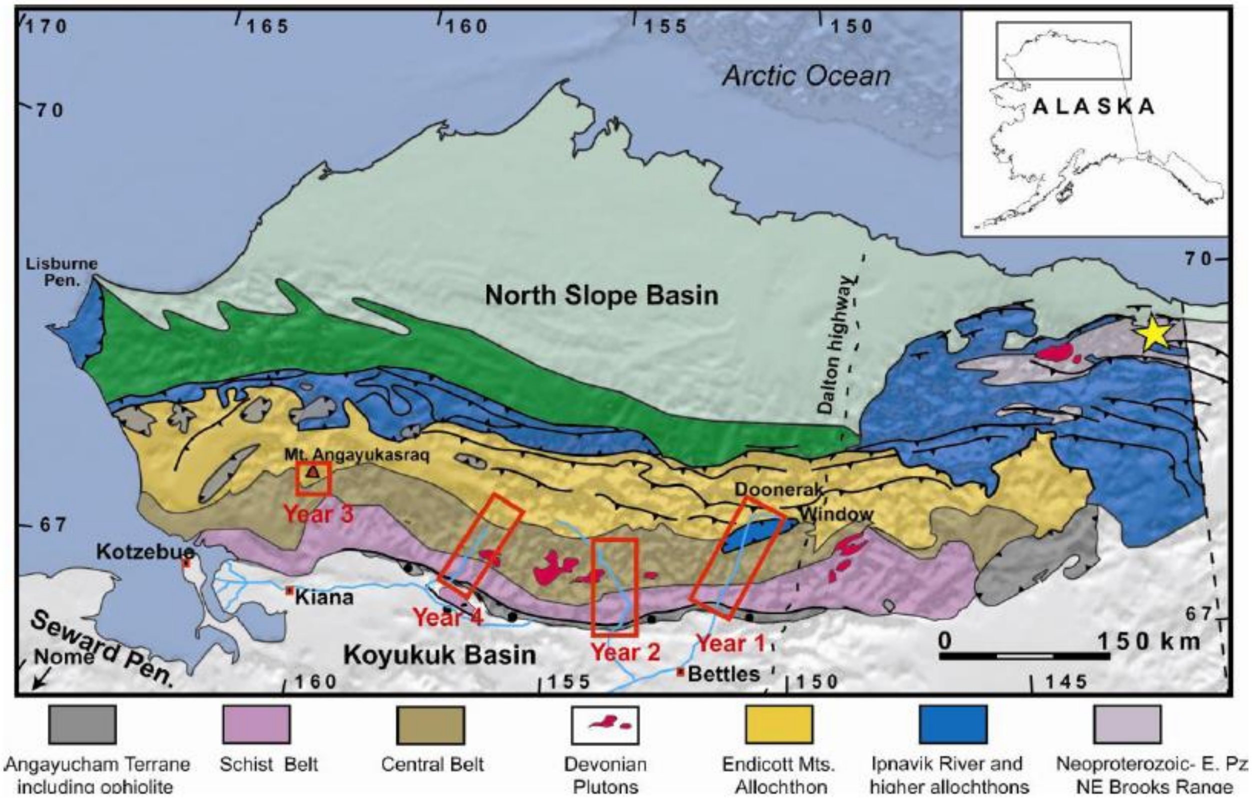


Figure 1. Simplified geological map of the Brooks Range (after Moore et al., 1994). Red boxes show the areas to be investigated over 4 years; samples from this study are associated with 'Year 1' and were collected in 2015.

The Schist belt mainly consists of different schist types (quarts-mica schist, chiefly and more) that are typically calcium rich (Aleinikoff et al, 1993, and references therein). It is also metamorphosed to greenschist facies, but overprints an earlier blue-schist event that is only locally preserved (Gottschalk, 1990).

Several N-S traverses across the southern Brooks Range have been planned in order to document and assess the role of extension across the fold and thrust belt (Fig. 1). The first and easternmost traverse along the Koyukuk River occurred in 2015. During this expedition samples of igneous rocks were collected by travelling down-river from north to south. This project applies advanced petrographic techniques (2V, interference figures, etc.) to document the mineralogy, texture, fabric, and alteration revealed in thin-sections of 21 metavolcanic samples from the Central and Schist belts. This information is then used to characterize the rocks and constrain their paragenesis (metamorphic grade, depth and temperature of deformation/formation, mineral composition) in order to test the hypothesis that metamorphism pre-dates late Cretaceous extensional deformation.

Optical Methods

Polarizing light microscopy is a corner-stone of geologic investigations. It is a well-established technique and some necessary terminology is defined below. These descriptions are condensed from the book 'Introduction to Optical Mineralogy' (Nesse, 2004).

An **isotropic** mineral has uniform crystal structure and chemical bonding, which results in uniform light velocity in all directions. **Anisotropic** minerals have non-uniform light speeds in different directions, the result of a non-uniform crystal structure/chemical bonding. When light enters an anisotropic mineral, at most angles the light splits into two rays (Fig. 2); these rays vibrate at right angles to each other and travel different paths through the mineral. These light rays are usually referred to as **fast** and **slow** rays; the fast ray has a lower **refractive index,** which means that it is not diverted when it enters the mineral. The slow ray has a higher refractive index which diverts the ray when it enters the mineral, thus it will always lag behind the fast ray travelling through the mineral. The difference between the refractive indices of the two rays is called **birefringence**. The difference in distance covered over a fixed time by the fast and slow rays is called **retardation**.

Anisotropic minerals are divided into two optical groups: uniaxial or biaxial, and this includes the orthorhombic, monoclinic, or triclinic crystal systems. **Interference figures** are used to determine a mineral's uniaxial or biaxial optical habit in thin-section. **Uniaxial** minerals have specific crystal structures: tetragonal or hexagonal - this means they only have uniform chemical bonding and crystal structure along the c-axis. In uniaxial minerals, the two light rays behave differently: one passes straight through the mineral (as in an isotropic mineral) and this is called the **ordinary ray** (ω): In figure 2, this ray enters the mineral parallel to the c-axis and is not refracted - it travels straight on, within the {001} plane and has a vibration direction at right angles to this plane. The second ray, on the other hand, is refracted by some angle as it enters the mineral and is no longer parallel to the c-axis - this is called the **extraordinary ray** (ε). The o- and e-rays vibrate in

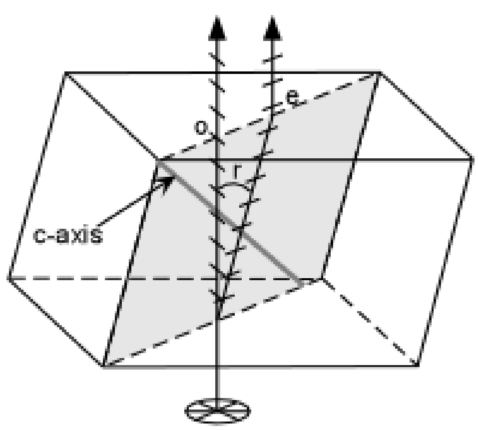


Figure 2. Model of an anisotropic mineral showing light split into two rays as it enters the mineral. O (ordinary) and E (extraordinary) rays (from Nelson, S.A., 2014).

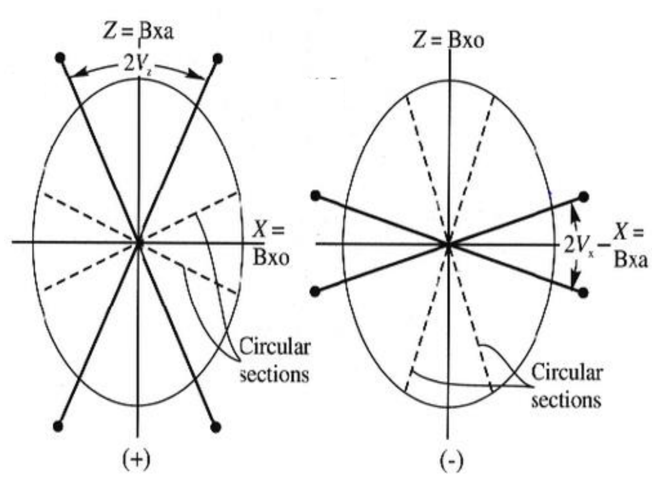


Figure 2. **Indicatrix's** displaying the difference between biaxial minerals positive and negative optical sign. Thick black line are **optical axes**, angles between them are **2V**. From Nesse (2004).

directions perpendicular to each other. For each mineral, the refractive index of the o-ray is unique, while the refractive index of the e-ray may vary and depends upon the direction of light propagation. If the e-ray is perpendicular to the c axis, its refractive index is at a minimum, while an e-ray almost parallel to c axis will have a maximum refractive index. Thus the refractive index of the e-ray is variable in uniaxial minerals.

Biaxial minerals are asymmetric due to variations in their crystal structure/chemical bonding and includes the monoclinic and triclinic crystal systems. To explain the properties of biaxial minerals three different refraction indices are used, α, β and γ, where by definition $\alpha > \beta > \gamma$. In biaxial minerals light splits into *two* extraordinary rays. The fast ray is α' and is between $\alpha \leq \alpha' \leq \beta$; the slow ray is γ' which is always $\beta \leq \gamma' \leq \gamma$. To visualize the optical structure a biaxial **indicatrix** is used (Fig. 3). This is constructed by projecting the indices of refraction onto the oval representing the long-axis of the crystal system. The ray vibration directions are shown as plains. Biaxial minerals have two optical axes (OA) and depending on the crystal system their optical sign is ether negative or positive. If the optical axes are centered around the mineral's z-axis, the mineral is optically positive; if they are centered around the x-axis, the mineral is optically negative. The angle between the optical axes is called **2V** and it can be measured as the acute or obtuse angle. Thus the **acute bisectrix** (**Bxa**) is the smaller angle and the **obtuse bisectrix** (**Bxo**) is the larger angle (Fig. 3).

The **upper polarizer,** referred to as the analyzer, is usually made of an optical-quality polarizing film that is set at right angles to the lower polarizer. It is normally mounted on a sliding plate which allows easy removal. The analyzer is used to look at samples in cross-polarized light (XPL). As the two rays leaving an anisotropic mineral are polarized, depending on the retardation of the slow ray, they will either result in constructive interference or cancelation of the ray. When the retardation is half the wavelength of the rays, the maximum amount of light will pass the polarizer; when the wavelength is the same as the retardation, no light is transmitted. The colors seen in XPL are the result of the thickness of the thin-section and mineral birefringence. Under XPL isotropic minerals are always black since the light is blocked by the combination of upper and lower polarizers.

Viewing without the analyzer inserted is called plane polarized light (PPL), and the light exiting the mineral is not polarized. The color that is seen under PPL is called **pleochroism**. This color can vary within a mineral as the stage is rotated. The color change is caused by the variable adsorption of particular wavelengths of light in a mineral. When rotating the stage both slow and fast light rays are present. If the slow ray is aligned with the lower polarizer, only the slow ray will be seen. If the fast ray is parallel to lower polarizer, only the fast ray will be visible.

Relief is the distance a mineral grain stands above or below the medium it is mounted in. It's usually measured relative to oil with known relief. When the grain has higher relief than the oil, it's positive; when less, it's negative. The categorization isn't especially useful in thin-sections as there is no oil to compare with, therefore is it more common to refer to low or high relief relative to the surrounding minerals.

The **Bertrand lens** is used for looking at **interference figures**, the visualization is created by a strongly convergent light passing through the mineral being collected by the Bertrand lens. If the light is along the optical axis in uniaxial minerals will it show a cross with rings around it (Fig. 4). The arms of the cross are called **isogyres** and the rings are called **isochromes**. Isogyres are the result of extinction when the vibration directions of the light are aligned with the upper and lower polarizers. At the middle of the cross is a dark circle called the **melatope** and this is visible when directly aligned with the optical axis. Interference colors of the isochromes increase outwards from the melatope. The optical sign of minerals is determined by using interference figures and **accessory plate** which is usually made of either gypsum, mica or quartz. The field of view in interference figures is often divide into north, east, west and south to ease navigation and remain stationary when thin-sections are rotated. The gypsum or mica plates are used to determine the optical sign by observing the change of interference colors before and after inserting the plate. If interference colors of the northeast or southwest quadrants increase the mineral is optically positive; if the colors decrease, the sample is optically negative. These effects are the result of aligning the slow ray with the slow direction of the accessory plate, i.e.- if the o-ray is aligned NE-SW and the e-ray is NW-SE, inserting the accessory plate NW-SE will increase the interference colors of the o-ray (in the NE quadrant). If the colors decrease, then the accessory plate is aligned with the e-ray.

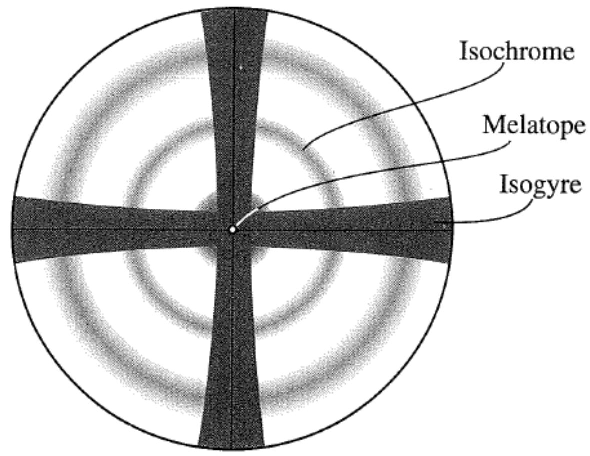


Figure 3. An illustration of a typical uniaxial interference figure, were the optical axis is centered in the view. Melatope is at the optical axis, the Isogyres are forming a cross around the melatope. The figure is taken from Nesse (2004).

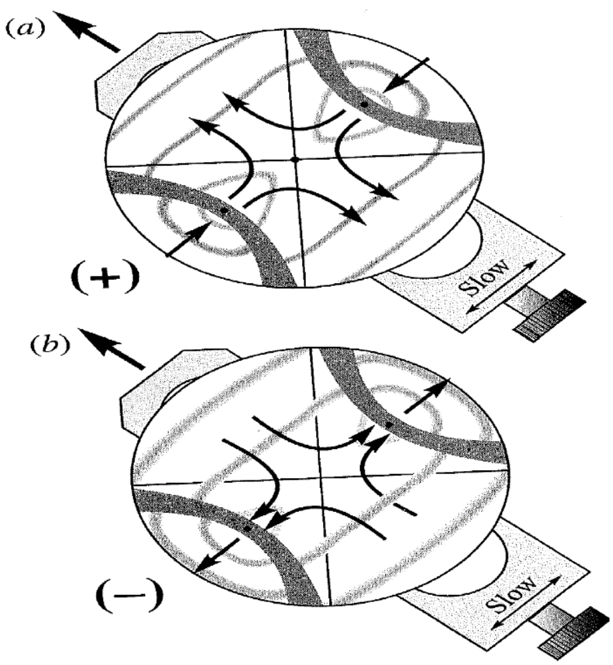


Figure 4. The effects of inserting the accessory wedge when looking at biaxial interference figures. By obseving the moment of the isocromes are optical sign determained. Taken from Nesse (2004).

Biaxial interference figures differ from uniaxial figures and are often used to determine if the mineral is uniaxial or biaxial. The main difference is that there are two melatopes associated with biaxial minerals, as there are two optical axes. The Bxa figure can look similar to the uniaxial cross, but they differ in that Bxa isogyres aren't symmetrical, are thinner in N-S direction, and the isochromes bend into ovals between the melatopes (Fig. 5). When the stage is rotated the cross separates into two convex isogyres. Depending on the 2V, the isogyres might completely leave the field of view. Determining the optical sign with a quartz wedge is done by having the maximum separation of convex isogyres oriented in the NE-SW quadrants and then inserting the accessory plate. If the isogyres move outwards in the NW-SE quadrant and inwards in the NE-SW quadrant, the mineral is positive; if the opposite, the mineral is negative. The gypsum and mica plates can also be used to observe the change in retardation associated with the isogyres as the slide is inserted. If the retardation is additive between the isogyres and subtracts outside the isogyres, the mineral is optically positive; if the opposite, the mineral is optically negative.

2V can be used to identify biaxial minerals when viewing the interference isogyres. Each mineral has a specific 2V range, thus knowing the 2V restricts the possibilities for which mineral is present. Advanced methods like Mallard´s, Tobi's, and Kamb´s, etc., are used for calculating the 2V and obtain exact measurements. The Tobi and Mallard methods' can also be used for simpler visual estimates; for example, if the isogyres form a cross, the 2V is equal to 0° and as the 2V increases the isogyres separate from each other – 2V can be estimated from this separation. Such visual estimates vary with the lens numerical aperture (NA), so the NA (usually displayed on the lens) should be taken into consideration when estimates are made. The Wright method can be used to estimate 2V when one isogyre is out of the field-of-view (FOV): if the isogyre forms a straight line though the middle of the FOV, the 2V equals 90°; if the isogyre forms a right angle curve, the 2V is equal to 45°.

Analytical Results

All the samples evaluated from the Central and Schist belts record greenschist grade metamorphism and many of the protolith minerals have been replaced. The majority of samples record static metamorphism, however the samples from two Devonian (Dfm and Da) units show alignment of matrix minerals consistent with shear. The Dfm samples are dived into two groups as there are collected from different zones (Central Belt and Schist Belt) and have different mineralogy; they are therefore dived into groups 1 and 2.

Ordovician volcanic (Oev) samples (01-18). These sample include Cambrian(?) & Ordovician volcanic (Oev) rocks and represent andesitic to basaltic volcanoclastic rocks with local tuffaceous phyllite, gabbro and diabase, and black phyllite (Dillon et al., 1986). Oev samples are dominated by mafic hornblende and their mineralogy is hornblende, pyroxene, and plagioclase. Calcite occurs as an accessory phase.

Primary phases: Pyroxene is present in variable amounts. **Augite** phenocrysts are seen in samples 02, 05, 11 and possibly 09, and tend to have simple twining. **Orthopyroxene** (Opx) and **Clinopyroxene** (Cpx) are found in samples 08 and 09 as **inverted Pigeonite** (opx host mineral with cpx exsolution lamellae) preserved in the center of hornblende coronas. **Hornblende** phenocrysts are present in all Oev samples with typical brown pleochroism. Hornblende replaces pigeonite and augite, forming corona structures; in turn, hornblende is partly replaced by chlorite. The hornblende in these samples regularly displays simple twining. **Plagioclase** phenocrysts are present in samples 09, 08 and 17. In the remaining samples, large euhedral crystals are completely pseudomorphed by plagioclase and cryptocrystalline material – the identification of the original mineral is not possible.

Accessory phases: Titanite is present in sample 09 and 11. **Calcite** is common in samples 08 and 09, and found in sample 11. Calcite occurs in both veins and the groundmass.

Secondary phases: Epidote is present in the matrix of the majority of samples and is likely a result of metamorphism. **Clinozoisite** is found in sample 17. **Chlorite** is present in the majority of samples and is partly replacing hornblende.

Devonian mafic (Dm) samples (25-27). The Devonian & Jurassic(?) metabasites (Dm) units in the southwestern portion of the study area are inferred to correlate with the bimodal Amber volcanics (Dillon et al., 1986). The samples are altered and veined. The mineralogy is dominated by low-grade metamorphic minerals. The mafic minerals still preserved in an unaltered state include hornblende and plagioclase. Secondary phase minerals are abundant and phenocrysts of cummingtonite are present in the samples. In veins calcite, clinozoisite and epidote are common. Titanite is rare in these samples.

Primary phases: Hornblende is highly altered and replaced. A few remainders of brown hornblende are present in sample 25. The hornblende in samples 26 and 27 has yellow/brown to green pleochroism. **Plagioclase** phenocrysts occur in samples 26 and 27 and have well defined polysynthetic twining.

Secondary phases: Altered **Hornblende** with patchy brown to green pleochroism is present. It seems to be replaced by cummingtonite. **Cummingtonite** phenocyrsts are present in all samples and also as fine grains in the groundmass. Cummingtonite displays multiple twining. **Calcite** occurs in veins in samples 26 and 27. **Clinozoisite** is common and most abundant in the veins, with distinctive abnormal blue interference colors. **Epidote** is found in all the samples. **Titanite** is found in samples 25 and 27.

Devonian(?) felsic and mafic (Dfm) samples, Group 1 (29-32). These metamorphosed bimodal igneous rocks include complexly interlayered felsic and mafic rocks, and are also inferred to be associated with Ambler metavolcanic rocks (Dillon et al., 1986). The samples have undergone a higher degree of alteration than the Dm and Ove groups, and the mineral compositions indicate greenschist grade metamorphism. Few magmatic minerals (with the exception of plagioclase) remain.

Primary phases: Plagioclase phenocrysts are found in sample 30. In the other samples, plagioclase is c. 0.2 mm and anhedral.

Secondary phases: Cummingtonite or pumpellyite phenocrysts are abundant in these samples and grains with fibrous habit and multiple twining are common. A few grains in sample 29 display ~60° and 120° cleavage. Cummingtonite is partly pseudomorphed by chlorite. **Chlorite** displays abnormal blue colors and it is replacing cummingtonite. **Clinozoisite** is present in all the samples and is concentrated in veins. It's abnormal blue color is common. **Epidote** and clinozoisite are concentrated in veins. Epidote is generally larger than clinozoisite but is less common. **Calcite** is common in all of the samples. **Ilmenite** has been altered to **titanite**

Dfm samples, Group 2 (49-53). Some Dfm samples have undergone high-grade alteration (*cf* description of Group 1, Dfm above). These metabasaltic samples are dominated by an aligned cryptocrystalline matrix. The mineralogy indicates greenschist conditions. Veins are abundant and generally contain either epidote or plagioclase and quartz, although epidote is the most abundant.

Secondary phases: Epidote phenocrysts in samples 49 and 50 are concentrated in veins. The epidote in 51, 52 and 53 has a random distribution, i.e.-lacks fabric. **Quartz** is present in all samples and is concentrated in clusters or veins. **Clinozoisite** is present in all samples and has the typical abnormal blue interface colors. **Plagioclase** is found in sample 49. **Chlorite** is partly replacing epidote in samples 49, 50 and 53. The matrix is cryptocrystalline and its composition cannot be determined.

Devonian Ambler (Da) samples (45-47). The Lower(?) Middle & Upper Devonian Ambler metavolcanic (Da) rocks include abundant mafic and felsic volcanic rocks interbedded with black quartz and quartzite, marble and calcareous schist. Devonian fossils have been described at one locality and this unit has been correlated with the Ambler Sequence of Hitzman et al. (1982). The samples seem to have undergone high grade metamorphism as they contain relicts of garnet, perhaps reflecting previous blueschist-facies conditions as documented elsewhere (Hoiland et al., *in press*). Chlorite pseudomorphs garnet in all samples. These Ambler rocks are more felsic than the other samples and quartz phenocrysts are common. The matrix is composed of cryptocrystalline grains. Oxides are abundant and clusters are aligned.

Secondary phases: Garnet relicts are pseudomorphed by chlorite. **Chlorite** in these samples has abnormal brown birefringence but have the garnet hexagonal shape. **Quartz** phenocrysts found in the samples are pristine and lack undulose extinction. Small crystals of **Plagioclase** are rare and **Epidote** is found in all Da samples. **Clinozoisite** is found in samples 47 and 45, with typical abnormal blue color. **Oxides** are abundant and oxide clusters are aligned.

Discussion

Metamorphic grade(s)

All samples are metamorphosed to some degree and therefore most likely predate the last deformation event. With the exception of the Da group samples, all other samples have similar metamorphic mineralogy that includes calcite, epidote, cummingtonite, clinozoisite or zoisite, chlorite, actinolitic hornblende, and titanite. These reflect greenschist facies metamorphism (Winter, 2014), with the exceptions of garnet and cummingtonite as discussed below. The Da samples are unusual because they preserve relicts of garnet now pseudomorphed by chlorite. Garnet is formed by both metamorphic and igneous processes (Deer et al., 1992). The Da samples represent a meta-felsic dike of unknown age but that clearly cross-cuts the surrounding rocks; the dike and host-rock were both metamorphosed. It is important to determine whether the garnet is igneous or metamorphic in origin; if the garnet is metamorphic, it would indicate a higher grade of metamorphism than greenschist facies.

Previous studies of the Schist Belt suggested that a blueschist event was overprinted by a lower-grade event (Gottschalk, 1998), as documented by pseudomorphs of glaucophane and lawsonite. Such textures have not been observed in the samples studied here. Instead cummingtonite (Ca-poor metamorphic amphibole) has been found in multiple samples from Dm and group 1 of Dfm. Cummingtonite is mostly found in Ca-poor mafic rocks of amphibolite facies, and is rare in felsic volcanic rocks (Deer et al., 1994). With the exception of secondary calcite, the samples of Dm and Dfm (group 1) lack Ca-rich minerals. In thin-section a few cores of hornblende are replaced by cummingtonite, thus cummingtonite is the product of metamorphism and clearly replaces brown hornblende. Cummingtonite forms during amphibolite to granulite facies conditions (Winter, 2014), which implies that these samples experienced metamorphism above greenschist facies. The temperature and pressure must have been high enough to create amphibolite which requires a minimum temperature of around 500° Celsius and a minimum pressure of around 0.2 GPa (Winter, 2014). If Dm and Dfm (goup 1) samples experienced granulite facies, there is no record of it preserved today; the samples preserve amphibolite facies overprinted by greenschist facies conditions, the result of retrograde metamorphism or a later overprinting event.

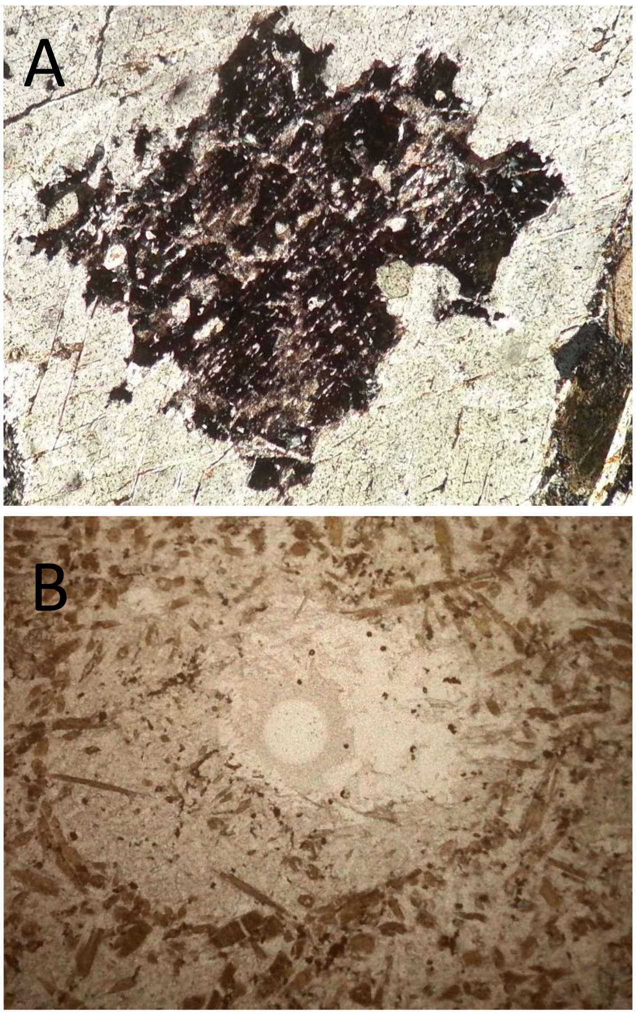


Figure 5. (A) Pigeonite with exsolution lamellae of augite inside a hornblende corona found in sample 09, viewed in XPL. (B) Pseudomorphed mineral in sample 02 surrounded by brown hornblende, viewed in PPL.

Igneous minerals

Original protolith minerals are present (Fig. 6). The Oev samples are the least metamorphosed of the units, with minerals that might be of volcanic origin including augite, plagioclase and hornblende. Augite is a common igneous mineral which rarely forms during metamorphism (although aluminum-rich augite can form during contact metamorphism between igneous-carbonate; Deer et al., 1992). Pigeonite with exsolution lamellae of augite is found in samples 09 and 10; the preservation of this texture requires quick cooling from magmatic conditions, consistent with rapid intrusion and cooling associated with volcanic rocks (Deer et al., 1992). Augite phenocrysts in the samples are regularly found surrounded by coronas of brown hornblende, consistent with igneous augite mantled by high temperature amphibole. Hornblende is common in both igneous and metamorphic rocks, and has a wide range of chemical composition (Deer et al., 1992). Nonetheless, an igneous origin for hornblende is often inferred from its brown color, whereas green hornblende is associated with metamorphism (Otten, 1984). However, under the high-grade conditions associated with granulite facies metamorphism (between 900° and 1040°) brown hornblende may also form (Otten, 1984; Winter, 2014). An igneous paragenesis for the brown hornblende in Oev samples is supported by the following observations: i) brown hornblende mantles pigeonite, ii) brown hornblende is surrounded by green hornblende (cummingtonite), and iii) green hornblende is in equilibrium with chloritization. Consequently, the brown hornblende in Oev samples is regarded as igneous in origin. Plagioclase is common in both igneous and metamorphic rocks (Winter, 2014; Deer et al., 1992). The composition of plagioclase could help to determine its paragenesis, i.e.- using the optical method of Michel-Lévy (1895), but few plagioclase grains in the Oev samples preserve clear twin lamellae. However, given that pigeonite, augite, and brown hornblende indicate an igneous protolith, the plagioclase phenocrysts are also assumed to be igneous. In Oev samples 02, 05 and 11, a few large crystals have been completely replaced by plagioclase and fine grain mineral(s). The replacing mineral(s) both enclose and are surrounded by hornblende (Fig. 6b), indicating that they grew simultaneously. As discussed, brown hornblende is most likely igneous in origin, therefore the original phenocryst would also have an igneous origin. Determining the composition of the original mineral that is now fully replaced needs further study.

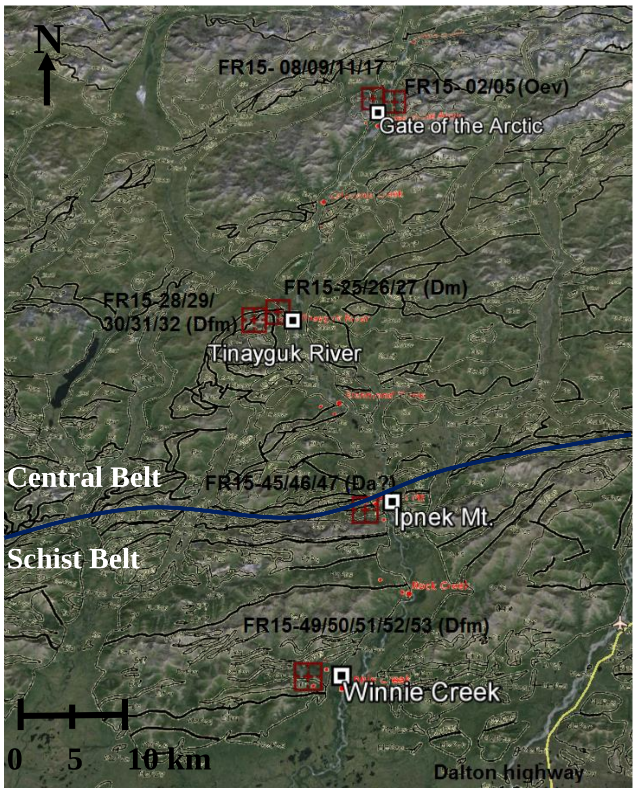


Figure 7. Map showing sample locations and major geological boundaries. The map is the northern part of the 'Year 1' box from figure 1. **Locations** = the red squares, **regional names** given in white, **Dalton highway** = yellow line, and the blue line is the border between the **Central Belt** (north) and the **Schist Belt** (south). Samples have been grouped together to provide a clearer view of the geological units. Geology after Dillon et al. (1986) and superimposed by F. Robinson.

Variations in metamorphic grade

Amphibolite facies has been identified in multiple samples and can be related to the geological map of the southern Brooks Range (Figs. 1 and 7). All samples evaluated in this study display greenschist facies metamorphism, with indications of amphibolite facies present in a few samples. The **Oev samples** (02 to 17; Fig. 7) are arguably the least altered of the groups. The samples experienced static metamorphism, as indications for shear or alignment of minerals are lacking, as are veins and fractures. The samples represent mafic intrusions from within the Doonerak Fenster (blue area near the top of 'Year 1' square in Fig. 1; near Gate of the Artic in Fig. 7). These represent the northernmost samples and are from the northern Central Belt. **Dm samples** (25 to 27; Fig. 7) are more altered than Oev samples, with mineral alignment indicating ductile conditions and multiple veins documenting later brittle conditions. Cummingtonite is first present in the Dm unit and documents a change from greenschist to epidote-amphibolite facies conditions. The volcanic mineralogy of the Dm and Oev samples are similar (igneous hornblende and plagioclase phenocrysts), but there are significant textural differences between these two groups. Original fabrics associated with Dm samples have been fractured and filled primarily with epidote-family minerals (epidote and clinozoisite) and calcite, indicating that fluid transport was associated with metamorphism of these samples and that, to allow fluids to infiltrate the samples, late-stage metamorphism most likely reflects a hydrating down-temperature path, rather than a dehydrating up-temperature path.

Dfm group 1 samples (28 to 32) are similar to Dm samples: abundant veins, increased alteration, mineral compositions, and similar metamorphic grade. The chloritization of cummingtonite is common in Dfm group 1 samples consistent with hydration of the samples – this is not seen in Dm samples. There is weak mineral alignment in all Dfm samples, with samples 31 and 32 having a strong alignment indicating ductile deformation and possibly shearing. Dm samples have similar textures which indicates that the whole Tinayguk River region has been deformed under ductile conditions at one time, followed by an abundance of fractures indicating later brittle conditions. The combination of brittle overprinting ductile conditions is further supported by crenulation cleavage found in Dfm samples.

There is likely a fault or fold contact separating the Gate of the Artic samples and Tinayguk River samples. Oev samples are brittley deformed, while Dm and Dfm samples preserve ductile overprinted by brittle deformation. This indicates the Dm and Dfm samples were once at a higher P/T regime. Folding and metamorphism began in the Brooks Range in the Early Cretaceous (Gottschalk, 1989) and likely affected the Dm and Dfm samples. This implies that amphibolite facies metamorphism predates the greenschist facies metamorphism associated with mid-Cretaceous extension in Brooks Range (Gottschalk, 1989; Miller & Hudson, 1991). This is consistent with a normal, retrograde (down-temperature) P/T exhumation path within the Central Belt.

Da samples (45 to 47) were collected from a felsic dike located adjacent to Ipnek Mountain near the boundary between the Central and Schist belts (Fig. 7). This unit lacks cummingtonite but has garnet. The lack of cummingtonite in Da samples is consistent with its non-basaltic (higher silica) composition. The origin of garnet in these samples needs further investigation and is important for defining the metamorphic grade of these samples. Earlier studies suggested that blueschist facies conditions were achieved in the Schist Belt (Gottshalk, 1998; Vogl, 2003). With the possible exception of garnet, minerals typically associated with blueschist facies have not been observed in Da samples. There are indications of a weak mineral alignment in these samples, with elongate quartz, plagioclase, and an oxide mineral(s) all parallel, indicating ductile conditions. **Dfm group 2** (49 to 53) samples are located furthest south and are the most deformed of all samples (Fig. 7). A strong ductile mineral alignment is present. There is a high abundance of epidote and zoisite, as well as a cryptocrystalline ground mass that has the second-order colors and habit of cummingtonite but is too fine-grained to be positively identified. Based on the high abundance of epidote combined with ductile textures, the metamorphic grade is upper-greenschist to lower-amphibolite facies (c. 550°C).

Conclusions

All units display greenschist metamorphism conditions associated with Early-Cretaceous compression (Gottschalk, 1989). Amphibolite facies indications (cummingtonite and ductile textures) are observed in Dm and Dfm group 1 samples (Central Belt, Fig. 7) and are relics of higher grade metamorphic conditions that were overprinted by later greenschist facies metamorphism. Mineral alignment as well as fractures are observed in the same units and indicates a combination of ductile and brittle conditions – this is interpreted to indicate uplift from higher-T to lower-T conditions. Crenulation cleavage is found in Dfm samples further supporting a scenario of two deformational events. Blueschist conditions may be indicated by garnet in the Da unit, but as its origin is at present indeterminate further investigations are needed. Units within the Schist Belt (Da and Dfm group 2) have undergone substantial recrystallization and mineral alignment indicating ductile conditions during deformation than seen in the Central Belt, but not necessarily a higher temperature. The data from this study allow the following conclusions to be made: i) Two metamorphic events have occurred, one under ductile conditions and a later one under brittle conditions, ii) units with relict amphibolite facies and ductile textures have been uplifted from higher temperatures; iii) regional greenschist facies metamorphism then occurred; and iv) some of these metamorphic events are associated with compression and must pre-date Late Cretaceous extension, while others may reflect Late Cretaceous extension.

Further studies including electron microprobe analyses of garnet in Da samples could provide compositional information to distinguish between an igneous or metamorphic genesis, thus constraining whether or not the garnet is a relicts of blueschist metamorphism. There are strong indications of shear in Da samples with possible sigma and delta structures; oriented thin-section analysis could be used to determine whether the shear fabric is associated with a compressional extensional deformation regime. Further investigations using pseudosections, for example, might provide more information regarding the unknown, fully-replaced crystals in Oev samples and their protolith.

Acknowledgments

I have a great gratitude to my supervisor Victoria Pease who has supported me in this study, always inspired me to look further into the subject and helped bouncing ideas, identifying minerals and refining the report. I also want to thank Frank Robinson provided his personal collection of thin-sections, helped explain the local geology, provided a map and further inspired me about this study.

References:

Aleinikoff, J.N., Moore, T.E., Walter, M., Nokleberg, Nokleberg, W.J., 1993. U –Pb Ages of Zircon, Monazite, and sphene from Devonian metagranites and metafelsites, central Brooks Range, Alaska. US Geological Survey Bulletin, volume 2068, 59-70.

Blythe A.E., Bird, J.M and Omar, G.I., 1996. Deformational history of the central Brooks Range, Alaska: Results from fission-track and $^{40}Ar/^{39}Ar$ analyses. Tectonics, vol 15, no 2, 440-455.

Deer W.A., Howie R.A., and Zussman J., 1992. An Introduction to the Rock-Forming Minerals (second edition). Longman Scientific & Technical and John Wiley & Sons, New York.

Dillon, J.T., Brosge, W.P., Dutro, J.T. Jr, 1986. Generalized geologic map of the Wiseman Quadrangle. Alaska. US Geological Survey Open File Report 86-219, 1 sheet, scale 1:250000.

Gottschalk, R. R., 1990. "Structural Evolution of the Schist Belt, South-Central Brooks Range Fold and Thrust Belt, Alaska". Journal of Structural Geology, volume, 12 no 4, 453-469.

Hoiland, C. W., Miller, E. L., Pease, V. and Hourigan, J. K.. (*in press*). Mid-Cretaceous (late Aptian) metamorphism of non-Laurentain lower Paleozoic strata in the Schist Belt, southern Brooks Range, Alaska. Geological Society Special Publication, Circum-Arctic Lithosphere Evolution.

Miller, Elizabeth L. and Hudson, Travis L.1991. Mid-Cretaceous Extensional Fragmentation of a Jurassic-Early Cretaceous Compressional Orogen, Alaska. Tectonics 10.4, 781-796.

Michel-Levy, A., 1895. Recherche des axes optique dans un minéral pouvant être considéré comme un mélange de deux minéraux détermineés. Soc franc, minéralogie Bull., vol 3, 79 – 94.

Nelson, A.S. 2014. Tulane University (Figure 2). Accessed 05/17/2016.
Online site: http://www.tulane.edu/~sanelson/eens211/uniaxial_minerals.htm

Nesse, W. D. 2004. . Introduction to Optical Mineralogy. Oxford University press, third edition. Chapters 1-8.

Otten M.T., 1984. The origin of brown hornblende in the Artfjället gabbro and dolerites. Contrib Mineral Petrol 86:189-199.

Till A.B., Dumoulin J.A., Harris A.G., Moore T.E., Bleick H.A., and Siwiec B.R., 2008. Bedrock Geologic Map of the southern Brooks Range, Alaska, and accompanying Conodont Data. U.S. Department of the Interior and U.S. Geological Survey. Geological Survey Open-File Report 2008- 1149, 88p.

Vogl J.J, 2003. Thermal-baric structure and P-T history of the Brooks Range metamorphic core, Alaska. Blackwell Publishing, Journal of Metamorphic Geology, Volume 21, Number 3.

Winter J.D., 2014. Principles of Igneous and Metamorphic Petrology. Pearson Education Limited second edition.

Appendix

Sample description were made in start of the study and haven't been corrected/updated but should provide some information about the textures and mineralogy found in specific samples.

Sample number: FR15 – 02

Hand sample:
Light coloured porphyritic (fine grain), glimmer and white circles.

Thin-section map:

<u>Major rock-forming mineral phases</u>

7 % Augite: ~90° cleavage, high relief, weak pleochroism, II order blue/purple, 2V ~45°, elongated and round euhedral shapes, simple twining and in disequilibrium being replaced by hornblende.

33 % Hornblende: 120° and 60° cleavage, moderate relief, brown pleochroism, II order brown and yellow colours, elongated and prismatic shapes, simple twining and reaction rims.

60 % Fine grain in the matrix, disequilibrium, high III order colours and low to moderate relief.

<u>Accessory phases</u>

Epidote: Circle shaped very fine grain with III order inference color.

Plagioclase: white/gray I order color with twining.

<u>Secondary/alteration phases</u>

Unknown mineral: Fibrous (needles), forming around the hornblende, weak pleochroism

<u>Crystallization sequence</u>

1 Augite
2 Hornblende

<u>Miscellaneous</u>

Amphibole/pyroxene empty circle a phenocryst that has been completely replaced section 1

Interesting twining (hourglass) section 8.

Sample number: FR15-05

Hand sample:
Fine grain, glimmer, amphibole or pyroxene 2mm and light grey colour.

Thin-section map:

Major rock-forming mineral phases

10% Augite: 90° Cleavage, high relief, high II order colour, 2V ~ 45 optically + , tabular or round shaped, twining, in disequilibrium being replaced by hornblende and reaction rims, large size difference two generations?

45 % Hornblende: 120° Cleavage, moderate relief, brown pleochroism, II order brown and yellow colour, prismatic or elongated shaped, twining, disequilibrium with reaction rims, is replacing augite.

45% Prehnite: moderate relief, no pleochroism, III order colours, tabular or cone/radiating shape, very fine grain and dominated the matrix.

Accessory phases

Epidote: fine grain, high relief and III order interference colors.

Plagioclase: I order White/grey color, twinning and moderate-low relief.

Secondary/alteration phases

Chlorite?: weak green pleochroism, I order blue color and low relief.

Muscovite?: III order colors, elongated and low relief.

Crystallization sequence
1 Augite
2 Hornblende

Miscellaneous
Hornblende being replaced by unknown mineral sec 5
Large phenocryst being completely replaced (like the one in FR15-02)
Light curvy line without amphiboles and pyroxenes sec 1 and 2
Body of oxides sec 7

Sample number: FR15 - 08

Hand sample:
Large amphibole or ~~pyroxene~~ 1-2 mm, grey ground mass with white circles, green dot epidote or olivine?

Thin-section map:

Major rock-forming mineral phases

~15% Hornblende: ~0.5 – 2.5 mm, 60° and 120° Cleavage, moderated relief, brown pleochroism, II order colour yellow/brown , 2V ~80, optically - , tabular elongated and diamond shape euhedral, simple twining, mostly equilibrium some reaction rims and glass in middle of crystals (section 8), weak zoning.

% Calcite: ~≥0.7 mm, moderate relief, no pleochroism, III or IV order colour, anhedral blobs or tabular shape, in equilibrium.

Plagioclase: ≥1mm, moderate -low relief, no pleochroism, I order white7 grey colour, elongated or tabular shape, simple and polysynthetic twining, in disequilibrium broken and replaced by calcite, both 1mm crystals and matrix size minerals. The matrix plagioclase has larger rounder and elongated small ones.

Accessory phases

Epidote: very fine grain, high relief and III order colors.

Secondary/alteration phases

Plagioclase replaced by calcite

Crystallization sequence

1 Plagioclase
2 Hornblende
3 Plagioclase

Miscellaneous

Calcite vain section 6
Hornblende melt section 8

Sample number: FR15 – 09

Hand sample: Misssing!

Thin-section map:

Major rock-forming mineral phases

Hornblende: ≥2 mm phenocryst, 60° and 120 ° Cleavage, moderate relief, brown pleochroism, II order yellow/brown colour, 2V ~75-80°, optically -?, tabular diamond and elongated euhedral shape, simple twining, disequilibrium is replaced by chlorite, zoning.

Calcite: low – moderate relief, no pleochroism, III or IV order colours, blobs and tabular shape anhedral, in equilibrium, large and small matrix crystals?

Plagioclase: ≥ 0.7 mm, low – moderate relief, no pleochroism, I order white yellow colour, elongated and tabular shape semi euhedral, polysynthetic and simple twining, disequilibrium all broken and partly replaced, present as lager crystals and in matrix.

Cleavage, relief, pleochroism, I order colour, 2V optically + or -, shape, twining, disequilibrium textures.

Accessory phases

Titanite: diamond shape, high relief, brown I order colors. (common)

Glass: small

Secondary/alteration phases

Chlorite replacing hornblende

Calcite replaceing plagioclase

Crystallization sequence

1 Hornblende
2 plagioclase

Miscellaneous

Hornblende being replaced by chlorite in sigma looking forms sec 4
Calcite and unknown mineral vain in sec 1
Calcite body surrounded by hornblende sec 2 - 6
Hornblende with melt in middle? Sec 1

Sample number: FR15 – 11

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Augite: ~ 0.7 mm, ~80° Cleavage, moderate to high relief, weak green/blue pleochroism, II order high - middle colour, tabular and round sub euhedral shape, simple twining, disequilibrium reaction rims and replacement by hornblende, extinction angle ~ 45°.

Hornblende: ~1 mm long and 0.2 wide, 120 and 60° Cleavage, moderate relief, brown pleochroism, II order brown/yellow colour, simple twining, disequilibrium replaced by chlorite.

Prehnite: moderate – low relief, weak blue pleochroism, high II order colour, anhedral shape, equilibrium, matrix size.

Accessory phases

Titanite: high relief, brown color.

Large epidote: ~0.3 mm, high relief, green/yellow pleochroism, high III order colors, blobby shape, disequilibrium.

Plagioclase: low relief, white/grey I order colors

Secondary/alteration phases

Calcite:

Chlorite: low relief, blue colors, green pleochroism.

Crystallization sequence

1 Augite
2 Hornblende

Miscellaneous

Completely replaced phenocrysts (like in sample 05 and 02)
Large chlorite clusters section 7.

Sample number: FR15 - 17

Hand sample: missing

Thin-section map:

Major rock-forming mineral phases

Hornblende: ~3.5 mm long and ~1 mm wide, 60° and 120° Cleavage, moderate relief, brown pleochroism, II order colours yellow/brown, 2V ~70, diamond elongated and tabular shape, simple twining, disequilibrium is being replaced by chlorite.

Plagioclase: ~3.8 mm long and 2 mm wide, low relief, I order white/grey, 2V ~75°, tabular shape, simple and polysynthetic twinning, disequilibrium being replaced by prehnite? Both larger and matrix size.

Prhnite: moderate relief, blue pleochroism, III order colour, anhedral shape, in equilibrium, matrix size.

Accessory phases

Epidote: ~0.2 mm, III order colors, green/yellow pleochroism, high – moderate relief, round and tabular shape.

Titanite: high relief, brown color

Glass:

Secondary/alteration phases

Chlorite: green pleochroism, replacing hornblende.
Plagioclase being replaced by prhnite?
Epidote: clinosiocite?

Crystallization sequence

1 Hornblende
2 Plagioclase

Miscellaneous

Radiating mineral in hornblende in sec 7 – 8
Hornblende in plagioclase
Small high order mineral section 7
Special twined hornblende section 7

Sample number: FR15 - 25

Hand sample:

Thin-section map:

<u>Major rock-forming mineral phases</u>

Hornblende: 120° and 60° Cleavage, moderate relief, green/brown pleochroism, II low order colour, anhedral shape, disequilibrium being replaced by Metamorphic hornblende.

Metamorphic hornblende:? 120° and 60° Cleavage, low relief, blue/green pleochroism, III order colour, 2V ~70, optically - , tabular or elongated shape phenocryst, simple twining, disequilibrium strain and reaction rims.

Plagioclase: 0.5 mm, low relief, no pleochroism, I order white/grey colour, tabular anhedral shape, simple twining, in disequilibrium.

<u>Accessory phases</u>

Blue high relief mineral, yellow/green pleochroism, I order blue.

Epidote: high relief, weak pleochroism, II or III order high colours, round shape.

Titanite:

<u>Secondary/alteration phases</u>

Hornblende to meta hornblende?

<u>Crystallization sequence</u>

1 Hornblende
2 plagioclase

<u>Miscellaneous</u>

Hornblende being replaced by? Sec 7, 1-5
Blue minerals sec 8
Replacement sec 5
Fluid vain sec 5
Pyroxene sec 5- 6?!

Sample number: FR15 - 26

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Plagioclase: ~1.5 mm low relief, no pleochroism, I order grey/white, 2V ~ 80°, tabular round shape phenocrysts, simple and polysymmetric twining, disequilibrium.

Calcite: low relief, no pleochroism, III or IV order colour.

Hornblende:? 60° and 120° Cleavage, moderate relief, brown/ green pleochroism?, II low order colour, round anhedral shape, disequilibrium being replaced by cummingtonite.

Cummingtonite: 60° and 120° Cleavage, moderate to low relief, yellow/blue pleochroism, II order blue/purple colour, 2V ~80 optically + ?, elongated tabular fabric shape, multiple twining.

Cleavage, relief, pleochroism, I order colour, 2V optically + or -, shape, twining, disequilibrium, textures.

Accessory phases

Clinozoisite: high relief, no pleochroism, I order Blue/yellow colour, round and tabular shape.

Epidote: high relief, III order colors.

Secondary/alteration phases

Plagioclase and hornblende to cummingtonite?

Crystallization sequence

1 Hornblende
2 Plagioclase

Miscellaneous

Fluid vain filled with Clinozoisite and epidote.

Sample number: FR15 - 27

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Plagioclase: low relief, no pleochroism, I order white/yellow colour, tabular shape, simple and polysymmetric twining.

Cummingtonite: 120 ° and 60° Cleavage, low – moderate relief, yellow/blue /green pleochroism, II order blue/purple colour, tabular fibrous elongated shape, multiple twining.

Clinozeosite: ~0.1mm, high relief, weak yellow pleochroism, I order abnormal blue and grey colour, round tabular shapes.

Hornblende: 120° and 60° Cleavage, moderate relief, green/yellow/brown pleochroism, I order yellow colour, broken tabular, disequilibrium.

Accessory phases

Titanite: large, high relief, brown, round shape.
Epidote: high II or III order colors, high relief.

Secondary/alteration phases

Calcite

Crystallization sequence

1 Hornblende?
2 Plagioclase?

Miscellaneous

Large Titanite sec 3- 4
Veins whole sample,
Weird chlorite looking in vain mineral 2 - 6

Sample number: FR15 - 29

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Cummingtonite: 60° and 120° Cleavage, moderate to high relief, blue/yellow/green pleochroism, II order blue colour, round tabular shape, multiple twining, equilibrium.

Plagioclase: low relief, no pleochroism, I order white/yellow colour, anhedral/broken shape interstellar in sample, simple twining, disequilibrium.

Clinozoisite: high relief, yellow pleochroism, I order yellow or abnormal blue colour, round tabular shape, equilibrium.

Epidote: high relief, yellow/green pleochroism, II or III order colour.
Chlorite?:

Accessory phases

Cleavage, relief, pleochroism, I order colour, 2V optically + or -, shape, twining, disequilibrium, textures.

Secondary/alteration phases

Calcite:

Large brown body titanite?- unlikely

Crystallization sequence

1
2
3

Miscellaneous

Large green chlorite? With abnormal colors.

Sample number: FR15 - 30

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Plagioclase: ~ 0.7 mm, low relief, no pleochroism, I order white/grey colour, tabular shape, simple and polysynthetic twining, disequilibrium being replaced by?

Cummingtonite: 60° and 120° Cleavage, low to moderate relief, green/yellow/pink pleochroism, purple/yellow I order colour, 2V ~85°?, tabular elongated shape, disequilibrium, replaced by chlorite.

Unknown mineral: moderate relief, brown/green strong pleochroism, I order yellow brown colour, fibbers prismic shape.

Accessory phases

Secondary/alteration phases

Calcite
Epidote:
Clinozeosite:
Chlorite?: ~2 mm, low to moderate relief, strong green pleochroism, I order abnormal blue colour, anhedral shape, equilibrium.

Crystallization sequence

1
2
3

Miscellaneous

Weird high relief brown mineral sec 6
Large blue mineral sec 7.

Sample number: FR15 – 31

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Cummingtonite: moderate relief, yellow/blue/pink pleochroism, III order colour, tabular prismatic shape, phenocryst.

Plagioclase: ~0.2 mm, low relief, no pleochroism, I order white colour, elongated tabular shape, simple twining, disequilibrium.

Chlorite?:

Cleavage, relief, pleochroism, I order colour, 2V optically + or -, shape, twining, disequilibrium, textures.

Accessory phases

Clinozoite:
Titanite looking mineral?

Secondary/alteration phases

Epidote:
Calcite:

Crystallization sequence

1
2
3

Miscellaneous

Alignment of whole sample
Red mineral xpl and ppl sec 3-4

Sample number: FR15-32

Hand sample:

Thin-section map:

<u>Major rock-forming mineral phases</u>

Cummingtonite: ~1 mm, relief ? pink/yellow/blue pleochroism, II order blue colour, fibrous tabular elongated shape, multiple twining, disequilibrium replaced by chlorite? Phenocryst.

Chlorite?: low relief, Green pleochroism, I order abnormal blue colour, equilibrium replacing cummingtonite.

Plagioclase: ~0.2mm, low relief, no pleochroism, I order white/yellow colour, anhedral interstellar shape, equilibrium?

Calcite: ~0.7mm

<u>Accessory phases</u>

Titanite looking?
Epidote: high relief, III order IV colors
Clino or zeosite: I order yellow or blue, high relief.

<u>Secondary/alteration phases</u>

<u>Crystallization sequence</u>

1
2
3

<u>Miscellaneous</u>

Minerals aligned in veins
Titanite looking with chlorite looking sec 8
Red mineral in Titanite looking sec 5- 6
Cummingtonite being partly replaced by chlorite sec 1

Sample number: FR15 – 45

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Plagioclase: low relief, no pleochroism, I order grey/white colour, elongated tabular shape, simple twining, disequilibrium.

Quarts: low relief, no pleochroism, I order grey/white colour, uniaxial optically +, round shape, disequilibrium reaction rims.

Garnet? high relief, no pleochroism, isotropic or dark brown colours, hexagonal shape.

Matrix crypto crystals cummingtonite.

Accessory phases

Oxides:
Epidote:
Zeolite: high to moderate relief, yellow pleochroism, purple I or II order colors.

Secondary/alteration phases

Green alteration ppl and xpl, low relief section 8

Crystallization sequence

1 Garnet
2 quarts
3 plagioclase

Miscellaneous

Black veins sec 7
Veins are aligned.
Volcanic darker area in section 4

Sample number: FR15 - 46

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Quarts: low relief, no pleochroism, I order grey/white colour, round tabular shape, disequilibrium reaction rims.

Garnet/chlorite: high relief, no pleochroism, I order abnormal brown colour, hexatones habit, disequilibrium is being pseudomorphed to chlorite.

Cummingtonite: moderate relief, weak yellow pleochroism, II order colour, tabular shape, disequilibrium.

Cleavage, relief, pleochroism, I order colour, 2V optically + or -, shape, twining, disequilibrium, textures.

Accessory phases

Plagioclase:

Secondary/alteration phases

Epidote: high relief, green/yellow pleochroism, III order colour, round tabular shape.

Oxides:

Crystallization sequence

1
2
3

Miscellaneous

Foliation of oxides black lines.

Sample number: FR15 – 47

Hand sample:

Thin-section map:

<u>Major rock-forming mineral phases</u>

Quarts: No cleavage, low relief, no pleochroism, I order grey/white colour, round shape phenocryst, no twining, disequilibrium reaction rims.

<u>Accessory phases</u>

<u>Secondary/alteration phases</u>

Oxides:

Clinozoisite or Zoisite: no cleavage, high relief, strong yellow pleochroism, I order yellow colour, tabular round shape, disequilibrium.

Epidote: high relief, green/pink pleochroism, III order colour, tabular round shape, equilibrium.

Garnet/chlorite: high relief, no pleochroism, I order brown/black colour, hexagon shape, disequilibrium garnet being replaced.

Cummingtonite: moderate relief, blue/pink pleochroism, II order colours, tabular elongated shape, equilibrium.

<u>Crystallization sequence</u>

1
2
3

<u>Miscellaneous</u>

Large Epidote, high relief, II order colures, strong green/brown pleochroism. Section 2

Lineation of oxides, minerals semi aligned.

Sample number: FR15 - 49

Hand sample:

Thin-section map:

<u>Major rock-forming mineral phases</u>

Chlorite: low relief, light green pleochroism, abnormal blue and pink colour?

Unknown mineral: ~2mm, 90° Cleavage? High relief, weak yellow pink pleochroism, I or II order yellow colour, 2V ~90°, tabular elongated shape, disequilibrium.

Epidote: ~0.7mm, high relief, strong green pink pleochroism, III or IV order colour, round diamond shape, disequilibrium reaction rims.

Matrix cryptocryst cummingtonite?

Clinozoisite: high relief, yellow pleochroism, I order blue yellow colour, round shape, disequilibrium?

Plagioclase: low relief, no pleochroism, I order white/grey colour, elongated shape, simple twining, disequilibrium.

Quarts: 0.1mm, low relief, no pleochroism, I order white/grey colour, undulose extinction.

<u>Accessory phases</u>

<u>Secondary/alteration phases</u>

<u>Crystallization sequence</u>

1
2
3

<u>Miscellaneous</u>

Large crystals with cleavage? Sec 3
Internal deformation in minerals sec 4-8
Alinement of matrix dark lines

Sample number: FR15 – 50

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Quarts: low relief, no pleochroism, I white/grey order colour, round interstellar shape, disequilibrium, undulose extinction.

Clinozoisite: high relief, yellow/pink pleochroism, I order yellow and abnormal blue colour, round tabular shape, equilibrium.

Cummingtonite?: moderate relief, no pleochroism, I yellow/white order colour, elongated fibrous shape, multiple twining? equilibrium.

Cleavage, relief, pleochroism, I order colour, 2V optically + or -, shape, twining, disequilibrium, textures.

Accessory phases

Epidote: high relief, III or IV order interference colors, green pleochroism.

Secondary/alteration phases

Crystallization sequence

1
2
3

Miscellaneous

Matrix alignment
Veins section 1
Clusters section 5-6

Sample number: FR15 – 51

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Chlorite:? Low relief, green pleochroism, abnormal brown white colour, anhedral shape, equilibrium replacing?

Epidote: high relief, pink pleochroism, III or IV order colour, tabular elongated shape, simple twining, disequilibrium reaction rim.

Quarts: low relief, no pleochroism, I order yellow/white colour, round anhedral shape, disequilibrium.

Unknown mineral:? moderate relief, no pleochroism, I order grey colour, 2V ~70°, tabular elongated shape, simple twining, disequilibrium reactions inside?

Cummingtonite:? moderate relief, no pleochroism? I order yellow white, elongated fibrous shape, multiple twining? Equilibrium.

Accessory phases

Clinozoisite: high relief, yellow pleochroism, I order blue yellow colour, round tabular shape, equilibrium.

Secondary/alteration phases

Muscovite: low relief, weak blue pleochroism? III or IV order colour, tabular shape, equilibrium? Section 5

Crystallization sequence

1
2
3

Miscellaneous

Red oxide mineral? Sec 7

Vein of epidote? Section 3-7

High relief brown mineral on top of a lot of minerals.

Sample number: FR15 - 52

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Epidote?: high relief, pink green pleochroism, III or IV order colour, tabular elongated round shape, simple twining, disequilibrium reaction rim.

Clinozoisite: high relief, yellow pleochroism, I order yellow colour, round tabular blobby shape, equilibrium.

Quarts: Cleavage, relief, pleochroism, I order colour, 2V optically + or -, shape, twining, disequilibrium, textures

Cummingtonite:? relief, green pink pleochroism? II order purple colour, elongated fibrous shape, multiple twining, equilibrium.

Chlorite

Unknown mineral 2:? moderate relief, brown pleochroism, I order brown or yellow, fibrous shape/texture.

Accessory phases

Secondary/alteration phases

Crystallization sequence

1
2
3

Miscellaneous

Brown round areas with uknown mineral 2 ~0.3 mm sections 5,6,7,8 similar to early sample 28?

Matrix minerals aligned and black veins?

Sample number: FR15 - 53

Hand sample:

Thin-section map:

Major rock-forming mineral phases

Qvarts: low relief, no pleochroism, I order grey/white colour, interstellar anhedral shape, disequilibrium.

Cummingtonite: moderate relief, blue/green pleochroism, II or III order blue colour, elongated fibrous tabular shape, simple twining, disequilibrium?

Epidote: high relief, green/pink pleochroism, III or IV order colour, round shape, disequilibrium cover by brown stuff.

Clinozoisite: relief, yellow pleochroism, I order yellow colour, tabular round shape, disequilibrium covered by brown mineral.

Chlorite? Low – moderate relief, green pleochroism, abnormal black/brown color. Anhederal shape, replacing cummingtonite?

Accessory phases

Secondary/alteration phases

Crystallization sequence

1
2
3

Miscellaneous

Redd ppl xpl, high relief mineral.

Abnormal black chlorite section 6

Alignment of matrix minerals. Brown mineral grown on top of minerals?