Fluids in Subduction Zones: Production of Jadeite in Panoche Pass

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Abstract:

The metagraywacke rocks of Panoche Pass are coherent exhumed rocks in the Franciscan Complex, a fossil subduction zone, in California. The majority of the metagraywacke in the region contains albite, calcite, quartz, phengite, chlorite, titanite and minor amounts of lawsonite. However, there are irregular shaped mappable regions of metagraywacke which contain jadeite, more abundant lawsonite, and rutile instead of titanite. Jadeite and lawsonite are diagnostic minerals for high pressure, low temperature conditions found within subduction zones. The occurrence of these minerals in these irregularly shaped map patterns, but not throughout the region, suggests a role for fluid in driving the formation of jadeite and lawsonite rather than temperature, pressure, or chemical composition. These two mineral assemblages suggest that the rocks experienced different fluid compositions during metamorphism. The loss of calcite from the jadeite-bearing rocks suggests that CO_2 is released during metamorphism which has implications for our understanding of the carbon cycle. This study uses point counting, EPMA major element oxide data, and the TWQ thermodynamic modeling database to determine fluid compositions in equilibrium with the minerals present and to quantify the amount of CO_2 released during metamorphism of the jadeite-bearing rocks. The estimated release of CO_2 from these calculations is compared to measured CO_2 loss. The estimated fluid composition is less than 0.0025 X_{CO2}, and the calculated CO_2 loss is between the estimated value of 0.07 g/100cm^3 and the measured value of 0.097 g/100cm^3. This calculation shows that an H_2O-rich fluid infiltrated these metagraywackes, allowing for jadeite to grow and CO_2 to be released. This data is used to investigate the role of fluids in the metamorphism of these rocks.

Introduction:

Subduction zones are the locations of many important geologic hazards, including arc volcanoes, and some of the deepest and largest registered earthquakes on Earth. While much is known about subduction zone processes that cause these hazards, there are still aspects that are poorly understood. One aspect that is not well understood is the influence of fluid and fluid release during metamorphism on seismicity (Hacker at al., 2003). Fluids are also thought to facilitate melting in the mantle that contributes to arc volcanism. Isotopic evidence from volcanic arc rocks suggests that these fluids are derived from the slab (Elliott, 2003; Cook-Kollars et al.,2014). This fluid release leads to transport of elements that is referred to as geochemical cycling. Measurements of total CO_2 entering subduction zones compared to CO_2 emitted from arc volcanism provides an understanding of whether complete return of CO_2 to the surface occurs. However, the CO_2 measured at the surface is less than the predicted concentration in the slab, suggesting the CO_2 is being recycled into the mantle (Gorman et al., 2006). The rest of the CO_2 remains in the mantle but is unmeasurable leading to large uncertainties in the estimate for global CO_2 flux (Kelemen and Manning, 2015; Winter, 2009). Two types of carbon-releasing reactions have been recognized in metamorphic rocks- Decarbonation (in which carbonate sometimes along with silicate react to release CO_2) and carbonate dissolution reactions (in which carbonate minerals completely dissolve in a fluid). Studies of calc-silicate decarbonation reactions in exhumed rocks from subduction zones, like the ones in this study, can lead to a better understanding of the amounts of CO_2 released from the slab (Cook-Kollars et al., 2014).

The study of the jadeite-bearing rocks in Panoche Pass (figure 1a) will contribute to understanding fluid and CO_2 involvement in subduction zones. These metagraywacke rocks were part of a subduction zone where they experienced pressures between 6 kbar to 8 kbar (0.6-0.8 GPa), and temperatures of 200°C -300°C (Ernst, 1965). The majority of the metagraywacke in the region contains albite, quartz, phengite, chlorite, calcite, titanite and minor amounts of lawsonite. However, there is some metagraywacke that has jadeite, larger amounts of lawsonite, and rutile instead of titanite, but they also lack calcite. These metagraywackes appear in irregular shapes on the map of the region, illustrated in figure 1b. The lack of calcite in the jadeite-bearing rocks also suggests a release of CO_2. This, as well as the irregular map pattern of the jadeite-bearing metagraywacke will be explored in this study. The irregularity of their occurrence and the absence of calcite suggests a fluid driven decarbonation reaction took place in the rocks of Panoche Pass.

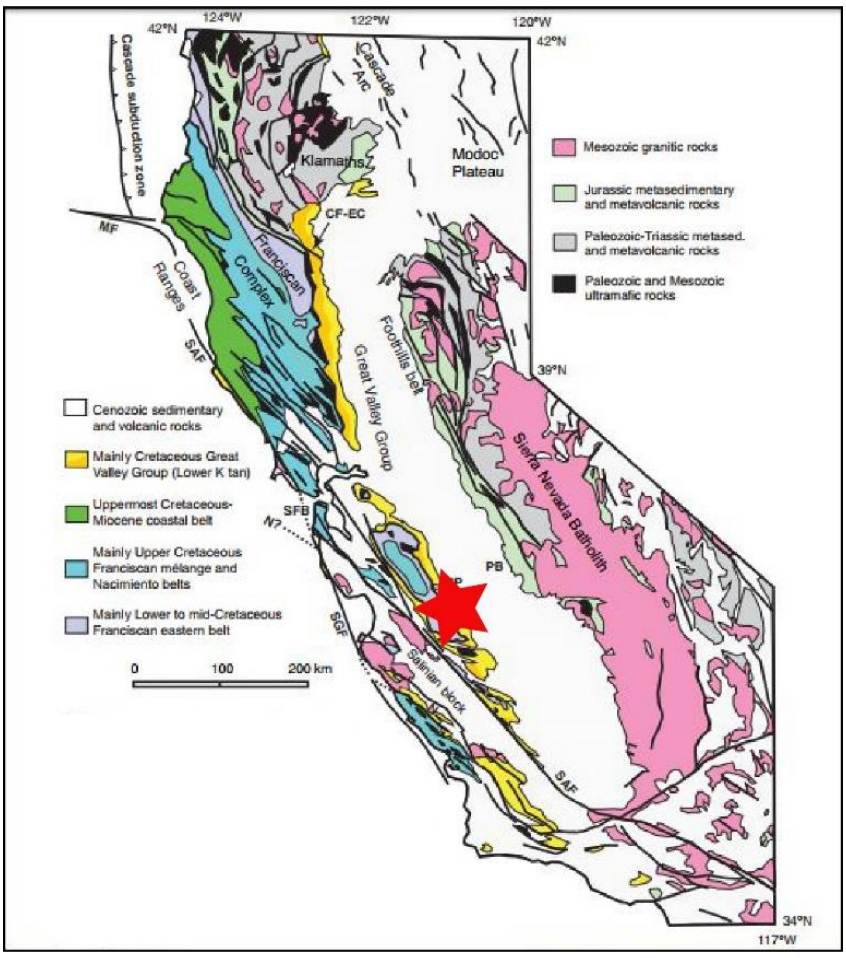

Figure 1a: This is a geologic map of the Franciscan Complex in California. The red star marks the location of Panoche Pass.

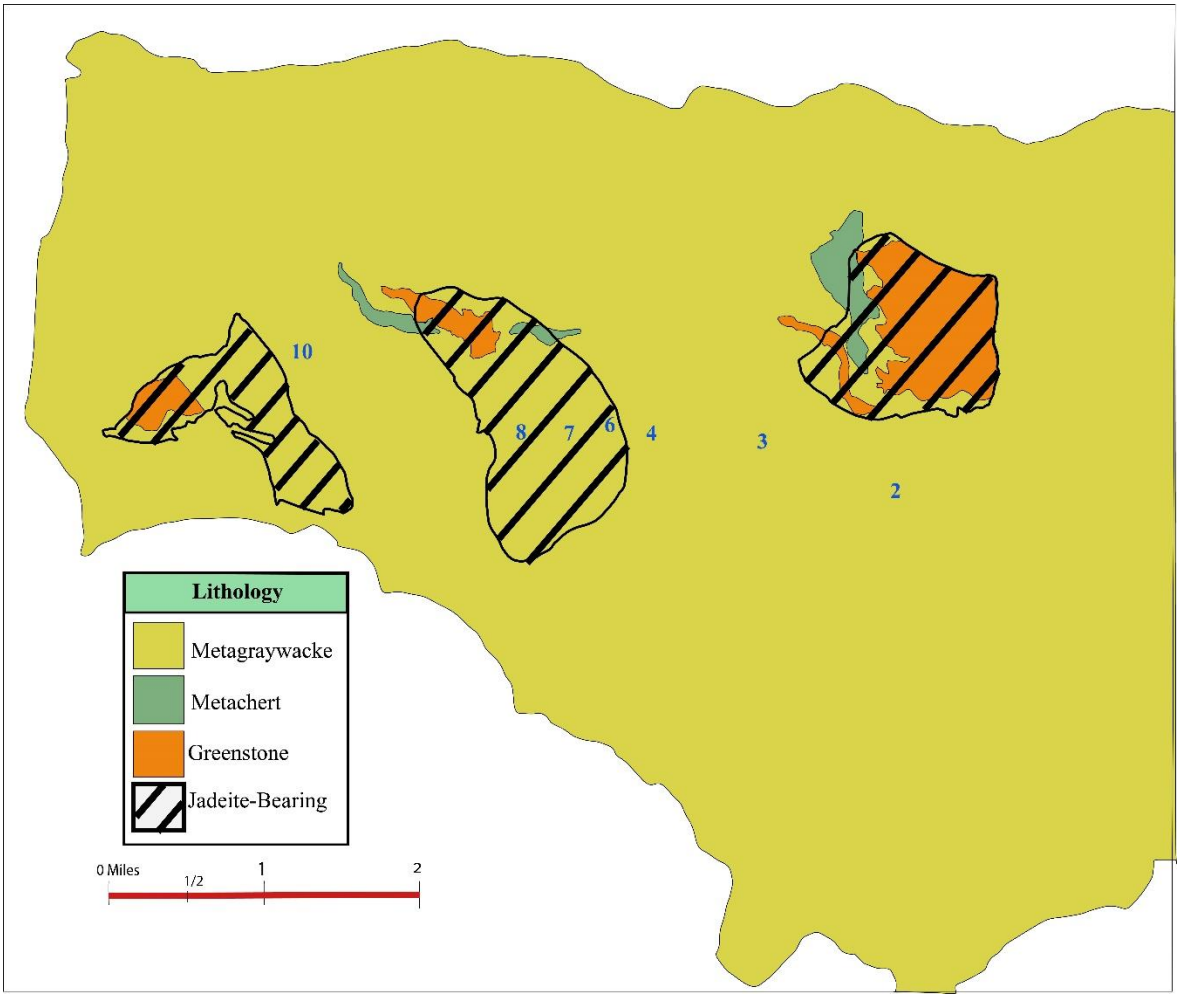

Figure 1b: The lower map is a map of Panoche Pass. The numbers represent the sample locations. The striped region represents the regions in which jadeite appears (Ernst, 2011).

Geologic Background:

The Franciscan Complex, located in California, is a fossil subduction zone formed during the late Jurassic to early Cretaceous periods (Ernst, 1965). The complex is made of multiple belts of coherent rock comprised of metasediments separated by mélange (Sadofsky and Bebout, 2004). A mélange is a mappable unit containing a variety of rocks in a fine-grained matrix. It typically forms in the accretionary prism of a subduction zone. Panoche Pass, located about 30 miles east of Monterey Bay, consists of more coherent rocks that are found in the Diablo Range (a belt of the Franciscan Complex) (Figure 1a; Ernst,1965). The Diablo Range is an anticlinorium (an anticline with minor superimposed folds) paralleling the coast of California (Ernst, 1965). The seven samples for this study were collected from a coherent section of the metagraywacke in this range.

The metagraywacke rocks in Panoche Pass are overlain by metachert and greenstone (Ernst, 1965). They are divided into two types of metagraywacke. The majority of the metagraywacke in Panoche Pass is composed of albite, quartz, phengite, chlorite, calcite, titanite and minor amounts of lawsonite and epidote, and will be referred to as the jadeite-absent metagraywacke for the rest of the paper (pictured in figure 2). The other metagraywacke rocks with the mineral assemblage of albite, quartz, phengite, chlorite, titanite, rutile, lawsonite and jadeite will be referred to as the jadeite-bearing metagraywacke (pictured in figure 3). The jadeite and lawsonite are high pressure and low temperature metamorphic minerals. Their presence in these rocks allows for these rocks to be interpreted as being exhumed from a fossil subduction zone (Ernst and Banno, 1991). However, the irregular map pattern of jadeite occurrence is atypical of a subduction zone environment.

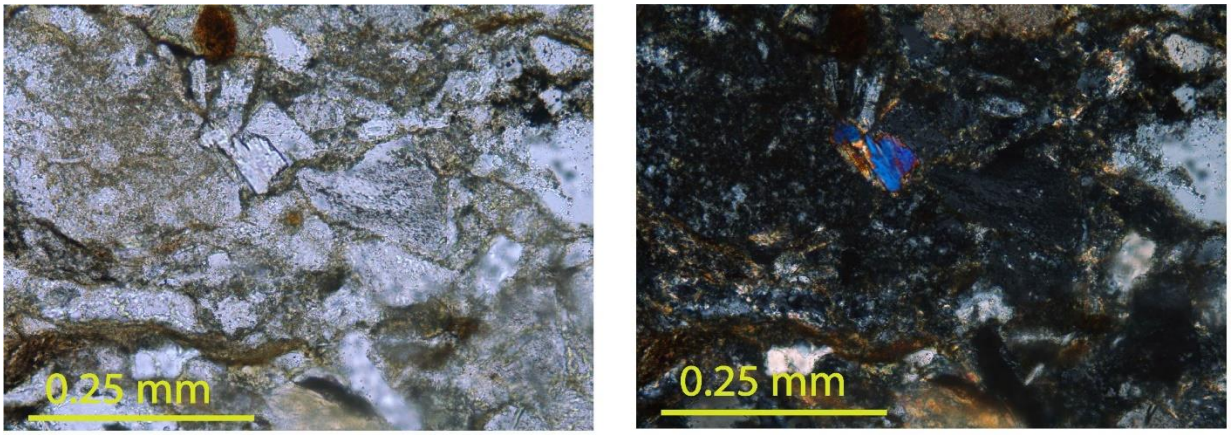

Figure 2: The PPL photomicrograph to the left is of a samplePnP13-3, one of the jadeite-absent samples. The figure to the left is the same field of view in XPL.

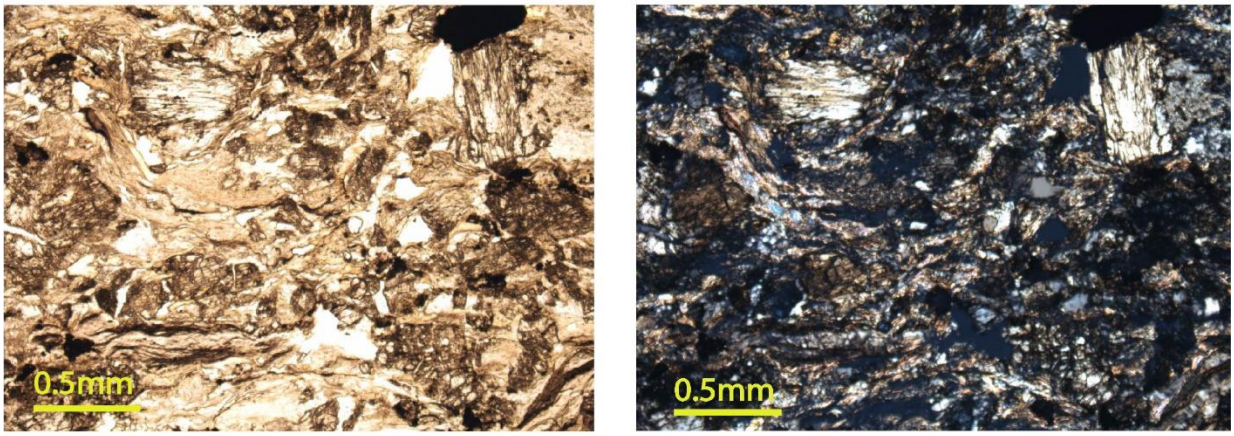

Figure 3: The PPL photomicrograph to the left is of a sample PnP13-8a, one of the jadeite-bearing samples. The figure to the left is the same field of view in XPL.

Objective:

This study focuses on understanding the growth of jadeite and lawsonite and their relationship with release of CO_2 during metamorphism. There are four main factors that control the mineral development in metamorphic rocks. These factors are temperature, pressure, lithology and fluid composition. In a region where temperature and pressure control mineral growth, there would be a gradient of jadeite growth across the map, yet its occurrence is irregular in Panoche Pass instead (figure 1b). If the growth of jadeite was the result of variations in the protolith composition before metamorphism, then the mineral should be restricted to specific rock types, whereas it appears to crosscut many lithologic boundaries (into metachert and greenstone). This suggests that the metamorphism is independent of lithology. This leaves subduction zone fluid flow as the most likely cause of jadeite growth in these rocks. I hypothesize that the formation of jadeite in these metagraywackes requires decarbonation reactions driven by H_2O-rich fluid infiltration. The null hypothesis that will be tested is that the formation of jadeite in these metagraywackes does not require decarbonation driven by H_2O-rich fluid infiltration.

Methods:

Point counting data, electron probe micro-analyzer (EPMA) major oxide data, whole-rock geochemistry (major element) analysis, and CO_2 content analysis are the methods of data collection in this study. Equilibrium fluid compositions were calculated for the jadeite-bearing metagraywackes using the thermodynamic program TWQ (Berman, 1991).

Sample Collection:

Seven samples were collected by my advisor, Dr. Penniston -Dorland (labeled across the map in figure 1) in 2013. The GPS coordinates are listed below. Thin sections were made from each of these samples.

Sample	GPS Coordinates		Mineral Assemblage
Pnp13-2	N 36.63082	W 121.05428	Jadeite-absent
Pnp13-3	N 36.6548	W 121.04613	Jadeite-absent
Pnp13-4a	N 36.65502	W 121.06193	Jadeite-absent
Pnp13-6	N 36.65551	W 121.06888	Jadeite-bearing
Pnp13-7	N 36.65447	W 121.07871	Jadeite-bearing
Pnp13-8a	N 36.65442	W 121.07871	Jadeite-bearing
Pnp13-10	N 36.66289	W 121.10138	Jadeite-absent

Table 1: This table lists each sample, their geographic locations, and their grouping based on mineral assemblage.

Point Counting:

Point counting on the EPMA was used to determine the mineral assemblages and mineral modes for the jadeite-bearing and jadeite-absent metagraywackes. A grid of 1200 points is used to overlay each thin section. The phase on which the cross hairs land is identified and recorded by using energy dispersive x-ray spectroscopy (EDS). If the cross hairs fall on a crack or hole, the point is not counted and therefore does not contribute to the representation of the mineralogy of the rock.

This method is used on all 7 thin sections. 3414 points were counted for the 3 jadeite-bearing samples, and 4619 points were counted on the 4 jadeite-absent samples. The grids had spacings that varied from ~550 to ~1000 microns (See appendix table 32). Uncertainties for point counting data were calculated according to the Van Der Plas and Tobi 1965 paper for judging the reliability of point counting results (figure 10). The uncertainties are calculated by finding the percent error range in which a known mineral abundance will fall (x-axis) by knowing the total number of points counted per thin section (y-axis).

EPMA:

In addition to point counting, the EPMA was used to determine major element composition of titanite, albite, rutile and calcite in the jadeite-absent rocks and albite, jadeite, titanite, and rutile in the jadeite-bearing rocks. This is done by using wavelength dispersive spectroscopy (WDS). These data are collected and reported as weight percent oxides for each major element in the phase. The points whose totals differ by more than 1.5% of expected total are discarded. Totals are expected to be 100% if it is a mineral that does not contain water or carbonate. The data whose mineral formulae are not stoichiometrically correct are also discarded. All formula units are reported to 2 significant figures.

The probe operating conditions for the WDS analyses were as follows: 15kV accelerating potential, 10 micron diameter beam, 10nA cup current. The following standards were utilized: calcite or plagioclase for Ca; barium glass for Ba; natural albite for Na, Al, and Si; Kakanui hornblende for Fe, Ti, and Mg; and spessartine for Mn. The operating conditions for jadeite and albite were the same beam diameter and current, but had a 10kV potential. The jadeite and albite were standardized on natural albite for Na, and Al, on Ilmen Mountains ilmenite for Fe and Ti, and K, Mg, Mn, Ba, Ca and Si were standardized on the same Kakanui hornblende.

Bulk Analysis and CO_2:

Ten grams of each sample were powdered to be used for CO_2 analysis as well as geochemical analysis by X-ray fluorescence (XRF). For XRF, these samples were heated until molten, then quenched into a disk that was analyzed for major and trace elements in the PANalytical 2404 X-ray fluorescence vacuum spectrometer. CO_2 content was measured by dissolving approximately 0.5g of sample with 3M HCl. The samples were reacted with the acid, washed 3 times, then dried in an 80-degree oven for 4 days. The difference in mass is interpreted to be the loss of the carbonate components in the rock. The remainder of the

powdered sample was sent to Franklin and Marshall College for XRF analysis. Major elements were analyzed and reported in table 33 in the appendix. The associated uncertainties for these analyses are reported in table 34.

Rock Density Calculation:

To solve for rock density (used for reaction progress calculations in discussion), one sample of the jadeite-absent rock (PnP13-10), and one sample of the jadeite-bearing rock (PnP13-7) was used. These samples were both weighed then placed into a graduated cylinder with a known volume of water. The displaced water volume is equal to the volume of rock. The mass divided by the rock volume equals the rock density in g/cm^3.

Results:

The point counting results are shown below in figures 4 and 5. The combined point counting data for the jadeite-bearing rocks are illustrated by the pie chart in figure 4. The combined point counting data for the jadeite-absent rocks are illustrated in figure 5 and the differences between these combines assemblages are discussed below. Individual sample point counting results can be found in the appendix on tables 9 and 10.

The jadeite-bearing rocks overall have 21% jadeite while the jadeite-absent rocks have close to none. Albite is more abundant in the jadeite-absent rock and there is a difference of 29% between the two metagraywacke types (39%-10%). Calcite appears in the jadeite-absent samples with an average abundance of 2%. There is no calcite in the jadeite-bearing samples. Lawsonite is more abundant on average in the jadeite-bearing samples than in the jadeite-absent samples although both have a wide range of lawsonite abundance, and has a difference of 5% between the overall analyses of the two types of metagraywackes (7%-2%). Quartz is less abundant in the jadeite-bearing samples and has a difference of 3% (30%-27%). The abundance of chlorite slightly decreases in the jadeite-absent samples by 3% compared to the jadeite-bearing samples (14%-11%). The jadeite-bearing samples have rutile and titanite with an abundance of less than 1% each, but the jadeite-absent sample has only titanite with an abundance of about 1%. Phengite is slightly more abundant in the jadeite-bearing sample with a difference of 7% (21%-14%). Epidote is found in the jadeite-absent samples with an abundance of 0.26%. Apatite, zircon, muscovite and iron oxide are found in trace abundance in all samples. Pyrite and barite appear in small amounts in the jadeite-bearing samples.

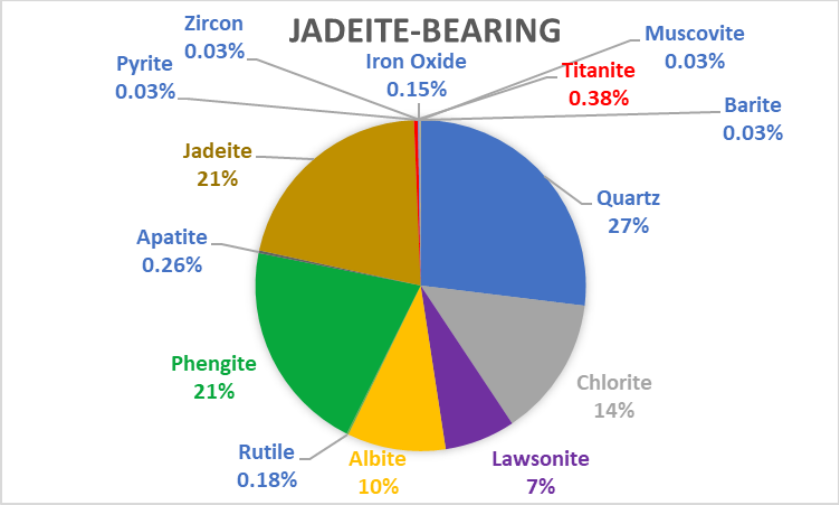

Figure 4: The combined point counting results from the three jadeite-bearing rocks are illustrated by this pie chart. It represents the sum of the data listed below in table 2 and has a sum of 3414 points.

Mineral	Sum of Jadeite-Bearing Points	Percentages	+/-	STDEV
Quartz	920.00	26.95	0.81	80.16
Epidote	0.00	0.00	0.00	0.00
Chlorite	468.00	13.71	0.41	32.42
Lawsonite	236.00	6.91	0.14	85.23
Albite	329.00	9.64	0.19	72.45
Rutile	6.00	0.18	0.00	1.73
Calcite	0.00	0.00	0.00	0.00
Phengite	709.00	20.77	0.62	27.47
Apatite	9.00	0.26	0.00	1.00
Jadeite	715.00	20.94	0.63	24.21
Titanite	13.00	0.38	0.00	2.08
Chromite	0.00	0.00	0.00	0.00
Iron Oxide	5.00	0.15	0.00	2.12
Zircon	1.00	0.03	0.00	N/A
Pyrite	1.00	0.03	0.00	0.58
Muscovite	1.00	0.03	0.00	0.58
Barite	1.00	0.03	0.00	0.58
SUM	3414.00	100.00		

Table 2: The sum of the point counting results from the three jadeite-bearing samples are listed in this chart. The pie chart in figure 4 displays the percentages of each mineral relative to the total number of points counted in both thin sections. Their uncertainties (counting statistics) are listed here in the form of a range of percentages (+/-).

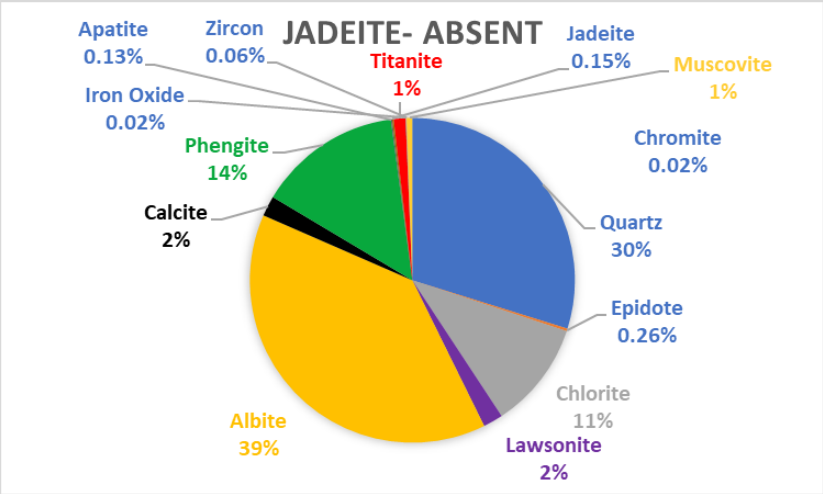

Figure 5: The combined point counting results from the four jadeite-absent rocks are illustrated by this pie chart. It represents the percentages of the total number of points counted per mineral listed below in table 3 and has a sum of 4619 points.

Mineral	Sum of Jadeite-Absent Points	Percentages	+/-	STDEV
Quartz	1377.00	29.81	0.89	53.88
Epidote	12.00	0.26	0.00	3.46
Chlorite	493.00	10.67	0.21	26.42
Lawsonite	91.00	1.97	0.02	8.85
Albite	1794.00	38.84	1.17	85.62
Rutile	0.00	0.00	0.00	0.00
Calcite	93.00	2.01	0.02	26.84
Phengite	661.00	14.31	0.43	27.18
Apatite	6.00	0.13	0.00	0.58
Jadeite	7.00	0.15	0.00	0.50
Titanite	54.00	1.17	0.01	4.12
Chromite	1.00	0.02	0.00	0.50
Iron Oxide	1.00	0.02	0.00	0.58
Zircon	3.00	0.06	0.00	0.71
Pyrite	0.00	0.00	0.00	0.00
Muscovite	26.00	0.56	0.01	7.51
Barite	0.00	0.00	0.00	0.00
SUM	4619.00	100.00		

Table 3: The three jadeite-absent samples are listed in this chart. The pie chart in figure 5 displays the percentages of each mineral relative to the total number of points counted in both thin sections. Their uncertainties (counting statistics) are listed here in the form of a range of percentages (+/-).

Mineral formulae were determined based on the mineral compositions measured using WDS analysis. The mole fractions of end member components were calculated based on this data for each of these minerals. The calcite is nearly pure calcite and has an average

composition of X_{Cal}=1.00. The albites were also nearly pure in the jadeite-bearing rock and also had an average composition of X_{Ab}=1.00. In the jadeite-absent sample, oligoclase occurred in addition to albite and had an average composition of X_{Ab}= 0.88. The titanite in the jadeite-bearing sample had a composition of X_{Ttn}=0.92, and an average composition of X_{Ttn}= 0.91 in the jadeite-absent sample. Rutile in the jadeite-bearing rock was nearly pure with an average composition of X_{Rt}=0.99. The jadeite composition in the jadeite-bearing rock was not pure and had an average composition of X_{Jd}=0.84. The pyroxene compositions are plotted on a ternary diagram in figure 6.

The WDS analyses and relative standard errors are reported for each point of analysis in the appendix below (tables 11-31).

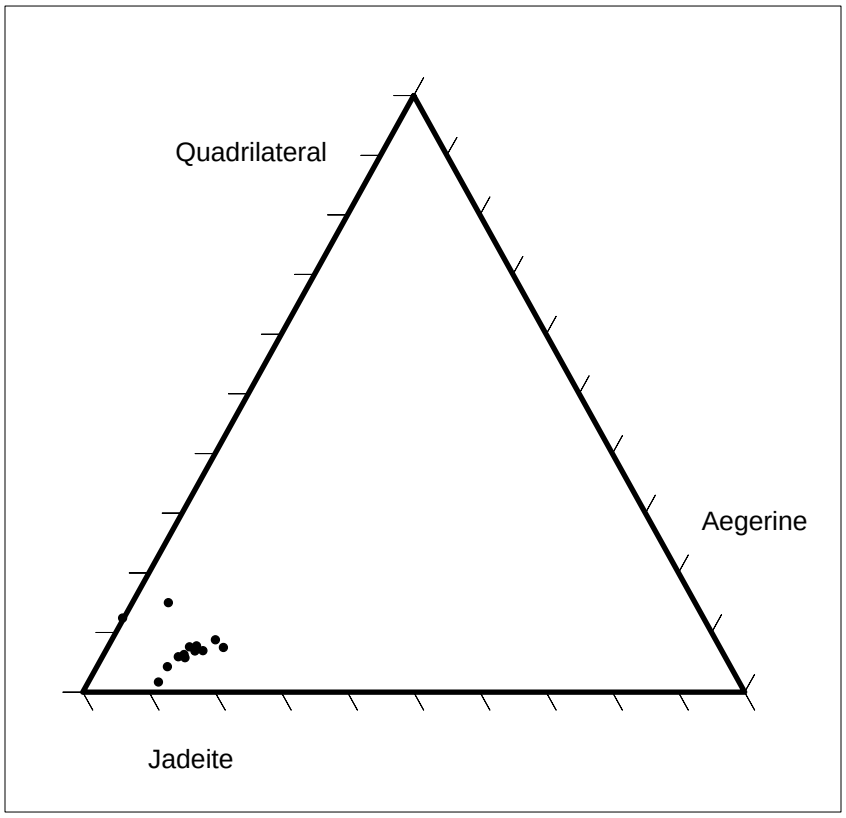

Figure 6: Pyroxene ternary diagram showing that the pyroxenes in sample PnP13-8a is jadeite in composition. The quadrilateral refers to the diopside-hedenbergite component of pyroxene.

Rock Density:

Jadeite-absent Sample PnP13-10	
Change in volume	16.00
Change in volume	14.00
Average volume	15.00
Mass	43.67

Jadeite-absent Sample PnP13-7	
Change in volume	9.00
Change in volume	9.00
Average volume	9.00
Mass	25.50

Table 4: These tables show the values that were found for a change in volume (ml) and mass of sample (g) and the density that was calculated for these two samples.

Specimen	Jadeite-bearing Samples	Jadeite-absent Samples	Difference
SiO2	65.97	68.88	-2.91
TiO2	0.73	0.59	0.15
Al2O3	15.07	14.45	0.62
Fe2O3T	6.35	5.02	1.33
MnO	0.08	0.07	0.01
MgO	3.73	2.32	1.41
CaO	2.04	2.60	-0.55
Na2O	3.93	4.09	-0.15
K2O	2.01	1.71	0.31
P2O5	0.16	0.24	-0.08
Total	100.09	99.95	0.13
LOI	3.78	3.54	0.24

Table 5: This table shows the average bulk composition of the both the jadeite-bearing and the jadeite-absent samples. These analyses were obtained at Franklin and Marshall College by XRF analysis.

Bulk Analysis:

The major element analysis shows a loss of silicon, iron, and magnesium. These losses are outside the analytical uncertainty. These variations may be due to variations in protolith or metamorphic processes but are unable to be confirmed (individual sample data on table 33 in appendix).

CO_2 Analyses:

Sample	% CO_2
10i	9.3774
10ii	9.8039
10iii	9.3974
10iv	9.6682
10v	9.5458
2	7.6629
8a	3.9806
4a	7.1583
6	3.4924
3	5.9016
7	2.8824

Table 6: This table lists the samples and their percent CO_2 by mass. The green lines highlight jadeite-bearing samples, while the white lines are jadeite-absent samples. Repeat analyses of PnP13-10 showed that there is a standard deviation of 0.001 which is the assumed to be the deviation of the remaining 6 samples as well.

The mass loss after reacting each sample with 3M HCl, washing, and drying the samples was assumed to be the mass of CO_2. However, there were no carbonate phases present in the jadeite-bearing rocks according to modal abundance calculations (see Table 2). The percent loss reported for these samples must be either loss of calcite along grain boundaries that was missed during point counting, and/or the loss of water from the hydrous minerals. Nonetheless, the jadeite-absent samples contained more CO_2 than the jadeite-bearing samples. This mass loss is attributed to loss of calcite so the average CO_2 content of the jadeite-absent sample was on average 7.57%. The average mass loss and therefore CO_2 content of the jadeite-bearing samples was 3.45%.

Discussion:

Mineral Reactions:

Mineral reactions that occurred in the rocks were determined by comparing the mineral modes in the jadeite-absent samples to those in the jadeite-bearing samples. Point counting

data shows the presence of jadeite in the jadeite-bearing samples while in the jadeite-absent samples, there is little to no jadeite. Jadeite and albite are the only two Na-bearing minerals present in the rocks, and therefore a reaction, already determined in previous studies of high pressure rocks (Ernst, 1965) in which albite reacts to produce jadeite and quartz, is likely to have occurred in these rocks (reaction 1). Epidote is present in the jadeite-absent rock, but it disappears from the mineral assemblage in the jadeite-bearing rock. A balanced reaction involving epidote and the other Ca-bearing minerals in the rocks is present in reaction 2. Similarly, rutile appears in the jadeite-bearing samples, while there is no rutile in the jadeite-absent samples. The only other Ti- bearing phase in the rocks is titanite suggesting that the titanite in the original metagraywacke was involved in a reaction to produce rutile in the jadeite-bearing metagraywacke (reaction3). The increase in the abundance of lawsonite (a major Ca-bearing phase in these rocks) and the impurity of jadeite/ diopside suggests that reaction 4 occurred in the rocks. The disappearance of calcite in the rocks also suggests a release of CO_2 that does not appear in any other mineral present in the jadeite-bearing rocks (reaction 4).

CO_2 is involved in 3 out of the 4 reactions below. We can use the mineral modes to constrain the amount of reaction (on average) that occurred between the jadeite-absent and jadeite-bearing rocks. This is referred to as reaction progress and is calculated as $\xi=\frac{\Delta n}{\nu}$ (Rice and Ferry, 1982).

The balanced reactions that could explain the transitions of minerals between assemblages are written below:

(1) $NaAlSi_3O_8 = NaAlSi_2O_6 + SiO_2$

Albite = Jadeite + Quartz

(2) $2\ Ca_2Al_3Si_3O_{12}(OH) + CO_2 + 5\ H_2O = 3\ CaAl_2Si_2O_8{\cdot}2H_2O + CaCO_3$

2 Epidote + CO_2 + 5 H_2O = 3 Lawsonite + Calcite

(3) $CaTiSiO_5 + CO_2 = TiO_2 + CaCO_3 + SiO_2$

Titanite + CO2= Rutile + Calcite + Quartz

(4) $Mg_4Al_4Si_2O_{10}(OH)_8 + 6\ CaCO_3 + 10\ SiO_2 = 4\ CaMgSi_2O_6 + 2\ CaAl_2Si_2O_8{\cdot}2H_2O + 6\ CO_2$.

Chlorite + 6 Calcite + 10 Quartz = 4 Diopside + 2 Lawsonite + 6 CO_2

Reaction Progress:

Reaction progress was calculated by using mineral modes to estimate the expected moles of CO_2 lost during these reactions. Changes in the abundance of minerals involved in

each reaction that are unique to that reaction can be used to constrain the amount of reaction. The average modal abundance data collected were converted to moles of each mineral (per 100 cm3 volume of rock) using molar volumes for each mineral (Holland and Powell, 2011). Reaction progress coefficients were calculated by solving for moles of jadeite produced in reaction 1, moles of epidote consumed in reaction 2, moles of rutile produced in reaction 3, moles of calcite consumed in reaction 4 (adjusted for moles of calcite produced in reactions 2 and 3 using reaction progress calculated for those reactions). The moles of CO_2 lost (on average) from a 100 cm3 volume of rock is calculated by taking the reaction progress for reaction 4, multiplying by 6 (the stoichiometric coefficient of CO_2 in reaction 4) and subtracting the calculated reaction progress for reactions 2 and 3 (in both cases multiplied by 1 which is the stoichiometric coefficient for CO_2 in both reactions). The reaction progress values are shown in table 7 below. The calculated value of lost CO_2 was 0.07 moles/100cm^3. These values can be compared to the CO_2 loss measured from the bulk rocks. The values in table 6 show the estimated loss of calcite in both the jadeite-bearing and jadeite-absent metagraywacke. These values were converted to moles/100cm^3. The estimated value of total lost calcite from the jadeite-absent rock was 0.0970 moles/100cm^3. This conversion was made by using a density of 2.91 g/cm^3. These values agree fairly well with each other and suggest that by two different methods, there was the same estimate of carbonate loss.

The bulk analysis data shows a loss of silicon in the jadeite-absent metagraywacke. This could be from the influence of the H_2O-rich fluid dissolving some elements as these reactions take place. The abundance of quartz veins in the rocks suggests that SiO_2 was mobilized during metamorphism (Penniston-Dorland et al., 2008). There are mass differences in many elements that are evident from the bulk rock data. It is difficult to determine whether these differences are due to variability in the protolith of the rocks or whether they are the result of metamorphic processes.

The calculated loss of CO_2, and the observed loss of calcite both suggest calcite was consumed by decarbonation reactions. Below we calculate the fluid composition in equilibrium with the rocks during these reactions. Thermodynamic calculations suggest that the fluid that drove these reactions was H_2O-rich. This fluid composition allowed for the growth of jadeite and lawsonite to occur and reach a state of equilibrium with the other minerals and the fluid.

Reaction	Reaction Progress
Reaction 1	0.343
Reaction 2	0.001
Reaction 3	0.010
Reaction 4	0.011

Table 7: The reaction progress values are the values used to estimate moles lost (reactions 2 and 4) and moles produced (reactions 1 and 3) which were used to calculate the overall loss of CO_2 expected in the rocks.

Equilibrium Fluid Composition:

The TWQ database uses thermodynamic properties of minerals to calculate equilibrium conditions for mineral reactions (Berman, 1991). Only two reactions proceeding simultaneously, are required for the calculations of equilibrium fluid composition. Reactions 1 and 3 were used. The major-element compositions of minerals measured using the EPMA were used in these calculations. Ideal solution and rock equilibrium was assumed for all minerals, which means that the activities of each component in the equilibrium constant were assumed to be equivalent to the mole fraction. These mineral activity values were used to calculate equilibrium temperature and pressure conditions, as well as H_2O-CO_2 fluid composition at equilibrium during these reactions.

A fluid component is not necessary for Reaction 1 to proceed. It can therefore be used to constrain the temperatures and pressures of metamorphism. A calculation to solve for fluid composition was performed using mineral compositions from the jadeite-bearing and jadeite absent samples. The average mole fraction of jadeite (X_{Jd}) was 0.84, therefore the activity of jadeite (a_{Jd}) was assumed to be 0.84 for these calculations. Similarly, the average mole fraction of albite (X_{Ab}) albite in the jadeite-bearing rock was 1.00, therefore the activity of albite (a_{Ab}) was assumed to be 1.00. The composition of albite in the jadeite-absent rock ranged from X_{Ab} =0.88 to 0.99, therefore calculations for both compositions were performed. Quartz was assumed to be a pure phase, so a_{Qz} =1.00. These calculations were performed using the average compositions of

Equilibrium P-T conditions calculated for reaction 1 are displayed in figure 7. The two lines illustrate the range of conditions for the measured albite compositions in the samples. These conditions range from low pressure (~0.5 kbar)/temperature (~100 °C) to high pressure (~20 kbar) /temperature (~1,000 °C). Jadeite occurs on the high-pressure side of the equilibrium lines in figure 7, and albite occurs on the low-pressure side. The equations for these graphs are used to calculate the temperatures at a pressure of 14 kbar (table 8). 14 kbar was used to perform these calculations because thermodynamic data for minerals at the estimated pressures of 6-8 kbar are not available in the TWQ database. The effect of lower pressure on the fluid composition is to decrease the X_{CO2} in equilibrium with the minerals, therefore the calculated fluid composition from these calculations is an overestimate.

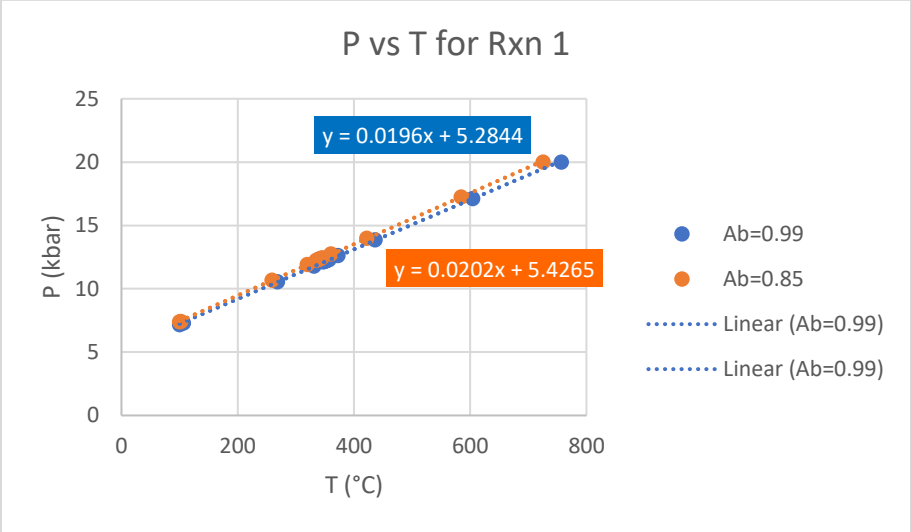

Figure 7: This graph displays the equilibrium pressure-temperature conditions calculated using the TWQ database using the range of plagioclase compositions (X_{Ab}) present in the rock. Jadeite is stable above the lines of equilibrium while albite is stable below them.

Trial	T at 14 kbars (°C)
Ab=0.99	445.42
Ab=0.85	424.14

Table 8: These temperature values were calculated using the equations on figure 7. The temperatures are superimposed on figure 9 to constrain the range of temperature and X_{CO2} resulting from equilibrium calculations of reactions 1 and 3.

Temperature and fluid composition can be constrained by reaction 3. This reaction produces rutile which requires the involvement of a fluid containing CO_2. These equations were performed using the calculated activities of titanite, rutile and calcite. The activities for these minerals were all calculated by the same method used previously for the T-P calculations. The average mole fraction (and therefore activity) of titanite in the jadeite-bearing rocks was 0.92. The average mole fraction (and therefore activity) of titanite in the jadeite-absent was 0.91. The average mole fraction (and therefore activity) of calcite in the jadeite-absent was 1.00, and the average mole fraction (and therefore activity) of rutile in jadeite-bearing rocks was also 1.00.

Calculations were performed for these minerals assuming ideal conditions, and a pressure of 14 kbars. The resulting graph of T vs X_{CO2} (figure 8) illustrates these minerals at equilibrium.

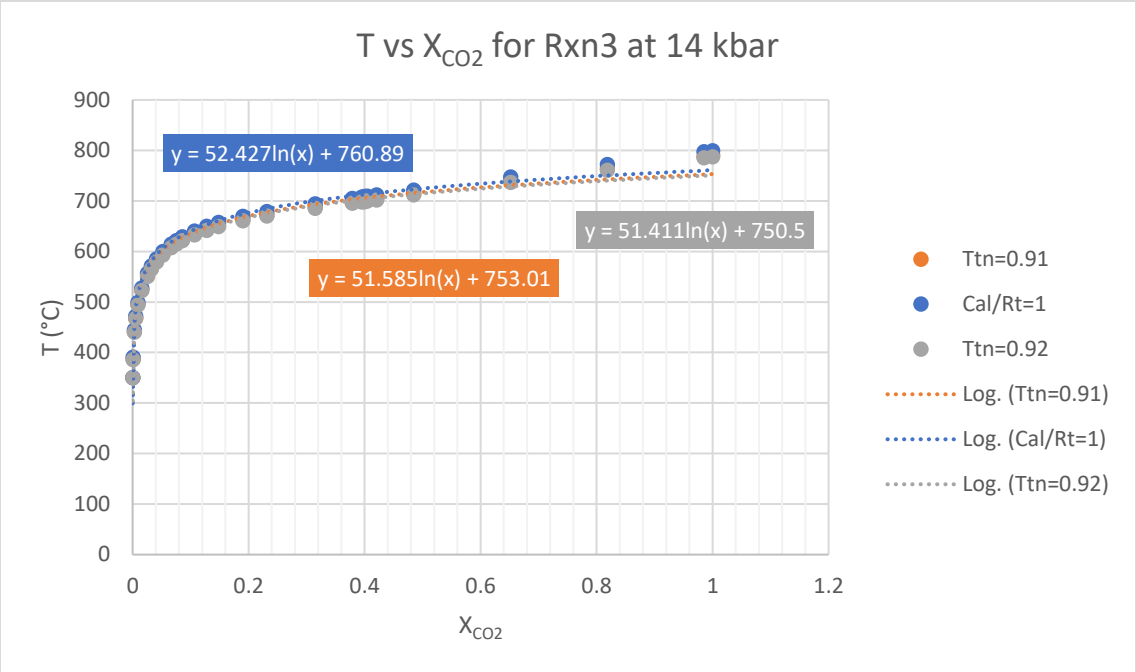

Figure 8: This graph displays the line of equilibrium above which, titanite and CO_2 are stable and below which, rutile, quartz and calcite are stable.

The equilibrium fluid composition for the two simultaneous reactions can be calculated by determining the intersection of the two equilibrium curves. Figure 9 shows both curves on a single T-X_{CO2} diagram. The intersection of these lines of equilibrium constrain the mole fraction of CO_2 in the fluid to a range of less than 0.0025. This suggests that if a fluid were involved in the production of these minerals an H_2O-rich fluid composition is required.

This H_2O rich fluid is maintained while these reactions take place and release CO_2 as calcite is consumed. As epidote is consumed, a small amount of H_2O is also consumed (see reaction 2) which also indicates that an H_2O-rich fluid was present for these reactions to take place. The fluid that is in equilibrium with the minerals at the estimated temperatures and pressures for Panoche Pass rocks is an H_2O-rich fluid.

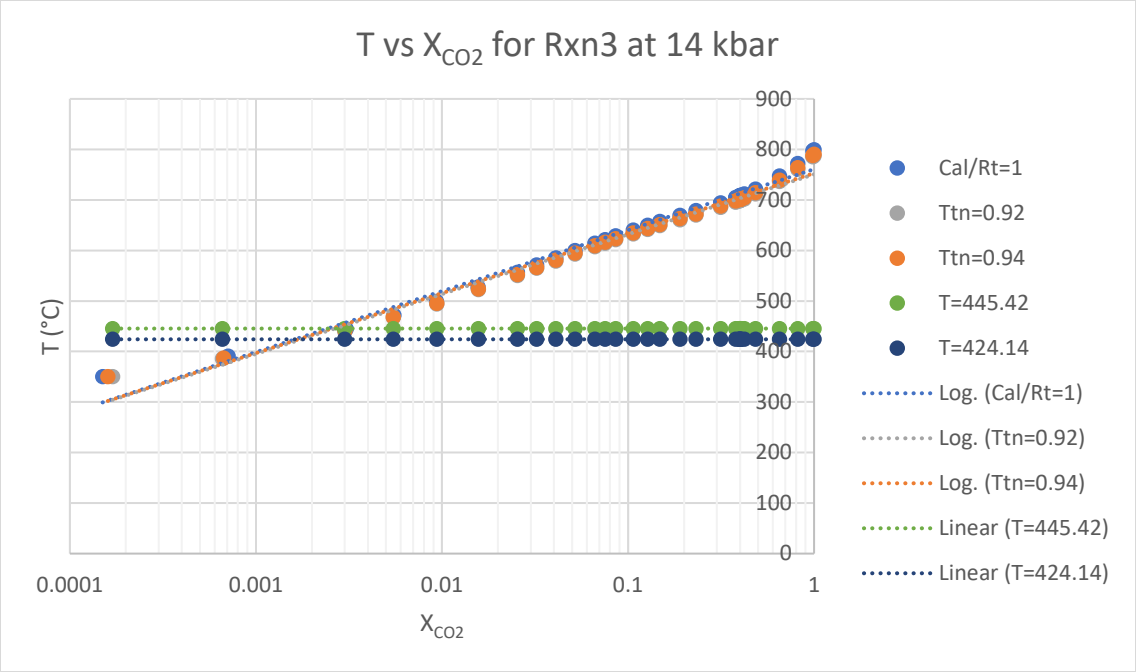

Figure 9: The horizontal lines represent the stability of reaction 1, the inclined lines represent the stability of reaction 3. The intersection of these line sets represents the required fluid composition for metamorphism. The graph is in log scale to show the intersection.

Conclusion:

The fluid composition calculated in equilibrium with the rocks during the metamorphic reactions that occurred between the jadeite-absent and jadeite-bearing rocks is $X_{CO2}<0.0025$. This means that an H_2O-rich fluid infiltrated these rocks allowing jadeite to be produced, and CO_2 to be released from the system. The calculated loss of CO_2 from the rocks is 0.07-0.09 moles/100cm^3 suggesting that CO_2 is lost during the infiltration of the rocks by an H_2O-rich fluid. These results confirm the hypothesis that the rocks were infiltrated by an H_2O-rich fluid causing decarbonation and allowing jadeite and lawsonite to grow. These results provide a quantitative estimate of the amount of CO_2 released from these metamorphic rocks that are going into subduction fluids. By quantifying the loss of CO_2 from the slab, we can estimate the CO_2 contributed to the mantle and better understand the global carbon cycle.

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Appendix

Jadeite - Bearing																
	Pnp13-6 Points Counted	Percentages	+/-		PnP13-8a Points Counted	Percent	+/-		PnP13-7 Points Counted	Percent	+/-	Mineral	Sum of Jadeite-Bearing Points	Percentages	+/-	STDEV
Quartz	328.00	27.91	0.84	Quartz	218.00	19.87	0.60	Quartz	374.00	32.75	0.98	Quartz	920.00	26.95	0.81	80.16
Epidote	0.00	0.00	0.00	Epidote	0.00	0.00	0.00	Epidote	0.00	0.00	0.00	Epidote	0.00	0.00	0.00	0.00
Chlorite	127.00	10.81	0.22	Chlorite	191.00	17.41	0.17	Chlorite	150.00	13.13	0.39	Chlorite	468.00	13.71	0.41	32.42
Lawsonite	171.00	14.55	0.44	Lawsonite	3.00	0.27	0.00	Lawsonite	62.00	5.43	0.05	Lawsonite	236.00	6.91	0.14	85.23
Albite	47.00	4.00	0.04	Albite	189.00	17.23	0.52	Albite	93.00	8.14	0.16	Albite	329.00	9.64	0.19	72.45
Rutile	1.00	0.09	0.00	Rutile	4.00	0.36	0.00	Rutile	1.00	0.09	0.00	Rutile	6.00	0.18	0.00	1.73
Calcite	0.00	0.00	0.00	Calcite	0.00	0.00	0.00	Calcite	0.00	0.00	0.00	Calcite	0.00	0.00	0.00	0.00
Phengite	268.00	22.81	0.68	Phengite	219.00	19.96	0.60	Phengite	222.00	19.44	0.58	Phengite	709.00	20.77	0.62	27.47
Apatite	4.00	0.34	0.00	Apatite	2.00	0.18	0.00	Apatite	3.00	0.26	0.00	Apatite	9.00	0.26	0.00	1.00
Jadeite	221.00	18.81	0.56	Jadeite	266.00	24.25	0.73	Jadeite	228.00	19.96	0.60	Jadeite	715.00	20.94	0.63	24.21
Titanite	2.00	0.17	0.00	Titanite	5.00	0.46	0.00	Titanite	6.00	0.53	0.01	Titanite	13.00	0.38	0.00	2.08
Chromite	0.00	0.00	0.00	Chromite	0.00	0.00	0.00	Chromite	0.00	0.00	0.00	Chromite	0.00	0.00	0.00	0.00
Iron Oxide	4.00	0.34	0.00	Iron Oxide	tr	0.00	0.00	Iron Oxide	1.00	0.09	0.00	Iron Oxide	5.00	0.15	0.00	2.12
Zircon	tr	tr	0.00	Zircon	tr	0.00	0.00	Zircon	1.00	0.09	0.00	Zircon	1.00	0.03	0.00	N/A
Pyrite	0.00	0.00	0.00	Pyrite	0.00	0.00	0.00	Pyrite	1.00	0.09	0.00	Pyrite	1.00	0.03	0.00	0.58
Muscovite	1.00	0.09	0.00	Muscovite	0.00	0.00	0.00	Muscovite	0.00	0.00	0.00	Muscovite	1.00	0.03	0.00	0.58
Barite	1.00	0.09	0.00	Barite	0.00	0.00	0.00	Barite	0.00	0.00	0.00	Barite	1.00	0.03	0.00	0.58
SUM	1175.00	100.00		SUM	1097.00	100.00		SUM	1142.00	100.00		SUM	3414.00	100.00		39.15

Table 9: This table lists the modal abundance of the jadeite-bearing samples. Their uncertainty was determined according to the Van Der Plas and Tobi 1965 paper (figure10). The total values of points, average abundance, and standard deviation between samples is also reported.

Jadeite - Absent																			
	PnP13-4a Points Counted	Percent	+/-		Pnp13-3 Points Counted	Percent	+/-		Pnp13-2 Points Counted	Percentages	+/-		Pnp13-10 Points Counted	Percentages	+/-	Mineral	Sum of Jadeite-Absent Points	Percentages	+/-	STDEV
Quartz	314.00	31.00	0.93	Quartz	319.00	26.52	0.80	Quartz	319.00	26.17	0.79	Quartz	425.00	35.90	1.08	Quartz	1377.00	29.81	0.89	53.88
Epidote	0.00	0.00	0.00	Epidote	6.00	0.50	0.00	Epidote	6.00	0.49	0.00	Epidote	0.00	0.00	0.00	Epidote	12.00	0.26	0.00	3.46
Chlorite	104.00	10.27	0.21	Chlorite	146.00	12.14	0.36	Chlorite	146.00	11.98	0.24	Chlorite	97.00	8.19	0.16	Chlorite	493.00	10.67	0.21	26.42
Lawsonite	19.00	1.88	0.94	Lawsonite	30.00	2.49	0.02	Lawsonite	30.00	2.46	0.02	Lawsonite	12.00	1.01	0.01	Lawsonite	91.00	1.97	0.02	8.85
Albite	354.00	34.95	1.05	Albite	521.00	43.31	1.30	Albite	521.00	42.74	1.28	Albite	398.00	33.61	1.01	Albite	1794.00	38.84	1.17	85.62
Rutile	0.00	0.00	0.00	Rutile	0.00	0.00	0.00	Rutile	0.00	0.00	0.00	Rutile	0.00	0.00	0.00	Rutile	0.00	0.00	0.00	0.00
Calcite	4.00	0.39	0.20	Calcite	13.00	1.08	0.01	Calcite	13.00	1.07	0.01	Calcite	63.00	5.32	0.05	Calcite	93.00	2.01	0.02	26.84
Phengite	206.00	20.34	0.61	Phengite	151.00	12.55	0.38	Phengite	151.00	12.39	0.25	Phengite	153.00	12.92	0.26	Phengite	661.00	14.31	0.43	27.18
Apatite	2.00	0.20	0.10	Apatite	1.00	0.08	0.00	Apatite	1.00	0.08	0.00	Apatite	2.00	0.17	0.00	Apatite	6.00	0.13	0.00	0.58
Jadeite	1.00	0.10	0.05	Jadeite	2.00	0.17	0.00	Jadeite	2.00	0.16	0.00	Jadeite	2.00	0.17	0.00	Jadeite	7.00	0.15	0.00	0.50
Titanite	8.00	0.79	0.39	Titanite	14.00	1.16	0.01	Titanite	14.00	1.15	0.01	Titanite	18.00	1.52	0.02	Titanite	54.00	1.17	0.01	4.12
Chromite	1.00	0.10	0.05	Chromite	0.00	0.00	0.00	Chromite	0.00	0.00	0.00	Chromite	0.00	0.00	0.00	Chromite	1.00	0.02	0.00	0.50
Iron Oxide	tr	0.00	0.00	Iron Oxide	0.00	0.00	0.00	Iron Oxide	1.00	0.08	0.00	Iron Oxide	0.00	0.00	0.00	Iron Oxide	1.00	0.02	0.00	0.58
Zircon	tr	0.00	0.00	Zircon	tr	0.00	0.00	Zircon	2.00	0.16	0.00	Zircon	1.00	0.08	0.00	Zircon	3.00	0.06	0.00	0.71
Pyrite	0.00	0.00	0.00	Pyrite	0.00	0.00	0.00	Pyrite	0.00	0.00	0.00	Pyrite	0.00	0.00	0.00	Pyrite	0.00	0.00	0.00	0.00
Muscovite	0.00	0.00	0.00	Muscovite	0.00	0.00	0.00	Muscovite	13.00	1.07	0.01	Muscovite	13.00	1.10	0.01	Muscovite	26.00	0.56	0.01	7.51
Barite	0.00	0.00	0.00	Barite	0.00	0.00	0.00	Barite	0.00	0.00	0.00	Barite	0.00	0.00	0.00	Barite	0.00	0.00	0.00	0.00
SUM	1013.00	100.00		SUM	1203.00	100.00		SUM	1219.00	100.00		SUM	1184.00	100.00		SUM	4619.00	100.00		

Table 10: This table lists the modal abundance of the jadeite-absent samples. Their uncertainty was determined according to the Van Der Plas and Tobi 1965 paper (figure10). The total values of points, average abundance, and standard deviation between samples is also reported.

PnP13-2

Albite

NO.	sample 2 alb 1-1	Formula	sample 2 alb 1-2	Formula	sample 2 alb 1-3	Formula	sample 2 alb 2-1	Formula	sample 2 alb 2-2	Formula	sample 2 alb 2-3	Formula	sample 2 alb 3-1	Formula	sample 2 alb 3-2	Formula	sample 2 alb 3-3	Formula	sample 2 alb 4-1	Formula
Na2O	11.85	1.00	11.85	0.98	11.82	1.00	11.59	0.98	11.96	1.01	11.90	1.00	10.34	0.87	11.72	0.98	11.77	1.00	11.72	0.99
FeO	0.10	0.00	0.08	0.00	0.08	0.00	0.02	0.00	0.03	0.00	bd	0.00	0.46	0.02	0.06	0.00	0.12	0.00	0.12	0.00
TiO2	bd	0.00	bd	0.00	bd	0.00	0.00	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00	0.04	0.00	bd	0.00
CaO	0.08	0.00	0.18	0.01	0.09	0.00	0.14	0.01	0.11	0.01	0.05	0.00	0.71	0.03	0.03	0.00	0.15	0.01	0.10	0.00
Al2O3	19.41	1.00	19.93	1.00	19.16	0.99	19.70	1.01	19.37	0.99	19.56	1.00	17.57	0.90	19.59	1.00	19.62	1.01	19.49	1.00
MgO	0.02	0.00	bd	0.00	bd	0.00	0.00	0.00	bd	0.00	0.02	0.00	0.03	0.00	bd	0.00	bd	0.00	0.02	0.00
MnO	bd	0.00	bd	0.00	bd	0.00	0.01	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00
K2O	0.03	0.00	0.04	0.00	0.05	0.00	0.03	0.00	0.01	0.00	bd	0.00	0.12	0.01	0.02	0.00	0.04	0.00	0.02	0.00
SiO2	68.80	3.00	70.10	3.00	68.65	3.00	68.83	2.99	69.15	3.00	69.08	3.00	70.69	3.08	69.46	3.00	68.50	2.99	68.90	3.00
Total	100.31		102.20		99.85		100.32		100.65		100.64		99.94		100.91		100.24		100.38	
Mole Fraction	0.99		0.99		0.99		0.99		0.99		1.00		0.96		1.00		0.99		0.99	
Na	1.02		1.03		1.02		1.03		1.01		1.01		1.10		1.02		1.03		1.02	
Fe	26.67		34.08		33.95		>100		98.67		>100		7.36		43.31		23.27		26.07	
Ti	100.00		100.00		100.00		100.00		100.00		>100		>100		100.00		64.84		100.00	
Ca	23.58		10.39		20.40		13.28		15.78		35.95		3.87		54.08		11.67		17.00	
Al	0.54		0.54		0.55		0.54		0.54		0.54		0.57		0.54		0.54		0.54	
Mg	71.44		100.00		100.00		100.00		100.00		70.57		50.00		>100		100.00		90.73	
Mn	>100		>100		>100		>100		>100		100.00		>100		>100		100.00		>100	
K	39.81		31.23		28.04		40.55		94.28		100.00		12.88		54.16		30.09		50.62	
Si	0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.42		0.41	

NO.	sample 2 alb 4-2	Formula	sample 2 alb 4-3	Formula	sample 2 alb 4-4	Formula	sample 2 alb 5-1	Formula	sample 2 alb 5-2	Formula	sample 2 alb 5-3	Formula	sample 2 alb 6-1	Formula	sample 2 alb 6-2	Formula	sample 2 alb 6-3	Formula
Na2O	11.75	0.99	12.05	1.02	11.80	0.99	12.03	1.00	12.01	1.00	11.83	1.00	11.70	0.99	12.03	1.02	11.81	1.01
FeO	0.17	0.01	0.06	0.00	0.07	0.00	0.13	0.00	0.09	0.00	0.07	0.00	0.19	0.01	0.13	0.00	0.09	0.00
TiO2	bd	0.00	0.04	0.00	bd	0.00	0.00	0.00	0.02	0.00	bd	0.00	0.04	0.00	bd	0.00	bd	0.00
CaO	0.06	0.00	0.06	0.00	0.03	0.00	0.04	0.00	0.06	0.00	0.03	0.00	0.10	0.00	0.04	0.00	0.08	0.00
Al2O3	19.49	1.00	19.46	1.00	19.74	1.00	19.93	1.00	19.75	1.00	19.37	1.00	19.34	0.99	19.48	1.00	19.15	0.99
MgO	bd	0.00	bd	0.00	0.02	0.00	0.00	0.00	bd	0.00	bd	0.00	bd	0.00	0.02	0.00	bd	0.00
MnO	0.03	0.00	bd	0.00	bd	0.00	0.00	0.00	bd	0.00	bd	0.00	bd	0.00	0.03	0.00	bd	0.00
K2O	0.04	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.03	0.00	bd	0.00	0.06	0.00	0.09	0.01	0.05	0.00
SiO2	68.87	3.00	68.18	2.99	69.38	3.00	70.15	3.00	69.91	3.00	68.44	3.00	68.72	3.00	68.41	2.99	68.29	3.00
Total	100.41		99.89		101.05		102.30		101.88		99.76		100.14		100.24		99.47	
Mole Fraction	1.00		1.00		1.00		1.00		1.00		1.00		0.99		0.99		0.99	
Na	1.02		1.01		1.03		1.02		1.02		1.02		1.03		1.01		1.02	
Fe	15.49		45.10		39.35		20.56		31.14		40.82		15.77		23.64		32.27	
Ti	100.00		70.61		100.00		100.00		>100		100.00		77.81		100.00		100.00	
Ca	28.78		27.95		57.01		36.50		27.70		49.39		18.44		38.46		21.76	
Al	0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.55	
Mg	100.00		>100		83.23		100.00		>100		100.00		100.00		62.81		>100	
Mn	73.55		100.00		100.00		100.00		100.00		>100		100.00		83.54		>100	
K	35.41		55.79		78.47		67.59		46.18		>100		21.01		16.28		27.15	
Si	0.41		0.42		0.42		0.41		0.41		0.42		0.41		0.42		0.42	

Table 11: WDS major oxide data reported in weight percent for albite in sample PnP13-2. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Titanite

NO.	sample 2 ttn 1-4	Formula	sample 2 ttn 2-1	Formula	sample 2 ttn 2-2	Formula	sample 2 ttn 2-3	Formula	sample 2 ttn 2-4	Formula	sample 2 ttn 2-5	Formula	sample 2 ttn 3-1	Formula	sample 2 ttn 3-2	Formula
Na2O	bd	0.00	bd	0.00	0.06	0.00	0.04	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00
FeO	1.13	0.03	1.28	0.04	1.23	0.03	1.29	0.04	1.38	0.04	1.06	0.03	0.86	0.02	0.86	0.02
TiO2	37.02	0.91	35.91	0.89	36.51	0.90	36.33	0.90	35.79	0.88	36.39	0.91	37.14	0.92	36.62	0.91
CaO	30.88	1.08	30.29	1.07	30.26	1.07	30.08	1.06	30.32	1.06	29.27	1.04	30.04	1.06	29.98	1.06
Al2O3	0.92	0.04	1.02	0.04	1.02	0.04	0.98	0.04	1.43	0.05	1.12	0.04	0.92	0.04	0.99	0.04
MgO	0.02	0.00	bd	0.00	bd	0.00	0.04	0.00	bd	0.00	bd	0.00	bd	0.00	0.03	0.00
MnO	0.15	0.00	0.23	0.01	0.19	0.01	0.23	0.01	0.25	0.01	0.17	0.00	0.15	0.00	0.29	0.01
K2O	bd	0.00	bd	0.00	bd	0.00	bd	0.00	0.03	0.00	bd	0.00	bd	0.00	bd	0.00
SiO2	30.91	1.01	31.22	1.03	30.75	1.01	30.74	1.01	31.47	1.03	30.78	1.02	30.52	1.01	30.42	1.01
Total	101.03		99.98		100.04		99.73		100.67		98.82		99.63		99.20	
Mole Fraction	0.93		0.92		0.92		0.92		0.90		0.93		0.94		0.94	
Na	100.00		>100		44.72		56.79		100.00		>100		>100		>100	
Fe	3.98		3.75		3.64		3.66		3.71		4.21		5.01		4.90	
Ti	0.59		0.60		0.59		0.60		0.61		0.59		0.59		0.59	
Ca	0.50		0.51		0.51		0.51		0.51		0.52		0.51		0.51	
Al	3.19		2.97		2.96		3.08		2.42		2.83		3.17		3.04	
Mg	75.59		>100		>100		40.33		100.00		>100		100.00		64.20	
Mn	19.29		13.53		15.78		13.46		12.09		18.91		20.96		10.87	
Ba	27.83		28.13		23.19		25.72		29.22		17.11		15.70		18.20	
K	100.00		>100		>100		100.00		42.69		>100		100.00		81.65	
Si	0.62		0.61		0.62		0.62		0.62		0.62		0.62		0.62	

NO.	sample 2 ttn 3-3	Formula	sample 2 ttn 3-4	Formula	sample 2 ttn 4-1	Formula	sample 2 ttn 4-2	Formula	sample 2 ttn 4-3	Formula	sample 2 ttn 5-1	Formula	sample 2 ttn 5-2	Formula	sample 2 ttn 5-3	Formula
Na2O	bd	0.00	0.08	0.00	0.04	0.00	bd	0.00	0.02	0.00	0.04	0.00	0.06	0.00	0.03	0.00
FeO	1.27	0.04	1.22	0.03	1.33	0.04	1.26	0.03	1.25	0.03	1.39	0.04	4.22	0.12	2.20	0.06
TiO2	36.21	0.90	35.80	0.90	36.58	0.89	36.00	0.89	35.76	0.89	29.27	0.72	37.82	0.94	39.25	0.97
CaO	29.62	1.05	29.72	1.06	30.31	1.05	30.24	1.07	30.24	1.07	31.11	1.09	26.83	0.95	28.75	1.01
Al2O3	1.12	0.04	1.15	0.05	1.21	0.05	0.98	0.04	1.05	0.04	5.87	0.23	1.95	0.08	1.37	0.05
MgO	bd	0.00	bd	0.00	bd	0.00	0.02	0.00	bd	0.00	bd	0.00	0.49	0.02	bd	0.00
MnO	0.24	0.01	0.20	0.01	0.23	0.01	0.19	0.01	0.25	0.01	bd	0.00	0.49	0.01	0.33	0.01
K2O	bd	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00	bd	0.00
SiO2	30.69	1.02	30.44	1.02	31.57	1.02	31.14	1.03	30.96	1.02	32.27	1.05	28.52	0.95	28.70	0.95
Total	99.18		98.62		101.28		99.84		99.54		99.97		100.38		100.63	
Mole Fractior	0.92		0.92		0.92		0.92		0.92		0.73		0.83		0.90	
Na	100.00		29.86		65.56		100.00		>100		57.27		45.94		88.63	
Fe	3.75		3.96		3.57		3.73		3.75		3.55		1.75		2.57	
Ti	0.60		0.60		0.60		0.60		0.60		0.67		0.58		0.57	
Ca	0.51		0.51		0.51		0.51		0.51		0.50		0.54		0.52	
Al	2.78		2.74		2.65		3.01		2.98		1.04		2.00		2.43	
Mg	100.00		>100		>100		69.05		93.96		>100		5.77		100.00	
Mn	13.64		16.03		12.99		16.54		12.24		>100		6.96		9.82	
Ba	19.75		21.82		19.91		15.11		15.70		20.41		12.29		14.73	
K	73.42		>100		>100		>100		>100		81.57		>100		100.00	
Si	0.62		0.62		0.62		0.62		0.62		0.61		0.65		0.64	

Table 12: WDS major oxide data reported in weight percent for titanite in sample PnP13-2. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Calcite

NO.	sample 2 cc 1-2	Formula	sample 2 cc 1-3	Formula	sample 2 cc 2-1	Formula	sample 2 cc 2-2	Formula	sample 2 cc 3-3	Formula	sample 2 cc 4-1	Formula	sample 2 cc 5-1	Formula	sample 2 cc 5-3	Formula
CO2	44.01	2.96	44.01	2.98	44.01	2.96	44.01	2.98	44.01	2.98	44.01	2.98	44.01	2.97	44.01	2.99
Na2O	bd	0.00	bd	0.00	0.00	0.00	0.00	0.00	bd	0.00	bd	0.00	0.05	0.00	0.00	0.00
FeO	bd	0.00	bd	0.00	0.07	0.00	0.04	0.00	0.04	0.00	0.06	0.00	0.04	0.00	0.00	0.00
TiO2	bd	0.00	bd	0.00	0.01	0.00	bd	0.00	bd	0.00	0.02	0.00	bd	0.00	0.00	0.00
CaO	57.38	1.52	56.74	1.51	57.32	1.51	56.82	1.51	bd	1.51	56.63	1.51	56.97	1.51	56.34	1.50
Al2O3	bd	0.00	bd	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00
MgO	bd	0.00	bd	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.02	0.00	bd	0.00	0.01	0.00
MnO	bd	0.00	bd	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00
K2O	0.02	0.00	bd	0.00	0.02	0.00	0.01	0.00	bd	0.00	bd	0.00	0.01	0.00	0.01	0.00
SiO2	bd	0.00	bd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	57.45	0.00	56.74	0.00	57.47	0.00	56.90	0.00	bd	0.00	56.75	0.00	57.07	0.00	56.40	0.00
Mole Fraction	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	
Na	>100		100.00		100.00		100.00		100.00		100.00		46.90		100.00	
Fe	>100		100.00		37.08		67.07		44.80		82.15		69.73		100.00	
Ti	>100		100.00		>100		100.00		>100		100.00		100.00		100.00	
Ca	0.36		0.36		0.36		0.36		0.36		0.36		0.36		0.36	
Al	100.00		>100		42.73		>100		61.14		100.00		100.00		64.85	
Mg	90.22		100.00		100.00		100.00		87.43		50.44		>100		>100	
Mn	100.00		100.00		100.00		>100		100.00		>100		>100		>100	
K	63.11		>100		47.63		>100		100.00		>100		76.00		>100	
Si	100.00		100.00		100.00		100.00		100.00		100.00		100.00		100.00	

Table 13: WDS major oxide data reported in weight percent for calcite in sample PnP13-2. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

PnP13-3

Albite

NO.	Sample 3 alb 1-1	Formula	Sample 3 alb 1-2	Formula	Sample 3 alb 1-3	Formula	Sample 3 alb 1-4	Formula	Sample 3 alb 2-1	Formula	Sample 3 alb 2-2	Formula	Sample 3 alb 2-3	Formula	Sample 3 alb 3-2	Formula	Sample 3 alb 4-1	Formula	Sample 3 alb 4-2	Formula	Sample 3 alb 4-3	Formula
Na2O	11.60	0.99	11.63	0.99	11.78	0.99	11.18	0.93	12.18	1.03	11.48	0.97	11.76	1.00	11.78	1.00	11.60	0.98	11.67	0.98	11.49	0.97
FeO	0.08	0.00	0.05	0.00	0.05	0.00	0.11	0.00	0.07	0.00	0.09	0.00	0.07	0.00	0.06	0.00	0.06	0.00	0.19	0.01	0.14	0.01
TiO2	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.06	0.00
CaO	0.06	0.00	0.03	0.00	0.11	0.01	0.17	0.01	0.10	0.00	0.06	0.00	0.00	0.00	0.11	0.01	0.04	0.00	0.08	0.00	0.11	0.01
Al2O3	19.14	0.99	19.25	0.99	19.16	0.98	19.34	0.98	19.26	0.99	19.14	0.99	19.31	1.00	19.17	0.99	19.17	0.98	19.29	0.99	19.13	0.98
MgO	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.08	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O	0.01	0.00	0.04	0.00	0.08	0.00	0.12	0.01	0.02	0.00	0.01	0.00	0.02	0.00	0.02	0.00	0.04	0.00	0.02	0.00	0.03	0.00
SiO2	68.52	3.01	68.56	3.00	69.48	3.01	70.05	3.02	68.84	3.00	68.96	3.01	68.42	3.00	68.94	3.01	69.51	3.02	69.22	3.01	69.03	3.01
Total	99.40		99.59		100.68		100.97		100.59		99.85		99.62		100.13		100.43		100.48		100.04	
Mole Fraction	1.00		1.00		0.99		0.98		0.99		1.00		1.00		0.99		1.00		1.00		0.99	
Na2O	1.04		1.04		1.03		1.06		1.02		1.04		1.03		1.03		1.04		1.04		1.04	
FeO	35.29		52.88		50.14		23.19		40.21		31.63		38.98		51.46		53.03		15.65		19.48	
TiO2	100.00		94.84		100.00		100.00		100.00		>100		>100		100.00		>100		>100		60.60	
CaO	32.32		51.37		15.36		11.02		17.18		27.61		>100		15.72		44.19		19.08		14.40	
Al2O3	0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54	
MgO	>100		100.00		>100		100.00		100.00		>100		>100		100.00		100.00		100.00		87.43	
MnO	100.00		100.00		100.00		100.00		100.00		100.00		>100		>100		100.00		>100		92.74	
BaO	100.00		100.00		100.00		100.00		81.03		>100		100.00		>100		100.00		>100		100.00	
K2O	>100		31.87		16.71		12.12		55.28		>100		58.92		58.44		31.51		80.62		39.53	
SiO2	0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41	

Table 14: WDS major oxide data reported in weight percent for albite in sample PnP13-3. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Titanite

NO.	Sample 3 ttn 1-1	Formula	Sample 3 ttn 1-2	Formula	Sample 3 ttn 2-2	Formula	Sample 3 ttn 2-2	Formula	Sample 3 ttn 3	Formula	Sample 3 ttn 4	Formula	Sample 3 ttn 5-1	Formula	Sample 3 ttn 5-2	Formula
Na2O	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.00	0.00	0.00	0.10	0.01	0.00	0.00	0.06	0.00
FeO	0.98	0.03	1.11	0.04	1.07	0.04	0.68	0.02	0.74	0.02	0.35	0.01	1.29	0.04	1.26	0.04
TiO2	36.09	1.09	35.58	1.07	34.93	1.05	35.93	1.08	35.85	1.08	38.87	1.18	35.98	1.10	35.93	1.10
CaO	28.66	1.24	28.61	1.23	28.86	1.24	29.10	1.25	28.89	1.24	28.72	1.24	28.84	1.25	28.59	1.24
Al2O3	1.58	0.07	2.12	0.10	2.30	0.11	1.65	0.08	1.74	0.08	0.42	0.02	1.30	0.06	1.41	0.07
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MnO	0.12	0.00	0.07	0.00	0.09	0.00	0.09	0.00	0.11	0.00	0.00	0.00	0.14	0.00	0.09	0.00
BaO	0.70	0.01	0.88	0.01	0.46	0.01	0.71	0.01	0.54	0.01	0.84	0.01	0.67	0.01	0.62	0.01
K2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.00	0.01	0.00	0.00	0.00
SiO2	31.11	1.25	31.18	1.25	31.33	1.25	31.33	1.26	31.36	1.26	31.27	1.26	30.81	1.25	30.79	1.25
Total	99.23		99.54		99.06		99.56		99.24		100.60		99.04		98.74	
Mole Fraction	0.91		0.89		0.88		0.92		0.91		0.97		0.91		0.91	
Na	100.00		100.00		>100		93.96		100.00		26.26		100.00		42.42	
Fe	4.58		4.19		4.35		5.87		5.52		10.09		3.66		3.76	
Ti	0.60		0.60		0.61		0.60		0.60		0.58		0.60		0.60	
Ca	0.52		0.52		0.52		0.51		0.52		0.52		0.52		0.52	
Al	2.21		1.84		1.73		2.15		2.08		5.55		2.54		2.31	
Mg	100.00		100.00		100.00		>100		100.00		100.00		100.00		100.00	
Mn	23.30		41.76		31.57		29.16		25.77		100.00		20.82		34.83	
Ba	16.95		13.23		25.19		16.39		21.98		14.00		17.70		18.60	
K	100.00		100.00		100.00		>100		68.31		45.63		>100		>100	
Si	0.61		0.61		0.61		0.61		0.61		0.61		0.62		0.62	

Table 15: WDS major oxide data reported in weight percent for titanite in PnP13-3. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Calcite

NO.	Sample 3 Cc 2	Formula	Sample 3 Cc 3	Formula	Sample 3 Cc 4	Formula	Sample 3 Cc 5-2	Formula
Na2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	0.08	0.00	0.06	0.00	0.75	0.01	0.05	0.00
TiO2	0.01	0.00	0.06	0.00	0.07	0.00	0.00	0.00
CaO	56.55	1.00	56.43	1.00	53.04	0.93	55.92	0.99
Al2O3	0.17	0.00	0.02	0.00	1.27	0.02	0.27	0.01
MgO	0.12	0.00	0.02	0.00	0.10	0.00	0.01	0.00
MnO	0.39	0.01	0.21	0.00	0.52	0.01	0.17	0.00
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O	0.08	0.00	0.04	0.00	0.20	0.00	0.02	0.00
SiO2	0.00	0.00	0.00	0.00	1.45	0.02	0.09	0.00
CO_2	44.01	0.99	44.01	1.00	44.01	0.98	44.01	1.00
Total	57.40		56.83		57.41		56.52	
Mole Fraction	0.99		1.00		0.98		1.00	
Na	100.00		>100		100.00		100.00	
Fe	34.13		53.81		5.12		65.57	
Ti	>100		58.74		52.17		100.00	
Ca	0.37		0.37		0.38		0.38	
Al	10.44		97.60		2.42		7.59	
Mg	79.70		>100		93.60		>100	
Mn	8.51		13.75		6.27		17.32	
Ba	100.00		100.00		100.00		>100	
K	14.66		27.98		8.14		71.44	
Si	100.00		100.00		3.77		47.36	

Table 16: WDS major oxide data reported in weight percent for calcite in PnP13-3. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

PnP13-4a

Albite

No.	Grid 1-9 PnP-4a	Formula	Grid 3-16 PnP-4a	Formula	Grid 4-21 PnP-4a	Formula	Grid 10-24 PnP-4a	Formula	Grid 1-9 PnP-4a 9B	Formula	Grid 2-8 PnP-4a 33B	Formula	Grid 3-16 PnP-4a 66B	Formula
Na2O	11.44	0.97	10.05	0.86	11.27	0.96	11.41	0.97	11.30	0.95	11.48	0.97	10.07	0.86
FeO	0.17	0.01	0.23	0.01	0.00	0.00	0.06	0.00	0.39	0.01	0.41	0.01	0.20	0.01
TiO2	0.04	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
K2O	0.03	0.00	0.22	0.01	0.04	0.00	0.01	0.00	0.03	0.00	0.02	0.00	0.22	0.01
Al2O3	19.87	1.02	21.98	1.14	19.78	1.02	19.60	1.01	20.12	1.03	20.00	1.03	22.20	1.15
MgO	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.07	0.00	0.00	0.00	0.00	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BaO	0.15	0.00	0.06	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.03	0.00	2.21	0.10	0.14	0.01	0.21	0.01	0.05	0.00	0.05	0.00	2.19	0.10
SiO2	68.60	2.99	65.38	2.87	67.98	2.99	68.26	2.99	68.67	2.98	67.98	2.97	65.07	2.86
Total	100.33		100.15		99.31		99.57		100.62		99.94		99.99	
Mole Fraction	1.00		0.88		0.99		0.99		1.00		1.00		0.88	
Na	0.92		0.99		0.93		0.93		0.93		0.92		0.99	
Fe	16.72		11.92		100.00		42.07		7.68		6.74		14.04	
Ti	74.04		>100		100.00		>100		100.00		100.00		93.18	
K	44.24		7.55		37.88		>100		52.78		59.22		7.89	
Al	0.54		0.51		0.54		0.54		0.54		0.54		0.51	
Mg	>100		>100		100.00		80.36		23.16		>100		100.00	
Mn	100.00		100.00		100.00		100.00		>100		100.00		100.00	
Ba	55.34		>100		90.49		100.00		100.00		100.00		100.00	
Ca	58.84		2.01		13.68		10.25		35.82		35.43		2.01	
Si	0.29		0.30		0.29		0.29		0.29		0.29		0.30	

Table 17: WDS major oxide data reported in weight percent for albite in PnP13-4a. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Titanite

No.	Grid 3-7 PnP-4a Ttn #3 A	Formula	Grid 3-7 PnP-4a Ttn #6 A	Formula	Grid 3-7 PnP-4a Ttn #6 B	Formula
Na2O	0.00	0.00	0.01	0.00	0.03	0.00
FeO	0.63	0.02	0.47	0.01	0.46	0.01
TiO2	36.34	0.91	35.97	0.90	35.86	0.90
K2O	0.01	0.00	0.00	0.00	0.00	0.00
Al2O3	0.89	0.03	1.44	0.06	1.53	0.06
MgO	0.00	0.00	0.04	0.00	0.00	0.00
MnO	0.01	0.00	0.06	0.00	0.10	0.00
BaO	0.46	0.01	0.52	0.01	0.53	0.01
CaO	29.48	1.05	29.20	1.04	29.10	1.04
SiO2	31.01	1.03	30.89	1.03	30.95	1.03
Total	98.83		98.60		98.55	
Mole Fraction	0.95		0.93		0.93	
Na	100.00		>100		75.14	
Fe	5.34		7.07		7.52	
Ti	0.59		0.59		0.60	
K	>100		100.00		100.00	
Al	3.27		2.40		2.29	
Mg	>100		40.61		100.00	
Mn	>100		39.99		27.36	
Ba	25.20		21.52		21.51	
Ca	0.50		0.50		0.50	
Si	0.44		0.44		0.44	

Table 18: WDS major oxide data reported in weight percent for titanite in PnP13-4a. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Calcite

No.	Grid 4-18 PnP-4a	Formula Unit	Grid 5-20 PnP-4a	Formula Unit	Grid 12-15 PnP-4a	Formula Unit	Grid 4-18 PnP-4a 93B	Formula Unit	Grid 5-20 PnP-4a 120B	Formula Unit	Grid 3-2 PnP-4a Calcite	Formula Unit	Grid 3-2 PnP-4a Calcite B	Formula Unit	Grid 3-7 PnP-4a Calcite Near 57 A	Formula Unit	Grid 3-7 PnP-4a Calcite Near 57 B	Formula Unit
Na2O	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.04	0.00	0.03	0.00	0.00	0.00	0.00	0.00
FeO	0.02	0.00	0.21	0.00	0.00	0.00	0.10	0.00	0.05	0.00	0.02	0.00	0.02	0.00	0.05	0.00	0.04	0.00
TiO2	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00
K2O	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.01	0.00	0.00	0.00
MgO	0.07	0.00	0.06	0.00	0.01	0.00	0.02	0.00	0.05	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00
MnO	0.10	0.00	0.12	0.00	0.06	0.00	0.08	0.00	0.19	0.00	0.09	0.00	0.18	0.00	0.09	0.00	0.15	0.00
BaO	0.10	0.00	0.18	0.00	0.21	0.00	0.13	0.00	0.00	0.00	0.15	0.00	0.35	0.00	0.00	0.00	0.00	0.00
CaO	54.40	0.98	53.69	0.97	60.56	1.05	55.74	0.99	55.06	0.99	55.32	0.99	54.51	0.98	55.84	1.00	56.02	1.00
SiO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	44.01	1.01	44.01	1.01	44.01	0.97	44.01	1.00	44.01	1.00	44.01	1.00	44.01	1.01	44.01	1.00	44.01	1.00
Total	54.69		54.27		60.85		56.12		55.44		59.29		58.65		59.65		59.82	
Mole Fraction	1.00		0.99		1.00		1.00		1.00		1.00		0.99		1.00		1.00	
Na	100		>100		100		100		44.72		70.71		>100		100		100	
Fe	>100		19.29		100		33.08		80.46		>100		>100		77.67		95.12	
Ti	100		100		100		>100		100		100		100		>100		100	
K	>100		>100		>100		49.21		36.64		>100		100		100		100	
Al	100		100		100		100		100		37.83		100		>100		100	
Mg	32.43		32.31		>100		>100		41.8		>100		>100		>100		100	
Mn	42.06		33.53		59.09		47.89		17.84		45.07		20.16		43.16		26.42	
Ba	>100		73.66		68.19		>100		100		93.11		38.68		100		100	
Ca	0.52		0.52		0.49		0.51		0.51		0.51		0.51		0.51		0.51	
Si	100		100		100		100		100		100		100		100		100	

Table 19: WDS major oxide data reported in weight percent for calcite in PnP13-4a. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

PnP13-10

Albite

Comment	Sample 10 alb 1-1	Formula	Sample 10 alb 1-2	Formula	Sample 10 alb 2-1	Formula	Sample 10 alb 2-2	Formula	Sample 10 alb 3-1	Formula	Sample 10 alb 3-2	Formula	Sample 10 alb 3-3	Formula	Sample 10 alb 3-4	Formula	Sample 10 alb 4-1	Formula	Sample 10 alb 4-2	Formula	Sample 10 alb 4-3	Formula	Sample 10 alb 5-1	Formula	Sample 10 alb 5-2	Formula	Sample 10 alb 5-3	Formula
Na2O	11.97	1.01	11.69	1.00	11.73	1.00	11.84	1.01	11.70	0.99	11.96	1.02	11.89	1.00	11.36	0.96	11.94	1.01	11.57	0.99	11.19	0.95	12.05	1.02	11.85	0.99	12.02	1.02
FeO	0.11	0.00	0.10	0.00	0.02	0.00	0.09	0.00	0.06	0.00	0.03	0.00	0.09	0.00	0.09	0.00	0.00	0.00	0.04	0.00	0.09	0.00	0.12	0.00	0.10	0.00	0.06	0.00
TiO2	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.08	0.00	0.21	0.01	0.10	0.00	0.11	0.00	0.06	0.00	0.03	0.00	0.04	0.00	0.04	0.00	0.04	0.00	0.09	0.00	0.09	0.00	0.02	0.00	0.11	0.00	0.08	0.00
Al2O3	19.46	1.00	19.31	1.01	19.14	0.99	19.25	1.00	19.08	0.99	19.40	1.00	19.40	0.99	18.86	0.96	19.23	0.99	19.24	1.00	19.17	0.99	19.22	0.99	19.43	0.99	19.48	1.00
MgO	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.03	0.00	0.02	0.00	0.00	0.00
MnO	0.00	0.00	0.01	0.00	0.05	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BaO	0.06	0.00	0.00	0.00	0.07	0.00	0.13	0.00	0.08	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.14	0.00	0.00	0.00
K2O	0.02	0.00	0.06	0.00	0.01	0.00	0.05	0.00	0.03	0.00	0.04	0.00	0.04	0.00	0.05	0.00	0.02	0.00	0.05	0.00	0.05	0.00	0.03	0.00	0.03	0.00	0.02	0.00
SiO2	68.56	2.99	67.63	2.99	68.57	3.01	68.30	3.00	68.65	3.01	68.08	2.99	69.47	3.00	69.95	3.03	68.84	3.00	68.01	3.00	68.55	3.01	68.91	3.00	69.55	3.00	68.68	2.99
Total	100.30		99.00		99.68		99.79		99.70		99.55		101.07		100.39		100.18		99.02		99.21		100.43		101.22		100.33	
Mole Fraction	0.99		0.99		0.99		0.99		1.00		1.00		1.00		0.99		1.00		0.99		0.99		1.00		0.99		1.00	
Na2O	1.02		1.04		1.04		1.03		1.04		1.02		1.03		1.05		1.02		1.04		1.06		1.02		1.03		1.02	
FeO	25.15		30.02		>100		28.13		45.32		>100		31.52		28.78		100.00		60.24		31.03		24.96		28.50		48.58	
TiO2	>100		100.00		100.00		>100		100.00		>100		100.00		>100		100.00		>100		>100		100.00		>100		>100	
CaO	20.27		9.42		18.95		15.67		29.83		52.89		39.29		36.63		48.45		18.29		21.44		60.81		17.16		22.80	
Al2O3	0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54		0.54	
MgO	64.29		100.00		100.00		>100		>100		100.00		100.00		100.00		>100		100.00		49.62		48.81		79.58		100.00	
MnO	>100		>100		45.00		100.00		89.00		100.00		>100		>100		100.00		>100		>100		100.00		>100		100.00	
BaO	>100		100.00		>100		71.92		>100		100.00		76.29		100.00		80.26		100.00		100.00		>100		66.32		100.00	
K2O	61.39		24.77		>100		23.18		44.86		32.75		34.61		27.13		50.70		26.38		28.58		46.18		43.57		75.18	
SiO2	0.41		0.42		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41		0.41	

Table 20: WDS major oxide data reported in weight percent for albite in PnP13-10. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Titanite

NO.	Sample 10 ttn 1-1	Formula	Sample 10 ttn 1-2	Formula	Sample 10 ttn 2	Formula	Sample 10 ttn 3-1	Formula	Sample 10 ttn 3-2	Formula	Sample 10 ttn 4-1	Formula	Sample 10 ttn 4-2	Formula	Sample 10 ttn 4-3	Formula	Sample 10 ttn 5-1	Formula	Sample 10 ttn 5-2	Formula	Sample 10 ttn 6-1	Formula	Sample 10 ttn 6-2	Formula	Sample 10 ttn 7-1	Formula	Sample 10 ttn 7-2	Formula
Na2O	0.07	0.01	0.01	0.00	0.04	0.00	0.10	0.01	0.05	0.00	0.08	0.01	0.00	0.00	0.11	0.01	0.04	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.00
FeO	0.74	0.03	0.66	0.02	0.18	0.01	0.37	0.01	0.62	0.02	1.38	0.05	3.40	0.12	0.61	0.02	1.04	0.03	2.85	0.10	1.17	0.04	1.24	0.04	0.18	0.01	1.45	0.05
TiO2	42.59	1.34	31.55	0.93	37.01	1.12	41.04	1.27	42.01	1.28	40.52	1.24	37.35	1.16	43.94	1.38	29.10	0.84	36.10	1.08	37.39	1.13	29.50	0.86	38.79	1.17	31.91	0.93
CaO	25.06	1.12	29.15	1.22	28.56	1.23	26.75	1.18	27.15	1.18	26.11	1.14	26.64	1.18	25.13	1.13	29.35	1.20	27.34	1.17	29.27	1.26	28.67	1.20	29.20	1.25	28.21	1.17
Al2O3	2.71	0.13	5.19	0.24	1.94	0.09	2.13	0.10	1.91	0.09	2.11	0.10	2.47	0.12	2.12	0.10	6.50	0.29	3.00	0.14	0.75	0.04	6.12	0.28	0.82	0.04	6.21	0.28
MgO	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.01	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00
MnO	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.01	0.03	0.00	0.00	0.00	0.03	0.00	0.32	0.01	0.00	0.00	0.02	0.00	0.01	0.00	0.03	0.00
BaO	0.66	0.01	0.64	0.01	0.42	0.01	0.85	0.01	0.63	0.01	0.88	0.01	0.67	0.01	0.88	0.01	0.61	0.01	0.64	0.01	0.74	0.01	0.62	0.01	0.61	0.01	0.56	0.01
K2O	0.01	0.00	0.03	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00
SiO2	27.62	1.15	31.56	1.23	31.14	1.25	28.75	1.18	29.24	1.18	29.34	1.19	28.45	1.18	27.41	1.15	32.39	1.24	30.20	1.20	31.17	1.25	31.70	1.23	31.23	1.25	31.11	1.21
Total	99.51		98.81		99.28		100.00		101.64		100.85		99.01		100.21		99.08		100.64		100.51		97.89		100.90		99.49	
Mole Fraction	0.89		0.78		0.92		0.92		0.92		0.89		0.83		0.92		0.72		0.82		0.94		0.73		0.96		0.74	
Na	37.48		>100		66.50		28.54		50.70		32.89		100.00		25.40		57.56		>100		100.00		>100		100.00		>100	
Fe	5.52		5.83		19.76		9.85		6.45		3.47		2.01		6.50		4.49		2.20		3.88		3.79		18.66		3.46	
Ti	0.55		0.65		0.59		0.56		0.56		0.56		0.59		0.54		0.67		0.60		0.59		0.67		0.58		0.64	
Ca	0.55		0.52		0.52		0.54		0.54		0.54		0.54		0.55		0.52		0.53		0.51		0.52		0.51		0.53	
Al	1.61		1.11		1.94		1.83		2.00		1.84		1.68		1.86		0.97		1.51		3.57		1.01		3.40		1.00	
Mg	100.00		>100		100.00		100.00		>100		100.00		100.00		100.00		100.00		57.93		100.00		100.00		>100		100.00	
Mn	62.61		>100		>100		100.00		100.00		8.09		>100		100.00		72.06		9.91		100.00		>100		>100		83.97	
Ba	18.81		17.89		29.06		13.70		20.08		13.29		17.75		14.22		17.86		18.39		15.68		19.08		19.99		19.84	
K	88.60		48.38		>100		>100		100.00		>100		>100		61.39		>100		>100		66.36		100.00		>100		100.00	
Si	0.65		0.61		0.61		0.64		0.64		0.63		0.65		0.66		0.61		0.63		0.61		0.61		0.61		0.62	

Table 21: WDS major oxide data reported in weight percent for titanite in PnP13-10. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Calcite

NO.	Sample 10 Cc 2-1	Formula	Sample 10 Cc 2-2	Formula	Sample 10 Cc 4-1	Formula	Sample 10 Cc 5-1	Formula	Sample 10 Cc 5-2	Formula
Na2O	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
FeO	0.03	0.00	0.06	0.00	0.00	0.00	0.02	0.00	0.00	0.00
TiO2	0.04	0.00	0.00	0.00	0.04	0.00	0.02	0.00	0.00	0.00
CaO	57.12	1.01	56.57	1.01	56.20	1.00	56.55	1.00	57.07	1.01
Al2O3	0.01	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.04	0.00
MnO	0.07	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00
BaO	0.01	0.00	0.09	0.00	0.23	0.00	0.04	0.00	0.20	0.00
K2O	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.02	0.00
SiO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	44.01	0.99	44.01	1.00	44.01	1.00	44.01	1.00	44.01	0.99
Total	57.28		56.75		56.54		56.76		57.34	
Mole Fraction	1.00		1.00		1.00		1.00		1.00	
Na	100.00		100.00		>100		>100		100.00	
Fe	>100		47.78		100.00		>100		100.00	
Ti	81.49		100.00		94.49		>100		>100	
Ca	0.37		0.37		0.37		0.37		0.37	
Al	>100		100.00		38.18		100.00		100.00	
Mg	100.00		100.00		100.00		87.68		>100	
Mn	36.71		>100		>100		100.00		100.00	
Ba	>100		>100		47.31		>100		50.44	
K	100.00		81.01		82.38		48.15		44.42	
Si	100.00		100.00		100.00		100.00		100.00	

Table 22: WDS major oxide data reported in weight percent for calcite in PnP13-10. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

PnP13-6

Jadeite

NO.	Sample 6 jad 1-1	Formula	Sample 6 jad 1-2	Formula	Sample 6 jad 1-3	Formula	Sample 6 jad 2-1	Formula	Sample 6 jad 2-2	Formula	Sample 6 jad 2-3	Formula	Sample 6 jad 3-2	Formula	Sample 6 jad 3-3	Formula	Sample 6 jad 3-4	Formula
Na2O	13.40	0.90	13.70	0.92	13.00	0.88	13.90	0.95	13.63	0.91	13.21	0.90	13.61	0.91	13.21	0.88	13.00	0.87
FeO	6.52	0.19	5.46	0.16	5.76	0.17	8.57	0.25	5.95	0.17	5.28	0.15	3.10	0.09	4.15	0.12	4.51	0.13
TiO2	0.00	0.00	0.04	0.00	0.04	0.00	0.02	0.00	0.56	0.01	0.38	0.01	0.26	0.01	0.08	0.00	0.59	0.02
CaO	2.22	0.08	1.42	0.05	2.50	0.09	1.37	0.05	2.05	0.08	2.34	0.09	1.62	0.06	1.48	0.05	1.68	0.06
Al2O3	19.20	0.78	20.31	0.83	19.48	0.80	18.28	0.76	19.36	0.79	19.67	0.81	21.77	0.88	21.29	0.87	20.46	0.84
MgO	1.23	0.06	0.71	0.04	1.43	0.07	0.68	0.04	1.07	0.05	1.41	0.07	1.06	0.05	1.03	0.05	1.35	0.07
MnO	0.11	0.00	0.12	0.00	0.09	0.00	0.08	0.00	0.08	0.00	0.10	0.00	0.11	0.00	0.06	0.00	0.13	0.00
BaO	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00
K2O	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
SiO2	58.38	2.02	57.98	2.02	57.67	2.01	57.05	2.02	58.39	2.02	57.30	2.00	58.41	2.01	58.43	2.01	57.97	2.01
Total	101.06		99.76		100.01		99.94		101.09		99.69		100.07		99.73		99.69	
Mole Fraction	0.81		0.84		0.83		0.75		0.82		0.84		0.91		0.88		0.86	
Na	0.99		0.97		1.00		0.98		0.98		0.99		0.96		0.98		0.99	
Fe	1.44		1.56		1.51		1.22		1.52		1.62		2.16		1.84		1.73	
Ti	100.00		83.62		72.67		>100		7.74		10.43		14.66		47.85		7.38	
Ca	2.04		2.64		1.92		2.66		2.12		1.97		2.42		2.59		2.37	
Al	0.57		0.55		0.56		0.58		0.57		0.56		0.53		0.53		0.55	
Mg	8.51		12.49		7.52		13.24		9.92		7.33		9.12		9.53		7.18	
Mn	24.02		20.63		27.97		33.28		30.20		22.73		21.92		44.14		19.81	
Ba	100.00		100.00		>100		100.00		100.00		100.00		74.41		100.00		100.00	
K	100.00		56.79		>100		100.00		100.00		100.00		>100		100.00		100.00	
Si	0.46		0.46		0.46		0.46		0.46		0.46		0.45		0.45		0.46	

Table 23: WDS major oxide data reported in weight percent for jadeite in PnP13-6. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Rutile

NO.	Sample 6 rt 1	Formula	Sample 6 rt 2-2	Formula	Sample 6 rt 3	Formula	Sample 6 rt 5-1	Formula	Sample 6 rt 5-2	Formula	Sample 6 rt 6-1	Formula	Sample 6 rt 6-2	Formula
Na2O	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00
FeO	0.40	0.01	0.31	0.01	0.29	0.01	0.22	0.00	0.32	0.01	0.33	0.01	0.31	0.01
TiO2	99.38	1.97	97.18	1.97	97.30	1.96	96.97	1.97	97.52	1.97	96.34	1.96	98.29	1.97
CaO	0.02	0.00	0.01	0.00	0.05	0.00	0.00	0.00	0.04	0.00	0.01	0.00	0.01	0.00
Al2O3	0.07	0.00	0.09	0.00	0.06	0.00	0.03	0.00	0.03	0.00	0.06	0.00	0.09	0.00
MgO	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.06	0.00	0.27	0.01	0.00	0.00
MnO	0.01	0.00	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BaO	1.59	0.02	1.47	0.02	1.74	0.02	1.44	0.02	1.55	0.02	1.73	0.02	1.58	0.02
K2O	0.04	0.00	0.05	0.00	0.09	0.00	0.06	0.00	0.05	0.00	0.07	0.00	0.02	0.00
SiO2	0.06	0.00	0.00	0.00	0.09	0.00	0.05	0.00	0.07	0.00	0.02	0.00	0.05	0.00
Total	101.59		99.15		99.68		98.81		99.65		98.85		100.35	
Mole Fraction	0.99		1.00		1.00		1.00		1.00		1.00		0.99	
Na	>100		>100		100.00		100.00		100.00		>100		100.00	
Fe	9.06		11.41		12.03		16.82		10.67		10.47		11.12	
Ti	0.35		0.35		0.35		0.35		0.35		0.35		0.35	
Ca	68.98		>100		32.83		>100		39.99		>100		>100	
Al	28.85		20.31		33.99		61.18		75.14		31.24		21.18	
Mg	100.00		100.00		>100		100.00		>100		39.46		100.00	
Mn	>100		>100		>100		58.49		100.00		100.00		>100	
Ba	8.18		8.91		7.46		8.91		8.50		7.82		8.49	
K	32.94		26.83		17.57		25.24		25.70		17.99		68.70	
Si	47.96		100.00		30.09		52.12		38.69		>100		52.02	

Table 24: WDS major oxide data reported in weight percent for rutile in PnP13-6. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

PnP13-7

Jadeite

Comment	Sample 7 jad 1-1	Formula	Sample 7 jad 1-2	Formula	Sample 7 jad 1-3	Formula	Sample 7 jad 2-1	Formula	Sample 7 jad 2-2	Formula	Sample 7 jad 2-4	Formula	Sample 7 jad 3-1	Formula	Sample 7 jad 3-2	Formula
Na2O	13.28	0.89	12.77	0.86	12.84	0.86	13.50	0.92	13.46	0.90	13.28	0.89	13.07	0.89	13.16	0.89
FeO	5.47	0.16	5.00	0.15	6.06	0.18	6.05	0.18	4.78	0.14	5.04	0.15	7.07	0.21	5.94	0.17
TiO2	0.18	0.00	0.03	0.00	0.00	0.00	0.36	0.01	0.08	0.00	0.00	0.00	0.03	0.00	0.13	0.00
CaO	2.12	0.08	2.58	0.10	3.05	0.11	2.22	0.08	1.80	0.07	2.89	0.11	3.48	0.13	2.73	0.10
Al2O3	19.67	0.81	20.03	0.82	18.88	0.77	19.37	0.80	20.53	0.84	19.91	0.81	17.81	0.73	18.95	0.78
MgO	1.56	0.08	1.58	0.08	1.87	0.10	1.46	0.08	0.95	0.05	1.73	0.09	1.82	0.09	1.59	0.08
MnO	0.09	0.00	0.04	0.00	0.10	0.00	0.03	0.00	0.01	0.00	0.02	0.00	0.04	0.00	0.01	0.00
BaO	0.10	0.00	0.01	0.00	0.00	0.00	0.06	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.12	0.00
K2O	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00
SiO2	57.84	2.01	57.51	2.00	57.98	2.01	56.80	1.99	58.26	2.02	57.75	2.00	57.46	2.01	57.63	2.01
Total	100.31		99.55		100.78		99.86		99.92		100.63		100.79		100.28	
Mole Fraction	0.84		0.85		0.81		0.82		0.86		0.85		0.78		0.82	
Na	0.98		1.00		1.01		0.98		0.97		0.98		1.01		1.00	
Fe	1.56		1.65		1.48		1.48		1.71		1.64		1.36		1.50	
Ti	21.59		>100		100.00		11.48		43.90		100.00		>100		29.91	
Ca	2.09		1.88		1.71		2.01		2.31		1.75		1.58		1.82	
Al	0.56		0.55		0.57		0.56		0.55		0.56		0.59		0.57	
Mg	6.58		6.94		5.70		7.01		10.02		6.25		6.18		6.79	
Mn	26.08		75.91		24.74		80.38		>100		>100		55.58		>100	
Ba	90.77		>100		100.00		>100		>100		100.00		>100		81.14	
K	100.00		>100		100.00		>100		>100		>100		>100		>100	
Si	0.46		0.46		0.46		0.46		0.46		0.46		0.46		0.46	

Table 25: WDS major oxide data reported in weight percent for jadeite in PnP13-7. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Albite

Comment	Sample 7 alb 2-2	Formula	Sample 7 alb 5-1	Formula	Sample 7 alb 6-2	Formula
Na2O	10.79	0.92	14.57	1.31	13.14	1.17
FeO	2.87	0.11	3.37	0.13	2.81	0.11
TiO2	0.01	0.00	1.84	0.06	0.23	0.01
CaO	0.90	0.04	0.62	0.03	1.35	0.07
Al2O3	15.47	0.80	19.32	1.06	20.64	1.11
MgO	0.10	0.01	0.21	0.01	0.30	0.02
MnO	0.09	0.00	0.04	0.00	0.08	0.00
BaO	0.09	0.00	0.00	0.00	0.07	0.00
K2O	0.02	0.00	0.00	0.00	0.00	0.00
SiO2	70.15	3.09	58.76	2.73	60.34	2.76
Total	100.50		98.72		98.96	
Mole Fraction	0.95		0.98		0.95	
Na2O	1.10		0.95		1.00	
FeO	2.20		2.01		2.19	
TiO2	>100		3.22		17.60	
CaO	3.45		4.38		2.76	
Al2O3	0.61		0.55		0.53	
MgO	16.50		9.00		7.03	
MnO	23.21		66.00		29.86	
BaO	>100		100.00		>100	
K2O	63.62		>100		>100	
SiO2	0.40		0.45		0.45	

Table 26: WDS major oxide data reported in weight percent for albite in PnP13-7. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Rutile

NO.	Sample 7 rt 1-2	Formula	Sample 7 rt 1-3	Formula
Na2O	0.00	0.00	0.00	0.00
FeO	1.29	0.02	0.62	0.01
TiO2	81.00	1.31	95.38	1.89
CaO	0.26	0.01	0.08	0.00
Al2O3	0.90	0.02	0.31	0.01
MgO	0.65	0.02	0.29	0.01
MnO	0.04	0.00	0.03	0.00
BaO	1.82	0.02	2.05	0.02
K2O	0.01	0.00	0.02	0.00
SiO2	13.77	0.30	0.85	0.02
Total	99.73		99.63	
Mole Fraction	0.97		0.99	
Na	100.00		100.00	
Fe	3.68		6.48	
Ti	0.38		0.35	
Ca	7.93		21.08	
Al	3.23		7.55	
Mg	18.94		35.62	
Mn	76.29		84.39	
Ba	7.20		6.47	
K	>100		69.80	
Si	0.94		4.98	

Table 27: WDS major oxide data reported in weight percent for rutile in PnP13-7. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

PnP13-8a

Jadeite

No.	PnP-8a Alb 4.2	Formula	PnP-8a Alb 4.1	Formula	PnP-8a Alb 4.2	Formula	PnP-8a Jd 1.1	Formula	PnP-8a Jd 1.2	Formula	PnP-8a Jd 2.1	Formula	PnP-8a Jd 2.2	Formula	PnP-8a Jd 3.1	Formula	PnP-8a Jd 3.2	Formula	PnP-8a Jd 4.1	Formula	PnP-8a Jd 4.2	Formula	PnP-8a Jd 6.1	Formula	PnP-8a Jd 6.2	Formula
Na2O	12.87	0.87	14.08	0.94	13.25	0.89	12.90	0.87	13.21	0.89	13.45	0.90	13.26	0.89	12.86	0.88	13.05	0.89	12.57	0.86	13.10	0.88	13.05	0.88	11.56	0.76
FeO	5.84	0.17	3.17	0.09	4.60	0.13	5.01	0.15	4.64	0.14	3.82	0.11	4.24	0.12	7.64	0.23	6.91	0.20	6.04	0.18	5.41	0.16	5.29	0.15	3.82	0.11
TiO2	0.08	0.00	1.57	0.04	0.54	0.01	0.18	0.00	0.48	0.01	0.34	0.01	0.04	0.00	0.00	0.00	0.05	0.00	0.06	0.00	0.31	0.01	0.01	0.00	0.06	0.00
K2O	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.01	0.00
Al2O3	19.77	0.81	21.77	0.88	20.66	0.84	20.38	0.84	20.66	0.85	21.80	0.88	21.32	0.87	18.29	0.76	18.67	0.77	19.02	0.79	20.44	0.83	20.38	0.84	18.33	0.73
MgO	1.04	0.05	0.64	0.03	1.13	0.06	1.21	0.06	1.07	0.06	0.89	0.05	1.16	0.06	1.29	0.07	1.05	0.05	1.48	0.08	1.11	0.06	1.34	0.07	0.91	0.05
MnO	0.06	0.00	0.08	0.00	0.12	0.00	0.09	0.00	0.01	0.00	0.02	0.00	0.10	0.00	0.05	0.00	0.00	0.00	0.03	0.00	0.05	0.00	0.08	0.00	0.06	0.00
BaO	0.00	0.00	0.02	0.00	0.00	0.00	0.04	0.00	0.14	0.00	0.12	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
CaO	1.74	0.07	0.44	0.02	1.61	0.06	1.92	0.07	1.46	0.05	1.08	0.04	1.70	0.06	2.05	0.08	1.91	0.07	2.19	0.08	1.75	0.06	1.98	0.07	1.31	0.05
SiO2	58.04	2.02	58.23	2.00	57.78	2.00	57.45	2.01	57.60	2.01	58.48	2.01	58.08	2.00	57.45	2.02	58.04	2.03	57.50	2.02	58.32	2.01	57.52	2.00	64.13	2.16
Total	99.43		99.99		99.69		99.20		99.27		100.01		99.91		99.65		99.68		98.91		100.51		99.66		100.26	
Mole Fraction	0.83		0.91		0.86		0.85		0.86		0.89		0.88		0.77		0.79		0.82		0.84		0.84		0.87	
Na2O	0.90		0.85		0.88		0.90		0.88		0.87		0.88		0.91		0.90		0.92		0.90		0.89		0.94	
FeO	1.21		1.75		1.38		1.31		1.37		1.53		1.45		1.04		1.10		1.19		1.27		1.29		1.52	
TiO2	41.57		3.49		7.54		20.26		8.30		11.06		92.86		100.00		67.21		57.68		11.74		>100		51.99	
K2O	100.00		100.00		100.00		60.40		>100		>100		61.03		100.00		100.00		94.88		76.87		89.47		89.47	
Al2O3	0.56		0.53		0.54		0.55		0.54		0.53		0.53		0.58		0.57		0.57		0.55		0.55		0.57	
MgO	2.90		3.79		2.78		2.69		2.84		3.19		2.67		2.55		2.94		2.34		2.83		2.48		3.07	
MnO	46.82		30.18		19.55		27.80		>100		>100		24.88		52.16		100.00		79.16		47.03		31.06		38.56	
BaO	100.00		>100		100.00		>100		65.93		68.60		100.00		>100		100.00		100.00		100.00		100.00		>100	
CaO	2.33		5.62		2.44		2.15		2.60		3.19		2.36		2.12		2.21		2.05		2.38		2.17		2.75	
SiO2	0.32		0.32		0.32		0.32		0.32		0.32		0.32		0.32		0.32		0.32		0.32		0.32		0.30	

Table 28: WDS major oxide data reported in weight percent for jadeite in PnP13-8a. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Albite

No.	PnP-8a Alb 6.1	Formula Unit	PnP-8a Alb 6.2	Formula Unit
Na2O	11.71	0.98	11.29	0.96
FeO	0.16	0.01	0.08	0.00
TiO2	0.04	0.00	0.00	0.00
K2O	0.01	0.00	0.03	0.00
Al2O3	20.22	1.03	19.97	1.03
MgO	0.00	0.00	0.00	0.00
MnO	0.00	0.00	0.00	0.00
BaO	0.00	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00
SiO2	68.65	2.97	68.26	2.99
Total	100.79		99.63	
Mole Fraction	1.00		1.00	
Na2O	0.92		0.93	
FeO	15.11		33.13	
TiO2	78.93		100.00	
K2O	>100		44.98	
Al2O3	0.54		0.54	
MgO	100.00		100.00	
MnO	100.00		>100	
BaO	100.00		100.00	
CaO	100.00		100.00	
SiO2	0.29		0.29	

Table 29: WDS major oxide data reported in weight percent for albite in PnP13-8a. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Titanite

No.	PnP-8a ttn 1.1	Formula	PnP-8a ttn 1.2	Formula	PnP-8a ttn 2	Formula	PnP-8a ttn 3.1	Formula	PnP-8a ttn 3.2	Formula	PnP-8a ttn 4.1	Formula	PnP-8a ttn 4.2	Formula	PnP-8a ttn 5.1	Formula	PnP-8a ttn 5.2	Formula
Na2O	0.12	0.01	0.06	0.00	0.15	0.01	0.27	0.02	0.13	0.01	0.06	0.00	0.47	0.03	0.09	0.01	0.14	0.01
FeO	0.52	0.01	0.33	0.01	0.56	0.02	0.57	0.02	0.58	0.02	0.23	0.01	0.18	0.00	0.21	0.01	0.59	0.02
TiO2	36.37	0.90	37.17	0.92	34.59	0.86	34.15	0.84	35.01	0.87	36.12	0.89	36.98	0.90	37.30	0.91	36.07	0.90
K2O	0.10	0.00	0.12	0.00	0.05	0.00	0.01	0.00	0.01	0.00	0.16	0.01	0.06	0.00	0.19	0.01	0.02	0.00
Al2O3	1.31	0.05	0.88	0.03	2.29	0.09	3.03	0.12	2.58	0.10	1.84	0.07	1.24	0.05	1.08	0.04	1.51	0.06
MgO	0.09	0.00	0.02	0.00	0.09	0.00	0.00	0.00	0.04	0.00	0.06	0.00	0.01	0.00	0.08	0.00	0.04	0.00
MnO	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00
BaO	0.49	0.01	0.57	0.01	0.46	0.01	0.58	0.01	0.65	0.01	0.71	0.01	0.52	0.01	0.58	0.01	0.58	0.01
CaO	28.25	1.00	28.88	1.02	28.74	1.01	28.96	1.02	28.13	1.00	28.41	1.00	28.33	0.99	28.98	1.01	28.64	1.02
SiO2	31.52	1.04	31.06	1.03	32.03	1.05	31.94	1.05	31.45	1.04	31.64	1.04	32.46	1.05	31.98	1.04	30.94	1.03
Total	98.78		99.11		98.97		99.52		98.60		99.23		100.25		100.53		98.53	
Mole Fraction	0.93		0.96		0.89		0.86		0.88		0.92		0.95		0.95		0.92	
Na	16.70		35.44		17.19		9.99		17.96		41.46		6.67		25.23		16.41	
Fe	6.39		9.71		6.13		6.10		6.02		13.95		17.41		14.92		5.75	
Ti	0.59		0.59		0.61		0.61		0.61		0.59		0.59		0.59		0.60	
K	15.65		12.69		25.11		>100		92.95		10.12		24.64		8.38		81.40	
Al	2.59		3.34		1.84		1.53		1.68		2.07		2.59		2.90		2.30	
Mg	20.21		69.73		19.73		100.00		39.38		27.37		>100		21.84		37.34	
Mn	>100		>100		>100		>100		>100		>100		>100		84.67		100.00	
Ba	22.97		19.61		25.12		18.88		17.19		15.89		21.66		19.20		19.16	
Ca	0.51		0.50		0.51		0.50		0.51		0.51		0.51		0.51		0.51	
Si	0.43		0.44		0.43		0.43		0.43		0.43		0.43		0.43		0.44	

Table 30: WDS major oxide data reported in weight percent for titanite in PnP13-8a. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

Rutile

NO.	PnP-8a Rut 1.1	Formula	PnP-8a Rut 1.2	Formula	PnP-8a Rut 2.1	Formula	PnP-8a Rut 2.2	Formula	PnP-8a Rut 3.1	Formula	PnP-8a Rut 3.2	Formula	PnP-8a Rut 4.1	Formula	PnP-8a Rut 4.2	Formula	PnP-8a Rut 6.1	Formula	PnP-8a Rut 6.2	Formula
Na2O	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00
FeO	0.30	0.00	0.13	0.00	0.08	0.00	0.16	0.00	0.08	0.00	0.09	0.00	0.31	0.00	0.14	0.00	0.23	0.00	0.18	0.00
TiO2	97.31	0.99	97.85	0.99	98.24	0.99	97.81	0.99	97.99	0.99	97.84	0.99	98.31	0.99	97.65	0.99	97.23	0.99	97.14	0.99
K2O	0.12	0.00	0.08	0.00	0.04	0.00	0.05	0.00	0.02	0.00	0.03	0.00	0.03	0.00	0.07	0.00	0.03	0.00	0.03	0.00
Al2O3	0.16	0.00	0.11	0.00	0.14	0.00	0.10	0.00	0.14	0.00	0.23	0.00	0.15	0.00	0.18	0.00	0.10	0.00	0.09	0.00
MgO	0.03	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.05	0.00	0.04	0.00	0.00	0.00
MnO	0.03	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.01	0.00
BaO	1.55	0.01	1.32	0.01	1.32	0.01	1.24	0.01	1.35	0.01	1.42	0.01	1.21	0.01	1.09	0.01	1.33	0.01	1.30	0.01
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.00	0.01	0.00	0.03	0.00	0.03	0.00	0.00	0.00	0.03	0.00
SiO2	0.17	0.00	0.03	0.00	0.14	0.00	0.05	0.00	0.13	0.00	0.13	0.00	0.07	0.00	0.28	0.00	0.06	0.00	0.03	0.00
Total	99.67		99.58		100.00		99.41		99.76		99.81		100.18		99.49		99.02		98.80	
Mole Fraction	0.99		1.00		1.00		1.00		1.00		1.00		0.99		1.00		1.00		1.00	
Na2O	>100		100.00		55.20		100.00		100.00		>100		>100		>100		100.00		100.00	
FeO	10.39		23.00		39.93		18.29		38.01		35.93		10.51		22.47		13.09		16.80	
TiO2	0.35		0.35		0.35		0.35		0.35		0.35		0.35		0.35		0.35		0.35	
K2O	12.92		16.86		36.39		30.23		55.65		48.28		47.92		21.63		37.04		41.09	
Al2O3	13.82		19.18		16.21		21.64		15.42		9.32		14.50		12.97		21.88		23.40	
MgO	62.33		100.00		>100		100.00		>100		68.05		100.00		35.12		48.96		100.00	
MnO	85.65		43.07		100.00		100.00		>100		89.12		42.31		100.00		100.00		>100	
BaO	7.99		9.64		9.56		9.86		9.42		8.66		10.31		11.43		9.16		9.75	
CaO	100.00		>100		100.00		95.08		44.61		>100		48.66		55.20		100.00		55.38	
SiO2	14.72		79.87		16.79		47.64		19.11		18.35		32.89		9.60		38.34		79.49	

Table 31: WDS major oxide data reported in weight percent for rutile in PnP13-8a. The bottom row is relative standard error of these analyses. The mole fraction for each sample is calculated under the totals.

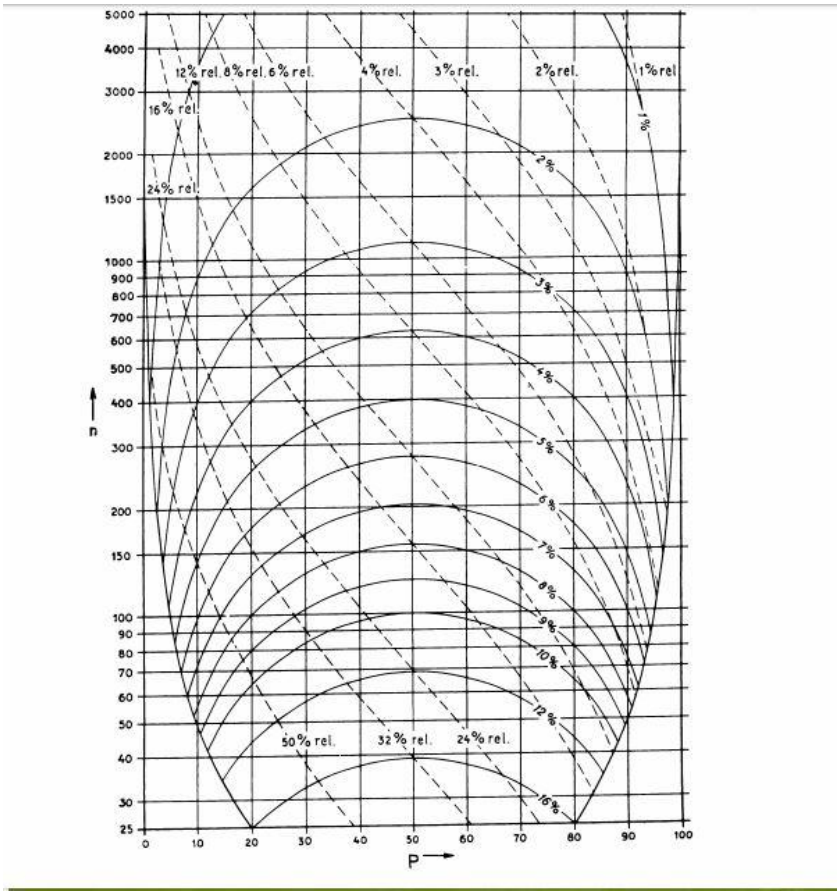

Figure 10: This figure was used to determine the error due to counting statistics of the point counting results (Van Der Plas and Tobi, 1965).

Sample	Distance Between Points (μm)
PnP13-2	550-1006
PnP13-3	620-825
PnP13-4a	820
Pnp13-6	1006
PnP13-7	808
PnP13-8a	819
PnP13-10	550-1006

Table 32: These are the spacings used on the EMPA to create point counting grids. Error for this point counting method was calculated according to the Van Der Plas and Tobi (1965) and are represented along with the modal abundances in tables 6 and 8.

Specimen	PnP13-2	PnP13-3	PnP13-4a	PnP-13-6	PnP-13-7	PnP13-8a	PnP13-10	Jadeite-bearing Samples	STDEV	Jadeite-absent Samples	STDEV	Difference
SiO2	65.95	69.20	69.67	66.20	70.31	61.39	70.70	65.97	4.46	68.88	2.05	-2.91
TiO2	0.70	0.58	0.55	0.77	0.65	0.78	0.51	0.73	0.07	0.59	0.08	0.15
Al2O3	15.84	14.23	14.79	15.49	12.95	16.77	12.93	15.07	1.94	14.45	1.21	0.62
Fe2O3T	5.77	5.29	5.13	6.16	5.51	7.39	3.90	6.35	0.95	5.02	0.80	1.33
MnO	0.08	0.06	0.08	0.09	0.07	0.08	0.06	0.08	0.01	0.07	0.01	0.01
MgO	2.49	2.43	2.25	3.36	3.54	4.30	2.11	3.73	0.50	2.32	0.17	1.41
CaO	2.42	2.69	1.05	2.98	2.28	0.87	4.23	2.04	1.07	2.60	1.30	-0.55
Na2O	4.53	3.77	4.15	2.78	2.84	6.18	3.89	3.93	1.95	4.09	0.34	-0.15
K2O	1.99	1.50	1.80	2.23	1.86	1.95	1.54	2.01	0.19	1.71	0.23	0.31
P2O5	0.17	0.50	0.14	0.17	0.15	0.16	0.14	0.16	0.01	0.24	0.18	-0.08
Total	**99.94**	**100.25**	**99.61**	**100.23**	**100.16**	**99.87**	**100.01**	100.09	0.19	99.95	0.26	0.13
LOI	3.95	3.31	3.08	3.60	4.51	3.24	3.83	3.78	0.65	3.54	0.42	0.24

Table 33: This is the Bulk analysis data from Franklin and Marshall College. Each sample is listed along with the averages of the two types of metagraywacke and the standard deviation for each type.

	BHVO-2									
Chemical	SiO2	TiO2	Al2O3	Fe2O3T	MnO	MgO	CaO	Na2O	K2O	P2O5
USGS accepted concentration	49.9	2.73	13.5	12.3	0.17	7.23	11.4	2.22	0.52	0.27
Units	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%	Wt%
Replicate 1	49.94	2.72	13.63	12.43	0.165	7.299	11.473	2.196	0.505	0.265
Replicate 2	50.02	2.73	13.66	12.45	0.165	7.292	11.482	2.19	0.507	0.267
Replicate 3	49.97	2.73	13.66	12.41	0.165	7.285	11.485	2.197	0.507	0.267
Replicate 4	49.94	2.72	13.65	12.42	0.165	7.294	11.49	2.2	0.505	0.266
Replicate 5	49.83	2.72	13.61	12.4	0.165	7.291	11.473	2.202	0.504	0.267
Replicate 6	49.95	2.73	13.62	12.43	0.165	7.309	11.505	2.191	0.504	0.266
Replicate 7	50	2.73	13.65	12.42	0.164	7.304	11.491	2.19	0.505	0.266
Replicate 8	49.92	2.73	13.62	12.42	0.166	7.29	11.486	2.199	0.507	0.268
Replicate 9	49.97	2.73	13.64	12.43	0.165	7.289	11.488	2.192	0.508	0.268
Replicate 10	49.95	2.72	13.66	12.43	0.165	7.29	11.479	2.197	0.507	0.266
Mean	49.9490	2.7260	13.6400	12.4240	0.1650	7.2943	11.4852	2.1954	0.5059	0.2666
Standard Deviation	0.0513	0.0052	0.0189	0.0135	0.0005	0.0075	0.0094	0.0044	0.0014	0.0010
LOD - t value 2.764	0.1418	0.0143	0.0521	0.0373	0.0013	0.0206	0.0261	0.0121	0.0040	0.0027
LOQ	0.5131	0.0516	0.1886	0.1350	0.0047	0.0745	0.0945	0.0438	0.0145	0.0097
mean % recovery	100.1%	99.9%	101.0%	101.0%	97.1%	100.9%	100.7%	98.9%	97.3%	98.7%
(+/-)	0.142	0.014	0.052	0.037	0.001	0.021	0.026	0.012	0.004	0.003

Table 34: These are the uncertainties associated with XRF analysis as provided by Stan Mertzman from Franklin and Marshall College. t=0.764 and limit of quantitation