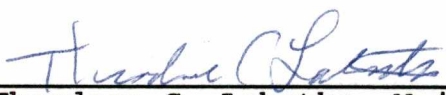
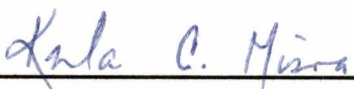


To the Graduate Council:

I am submitting herewith a thesis written by Jonathan S. Novick entitled "Metamorphism of the Weeks Limestone: the Low Grade Reactions and Fluid Inclusions." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.


Theodore C. Labotka, Major Professor

We have read this thesis
and recommend its acceptance





Accepted for the Council:



Vice Provost
and Dean of the Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at The University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of the source is made.

Permission for extensive quotation from, or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature

Date

James A. Smith
12/9/87

METAMORPHISM OF THE WEEKS LIMESTONE,
NOTCH PEAK, UTAH: THE LOW GRADE REACTIONS
AND FLUID INCLUSIONS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jonathan S. Novick

March 1988

DEDICATION

This thesis is dedicated to the memory of my grandfather, Herman Novick, who passed away in Tucson, Arizona on November 22, 1987.

ACKNOWLEDGEMENTS

I would like to acknowledge Professor Kula C. Misra and Professor Larry A. Taylor for reviewing my thesis and providing many excellent comments and suggestions. I would also like to thank my major advisor, Professor Theodore C. Labotka for suggesting this project, providing me with lots of guidance along the way and for also funding my field work. Additional funding for fieldwork was obtained through the discretionary fund of the Department of Geological Sciences.

In addition I feel that it is also necessary for me to recognize Professor Peter I. Nabelek of the University of Missouri for providing me with insight into the effects of metamorphism at Notch Peak. James Thornburg should be thanked for his help with fieldwork, as should Dennise Stansbury who helped retype this thesis after it was recently lost due to a mishap on the computer.

Finally a special thanks goes to my parents who provided funding towards the completion of this project.

.

ABSTRACT

Upper Cambrian argillaceous limestones of the Weeks Limestone were intruded and contact metamorphosed by the Notch Peak quartz monzonite stock during Jurassic times. The unmetamorphosed rocks contain the assemblage calcite + quartz + dolomite + muscovite + chlorite + plagioclase. The first signs of metamorphism occur at the phlogopite isograd where dolomite and muscovite react to form phlogopite and chlorite. At the muscovite-out isograd, muscovite and chlorite react to form phlogopite and calcic plagioclase. The diopside zone is entered when phlogopite breaks down to form diopside and K-feldspar. In areas where X_{CO_2} was higher, tremolite and feldspar formed before diopside by the breakdown of chlorite and phlogopite. Diopside then formed when tremolite broke down.

In the higher-grade rocks, the assemblage wollastonite + vesuvianite + diopside + K-feldspar indicates extremely low values of X_{CO_2} , despite the loss of 23% CO_2 by decarbonation reactions as determined by mass balance. Fluid inclusions were examined to determine whether fluid compositions were consistent with mineral equilibria. Three rock types were examined: 1) the North Peak granite, 2) skarns adjacent to the granite, and 3) high grade rocks from the Weeks Limestone. Inclusions are secondary and consist of an

H₂O-rich liquid and a vapor phase at room temperature. Fluid inclusion melting temperatures of $-120^{\circ}\pm 120^{\circ}\text{C}$ give salinity values ranging from 0 to 28 equivalent weight percent NaCl. Homogenization temperatures ranging from 110° to 210°C gives filling temperatures of $325^{\circ}\pm 125^{\circ}\text{C}$ at 2 Kb. These filling temperatures indicate that fluid inclusions do not contain fluids from the presumed peak of metamorphism (400° to 500°C). Moderate salinities are consistent with the widespread occurrence of scapolite. The presence of salinity greater than that of the H₂O-NaCl eutectic and the absence of daughter crystals in inclusions imply that the fluids that passed through these rocks must have contained salts other than NaCl. Even though fluid inclusions contain late metamorphic fluids, their composition is consistent with fluid compositions indicated by mineral assemblages. The presence of H₂O-rich fluids does not appear to be a result of fluid-phase separation of a low density CO₂ phase, because evidence for "boiling" was not observed. Unless the CO₂-rich phase failed to be trapped, the H₂O-rich fluid composition only could have been attained by massive infiltration of a water rich-brine.

TABLE OF CONTENTS

CHAPTER		PAGE
1.	INTRODUCTION	1
	A. Geologic Setting	1
	B. Metamorphism at Notch Peak	6
	C. Purpose of this Study	10
2.	PETROLOGY OF THE LOW GRADE ROCKS	12
	A. Introduction	12
	B. Petrography of the Low Grade Rocks	13
	C. Mineral Assemblages and Reaction Relations	21
	D. T-X _{CO2} Conditions	29
	E. Summary	36
3.	FLUID INCLUSIONS	38
	A. Introduction	38
	B. Results	45
	Data from Granite Samples	48
	Data from Skarn Samples	51
	Data from Wollastonite Zone Samples	59
	C. Discussion and Summary of Data	62
4.	CONCLUSIONS	80
	LIST OF REFERENCES	84
	APPENDICES	91
	Appendix 1. Mineral Assemblages	92
	Appendix 2. Fluid Inclusion Data	93
	VITA	102

LIST OF FIGURES

FIGURE		PAGE
1.	Geologic Map of the Notch Peak Area	2
2.	Generalized Stratigraphic Column of the Notch Peak Area	4
3.	Representative X-ray Diffractograms from Low Grade Rocks	14
4.	Photomicrograph of an Unmetamorphosed Sample	16
5.	Photomicrographs of Phlogopite Zone Samples	18
6.	Photomicrograph of a Tremolite Zone Sample .	22
7.	Photomicrograph of a Diopside Zone Sample .	24
8.	AKM Diagram Showing Progressive Metamorphism of the Low Grade Rocks at Notch Peak . . .	30
9.	μ - μ Grid for the $\text{CaO-K}_2\text{O-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-}$ $\text{NaCl-H}_2\text{O-CO}_2$ System	32
10.	Schematic T- X_{CO_2} Grid for the $\text{CaO-K}_2\text{O-MgO-}$ $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-NaCl-H}_2\text{O-CO}_2$ System	35
11.	Photomicrograph of Fluid Inclusions	41
12.	Phase Diagram of the $\text{H}_2\text{O-NaCl}$ System	46
13.	Photomicrograph of a Granite Sample	49
14.	Histogram Showing the Melting Temperatures of Fluid Inclusions in the Granite Samples	52
15.	Histogram Showing the Homogenization Temperatures of Fluid Inclusions in the Granite Samples	52

16. Examples of Isochores Determined from Fluid	
Inclusion Data from the Granite Samples .	53
17. Photomicrograph of a Skarn Sample	55
18. Histogram Showing the Melting Temperatures	
of Fluid Inclusions in the Skarn Samples .	57
19. Histogram Showing the Homogenization	
Temperatures of Fluid Inclusions in the	
Skarn Samples	57
20. Examples of Isochores Determined from Fluid	
Inclusion Data from the Skarn Samples . .	58
21. Photomicrograph of a Wollastonite Zone	
Sample	60
22. Histogram Showing the Melting Temperatures	
of Fluid Inclusions in the Wollastonite	
Zone Samples	63
23. Histogram Showing the Homogenization	
Temperatures of Fluid Inclusions in the	
Wollastonite Zone Samples	64
24. Examples of Isochores Determined from Fluid	
Inclusion Data from the Wollastonite Zone	
Samples	65
25. T_h Versus T_m Diagram for the Granite Samples	68
26. T_h Versus T_m Diagram for the Skarn Samples .	69
27. T_h Versus T_m Diagram for the Wollastonite	
Zone Samples	70
28. Top Half of the NaCl-CaCl ₂ -H ₂ O Ternary . . .	72

CHAPTER 1

INTRODUCTION

A. GEOLOGIC SETTING

Notch Peak is located approximately fifty miles west of Delta, Utah, and about 70 miles east of Ely, Nevada, in west central Utah (see Figure 1). It is situated in the middle of the House Range, a north-south trending, fault-block mountain range that is typical of the Basin and Range province. Bedding in unmetamorphosed units dips shallowly (about 10°) to the east. A geologic map of the Notch Peak area is shown in Figure 1; a stratigraphic column is shown in Figure 2.

Metamorphism at Notch Peak occurred during Jurassic time when the Notch Peak stock intruded limestones and calcareous argillites of Cambrian age. According to Nabelek et al. (1981, 1986a), the Notch Peak Stock is a composite of three smaller stocks, one of granitic composition and the other two of quartz monzonitic composition. The exposed portion of the stock is relatively small in area (≈ 30 square kilometers).

The metamorphosed units include (from youngest to oldest) the Orr Formation, the Weeks Limestone and the Marjum Formation. The Notch Peak Formation and the

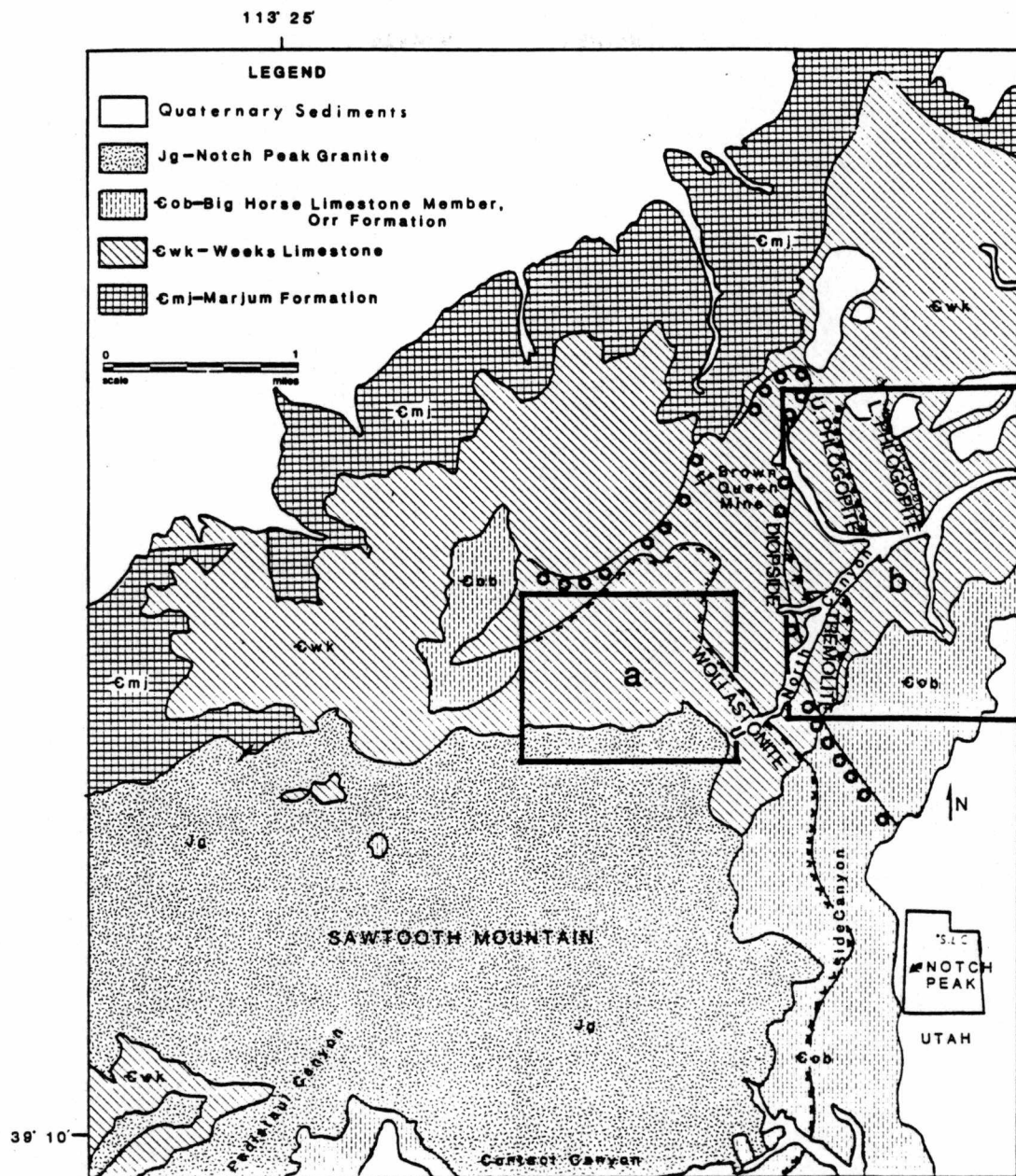


Fig. 1. Geologic map of the Notch Peak area. a) shows the location of the isograds. The diopside and wollastonite isograds, mapped in the Weeks Limestone by Labotka and Nabelek (1986) have been extended into the Big Horse Limestone (mapped by Hover, 1981). The Upper and Lower Phlogopite and the Tremolite isograds have been mapped in this study. The two boxed in areas are shown in close-up in b). Modified after Hintze (1974) and Hover-Granath et al. (1983).

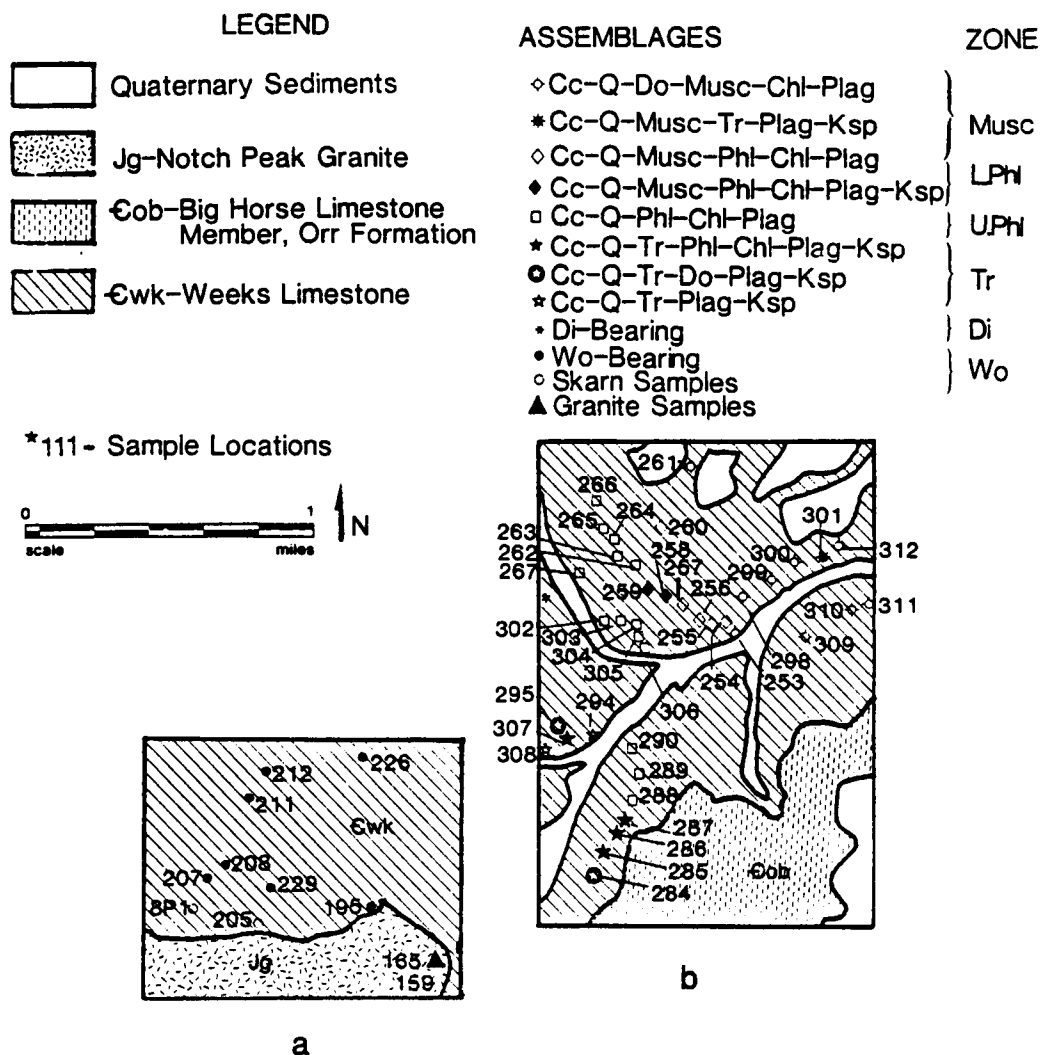


Fig. 1 (cont.). Geologic Map of the Notch Peak area. b) Shows the sample locations. The assemblages are indicated at the top of the diagram. The numbered locations correspond to those discussed in the text. Each inset corresponds to the boxed in areas in a). Modified after Hintze (1974) and Hover-Granath et al. (1983).

System	Group Formation and Member	Map Symbol	Thickness (m)
Jurassic	Granite stock and associated dikes and sills.		----

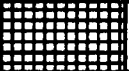
Cambrian	Orr Formation	Sneakover Pass Member		34-47
		Corset Spring Member		31-34
		Johns Wash Member		43-71
		Candland Canyon Member		64-82
		Big Horse Limestone Member		220
	Weeks Limestone			366
	Marjum Formation			415-430

Fig. 2. Generalized stratigraphic column of the Notch Peak area. Lithologic descriptions of the units are given in the text. Stratigraphic thicknesses are taken from Hover-Granath et al. (1983). Modified after Hintze (1974) and Hover-Granath et al. (1983).

House Limestone (not shown in Figure 1) also were metamorphosed, but to a lesser degree. Metamorphism of these units occurred at pressures up to 2kbars and temperatures of 600°C (Hover-Granath et al., 1983).

The Orr Formation contains several interbedded silty limestone and thinly bedded shale members. The limestone members are gray, thinly bedded, and finely crystalline. Oolitic, stromatolitic, and bioclastic beds are common in some units. Shale units are thinly bedded and are locally rippled. These units generally contain thin beds of nodular limestone. Fossil assemblages date this unit to Late Cambrian. Extensive work, done on the Big Horse Limestone member of the Orr Formation by Hover (1981), Hover et al. (1981) and Hover-Granath et al. (1983) will be reviewed in the following section.

The Weeks Limestone underlies the Orr Formation. It is a dark gray, fine grained, thin to medium bedded, shaly limestone. Upper units become progressively more argillaceous (Hanks, 1962). Hintze (1974) reports interbedded fine grained, gray laminated limestone beds. Occurrences of *Cedaria*, *Tricrepicephalus* and *Lejopyge* trilobites indicate that this unit is Middle to Late Cambrian in age (Hanks, 1962; Hintze, 1974).

The Marjum Formation lies below the Weeks. It consists of interbedded silty limestone, black shales

and mudstones. The limestone is fine grained and thinly bedded. Thin algal biostromes and intraformational flat pebble conglomerate are rare in occurrence. The presence of *Asaphicus* and *Elrathia* trilobites indicates that this unit is Middle Cambrian in age (Hanks, 1962).

Studies on the geology of the House range have been preformed by Hanks (1962), Hintze and Palmer (1976), Hintze and Robison (1975), Powell (1959) and Wheeler and Steels (1951). A geologic map of the Notch Peak area has been produced by Hintze (1974). Early studies of the Notch Peak Stock concentrated on the petrogenesis and economic deposits (Gehman, 1958). More recent studies by Nabelek et al. (1981, 1983, 1984, 1986a, 1986b) have concentrated on the geochemical evolution of the stock. Studies of metamorphism at Notch Peak by Feldman and Papike (1981), Hover et al. (1981), Hover (1981), Hover-Granath et al. (1983), Nabelek et al. (1984), Labotka and Nabelek (1986, 1987) and Nabelek and Labotka (1986) will be discussed in the following section.

B. METAMORPHISM AT NOTCH PEAK

Recent studies of the Big Horse Limestone Member of the Orr Formation by Hover et al. (1981a) Hover, (1981b) and Hover-Granath et al. (1983) have shown that the

limestones and the argillites of the Big Horse behaved in different manners during metamorphism.

In the relatively pure limestones of this unit, the development of the talc, tremolite, diopside and forsterite isograds implies that X_{CO_2} changed from 0.50 in the low grade rocks to 0.80 in the high grade rocks. This change in X_{CO_2} has lead to the conclusion that because the limestones of the Big Horse were relatively impermeable to fluid flow, they behaved as a system that was closed to externally derived fluids. This effectively prevented vertical fluid flow and convective cooling of the Notch Peak Stock. Therefore, changes in the fluid compositions within these units probably are a result of fluid buffering by metamorphic reactions. The presence in the limestones of talc plus quartz retrograde from tremolite near the contact with the intrusion has been taken to suggest an influx of H_2O rich fluids after the peak of metamorphism; however, a source for the fluids has not been suggested.

In the argillaceous units, the development of the phlogopite, tremolite, diopside, plagioclase, scapolite, vesuvianite, grossular, and wollastonite isograds implies that X_{CO_2} was much lower (0.2 in the highest grade rocks) than in the limestones. This has lead to the conclusion that relative to the limestones of the Big Horse, the argillites were open to fluid flow. The

extensive migration of fluids through the Big Horse therefore is believed to have been largely channeled through the argillaceous units.

Another study, by Feldman and Papike (1981), tried to determine fluid compositions in the Big Horse Limestone. They examined fluid inclusions from garnets in high-grade, non-graphitic, argillaceous rocks. These inclusions were found to contain fluids that had H_2O/CO_2 ratios as high as 40. Fluid salinities were highly variable, but were found to be 20 to 40 equivalent weight percent NaCl. Na, K, and Cl were the most important constituents in these fluids; however, Ca was also present in lesser amounts.

Nabelek (1984) did a stable-isotope study of the Big Horse Limestone in which he confirmed the work by Hover-Granath, et al. (1983). He found that in the limestones of the Big Horse, $\delta^{13}C$ and $\delta^{18}O$ remained constant with changing grade, suggesting that fluid infiltration had not occurred. In the argillaceous layers, he found that $\delta^{13}C$ and $\delta^{18}O$ decreased considerably with increasing grade. Since the amount of CO_2 released by devolatilization reactions during metamorphism was not enough to explain the change in $\delta^{18}O$, he suggested, on the basis of isotope data from the Notch Peak Stock, that the decrease in $\delta^{18}O$ in the metamorphosed argillites was due to interaction with

magmatic waters. From these isotopic data, Nabelek calculated an oxygen equivalent fluid/rock ratio of greater than one and an X_{CO_2} of less than 0.2 in the shaley units. Viewing these data in light of the mineral assemblages described by Hover-Granath et al. (1983), he concluded that water infiltration had a strong influence on the reaction relations in the argillaceous units, as well as the separate fluid and thermal fronts moving through them.

Preliminary studies of the Weeks Limestone by Labotka and Nabelek (1986, 1987) have revealed the locations of the wollastonite and diopside isograds (see Figure 1, page 2). Preliminary isotope data suggest that the wollastonite isograd is an infiltration front. This implies that the large salient that is present in the isograds in the Weeks (see Figure 1, page 2) reflects a channel through which the convecting fluids escaped. They also have shown by mass balance that $X_{CO_2} = 0.0025$ and that the highest-grade rocks may have lost as much as 9 to 22 weight percent CO_2 . Weight losses of this magnitude requires that at least 22.5±9 rock volumes of H_2O have flooded the Weeks during metamorphism. Labotka and Nabelek (1987) claim that these low X_{CO_2} values are not due to separation and escape of a low-density, CO_2 -rich phase from a saline fluid. This statement is supported by the fact when

that the wollastonite-forming reaction is plotted in T- X_{CO_2} space, it does not intersect the fluid-phase (i.e. $\text{H}_2\text{O}-\text{CO}_2$) solvus at salinities less than halite saturation under the conditions present at Notch Peak. They concluded that some other mechanism is necessary to explain fluid/rock ratios this high.

C. PURPOSE OF THIS STUDY

In the highest grade rocks of the Big Horse Limestone Member of the Orr Formation, a vesuvianite + grossular isograd has been mapped (Hover-Granath et al., 1983). Preliminary studies in the highest grade rocks of the Weeks Limestone have shown that grossular is absent, except in skarn deposits (Labotka et al., 1986). There are three possible explanations for this: 1) the composition of the metamorphic fluids permeating the two units was markedly different (specifically with respect to X_{CO_2}), 2) the temperature and pressure of metamorphism varied slightly along the margins of the intrusion, or 3) the bulk composition of the two rock units was different. It is apparent from the previous discussion that the fluid compositions in the Weeks and the argillites of the Big Horse are somewhat similar with respect to X_{CO_2} . It is also likely that the bulk rock compositions are different. So far, however, the conditions of metamorphism have not been determined

directly. In this study, fluid inclusions have been analyzed in order to constrain the conditions of metamorphism and to determine directly the fluid compositions. Fluid-phase equilibria and its relation to fluid migration and composition also will be discussed. Since these are already known for the Big Horse Limestone, direct comparison between the two units should be possible. In addition, x-ray diffraction analyses have been performed in order to determine the mineral assemblages (detailed mineral chemistries were not done due to the small size of the grains in the low grade rocks) and reactions leading up to the higher grade rocks. This information has also provided further constraints on the conditions of metamorphism; specifically, a $T-X_{CO_2}$ path has been determined from the sequence of reactions that occur in the Weeks Limestone.

CHAPTER 2

PETROLOGY OF THE LOW GRADE ROCKS

A. INTRODUCTION

The wollastonite and diopside isograds have been determined from thin section studies by Labotka and Nabelek (1986). They are shown in Figure 1 (page 2). The reactions forming these higher grade assemblages will be discussed in context with fluid inclusion data in Chapter 3.

The rocks outside the wollastonite and diopside zones are much finer-grained (less than 0.1 mm in size) than those inside it, but still show the effects of metamorphism. In order to determine the assemblages and reactions that occurred in these rocks, it has been necessary to use x-ray diffraction techniques. X-ray diffraction studies were done on a Phillips x-ray diffraction unit. Samples were prepared using a shatterbox in order to assure homogeneous particle size. Samples were then mounted in pack mounts and subjected to x-ray analysis. Each of the samples was then dissolved in acetic acid to remove calcite and dolomite. The purpose of this step was to remove the calcite and dolomite from the samples so that the weaker silicate peaks would stand out more. Sedimented slides were then prepared so that an x-ray analysis could be performed.

Identification of phases was done using the JCPDS powder diffraction cards (1974) for minerals whose presence in the rocks was suspected. A complete list of mineral assemblages determined from x-ray diffraction is given in Appendix 1. Typical x-ray diffractograms from each zone are shown in Figure 3. Sample localities are shown in Figure 1 (page 3) along with the geology and the location of the isograds at Notch Peak.

B. PETROGRAPHY OF THE LOW GRADE ROCKS

The unmetamorphosed samples from the Weeks Formation are intercalated pelsparites and biomicrites. Rip-up clasts, less than 1mm in size were also noted in some of the more micritic layers. Bioclasts generally consist of echinoderms, brachiopods, bivalves and occasional trilobites. Several partially silicified fossil fragments were also noted. Detrital quartz and K-feldspar grains are present as fine, subangular grains. Some of these grains were noted to have overgrowths on them. Occasionally detrital muscovite grains are present, but they are generally much less than 0.1mm in size. Late fractures are present cutting across the bedding. Generally these are filled with calcite, and rarely exceed 0.1mm in width. Stylolites are present; however they are rare in occurrence and

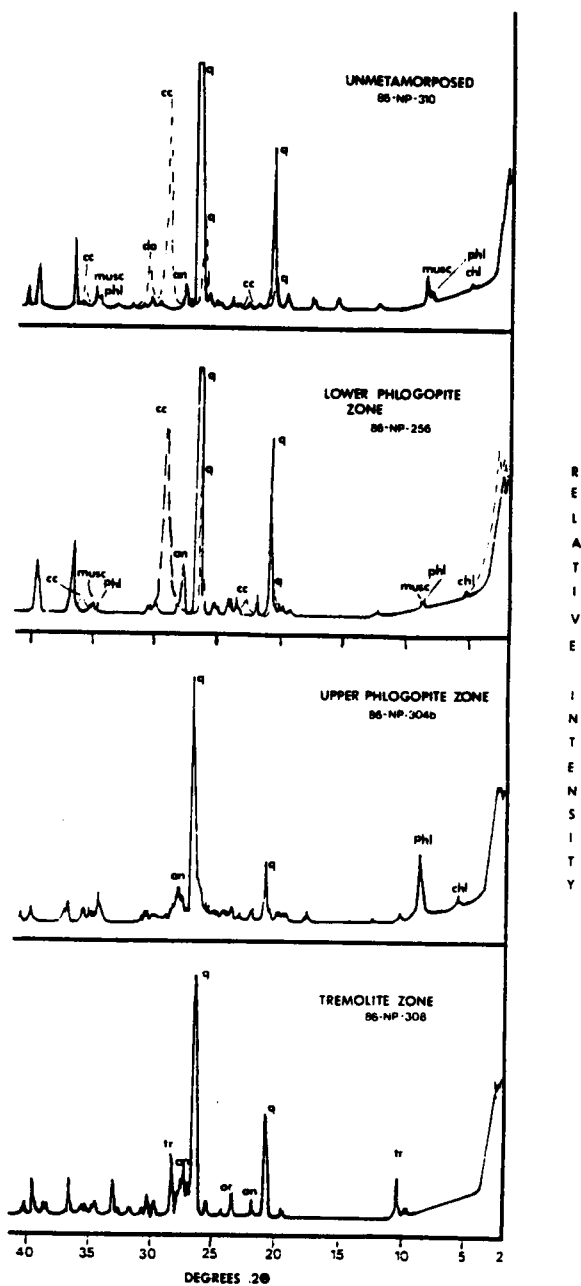


Fig. 3. Representative x-ray diffractograms from low-grade rocks. Samples were dissolved in acetic acid to remove the calcite and dolomite peaks. The dashed lines superimposed on the unmetamorphosed and the lower phlogopite patterns are patterns of the samples before dissolution in acetic acid. Degrees (2θ) refer to the angle of diffraction, 2θ , in Bragg's law. The largest peaks in each pattern have been cut off at the top.

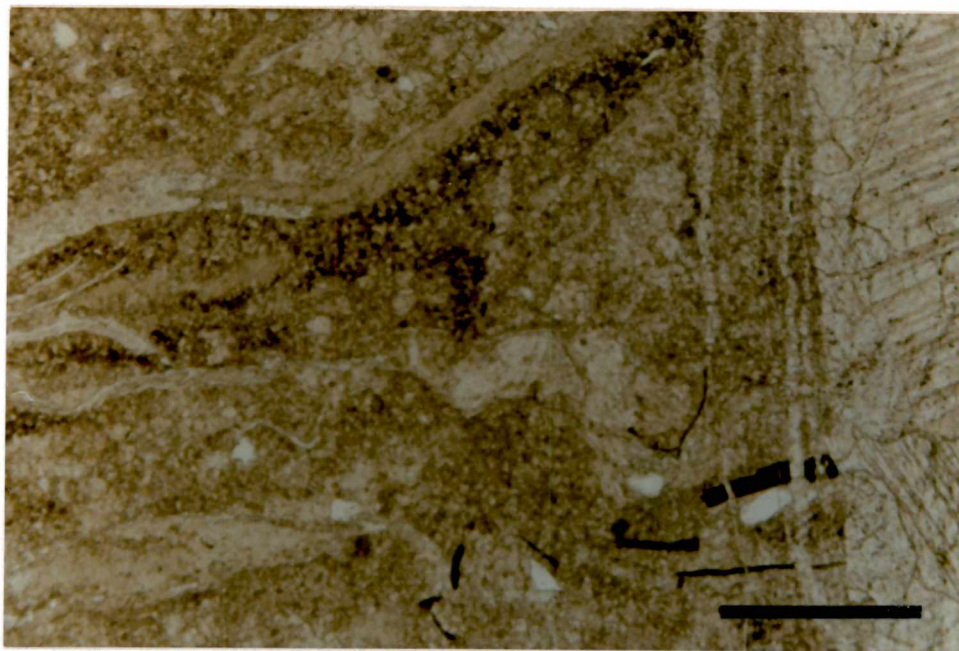
generally generally poorly developed. A photomicrograph of an unmetamorphosed sample is shown in Figure 4.

Samples from the lower-phlogopite zone are very similar to the unmetamorphosed samples; however dolomite is no longer present. Relict oolites and fossils are rimmed by polycrystalline quartz in several thin sections from this zone. In addition, white mica, which is commonly found in the more micritic layers, is much more common in these samples than in the unmetamorphosed samples. Photomicrographs of a sample from the lower-phlogopite zone are shown in Figures 5a and 5b.

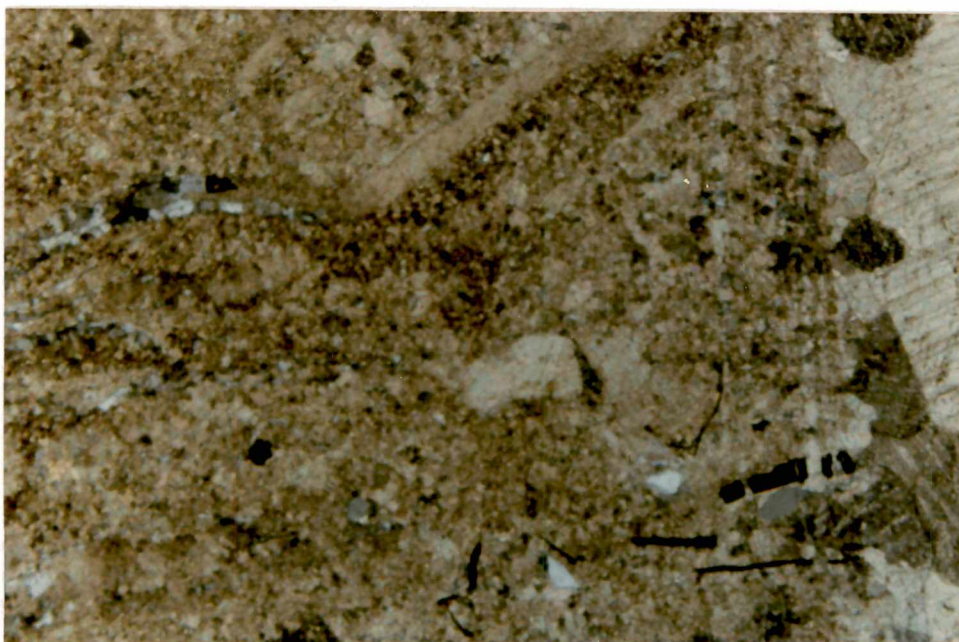
Samples from the upper-phlogopite zone are the lowest grade samples in which metamorphic minerals are easily seen in thin section. These samples contain fewer relict organic features than the lower-phlogopite zone and unmetamorphosed samples. Quartz and feldspar grains are much more abundant and also larger in size. Large grains of phlogopite also are present in these samples. Stylolites are much better developed than in the previous samples. Mica, quartz, and feldspar grains are frequently more abundant in zones where pressure solution is well developed. Photomicrographs from the upper-phlogopite zone are shown in Figure 5c and 5d.

Samples from the tremolite zone are generally finer grained than those from the other zones. These samples contain small grains of tremolite which are usually

Fig. 4. Photomicrograph of an unmetamorphosed sample. Sample #86-NP-312a. In a) large brachiopod shells and other bioclastic material are apparent in plane polarized light. The large fracture to the right of the photograph is filled with calcite. Under crossed polars, shown in b), some of the fossil fragments are revealed to be silicified (see upper left corner). The cement in this sample is mostly micrite. The bar in a) represents 0.5 mm.

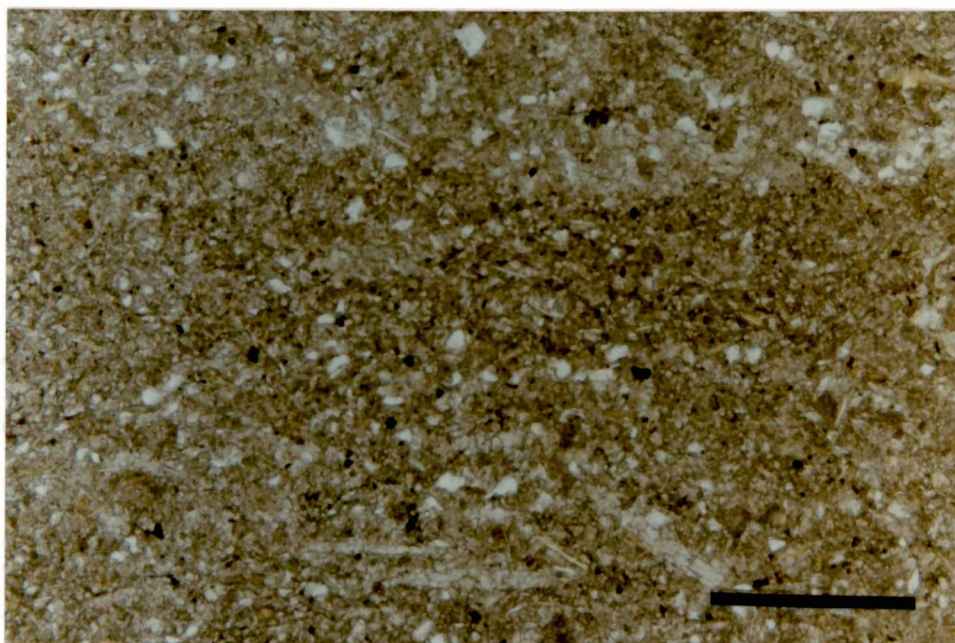


4a)

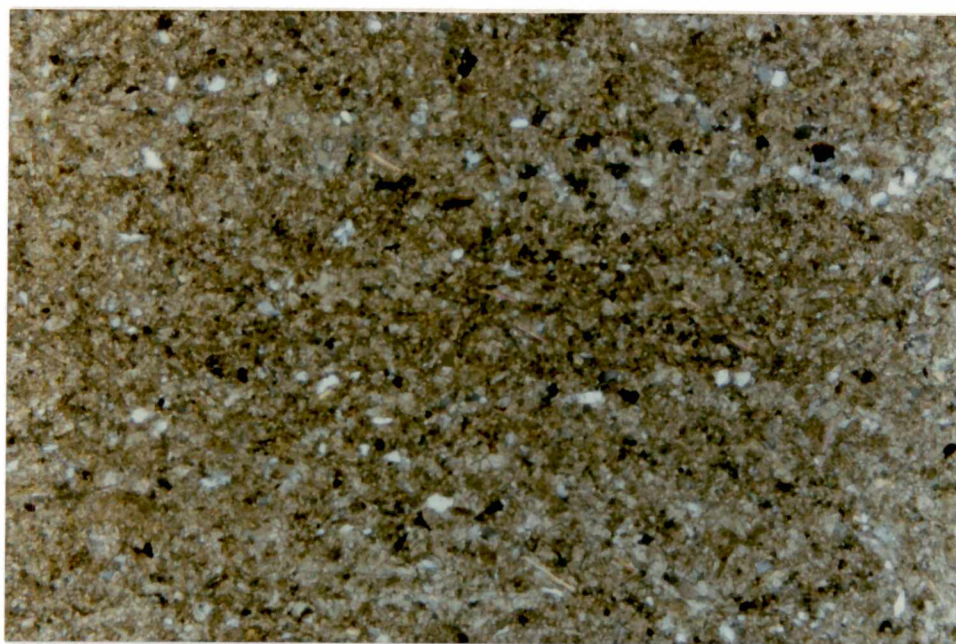


4b)

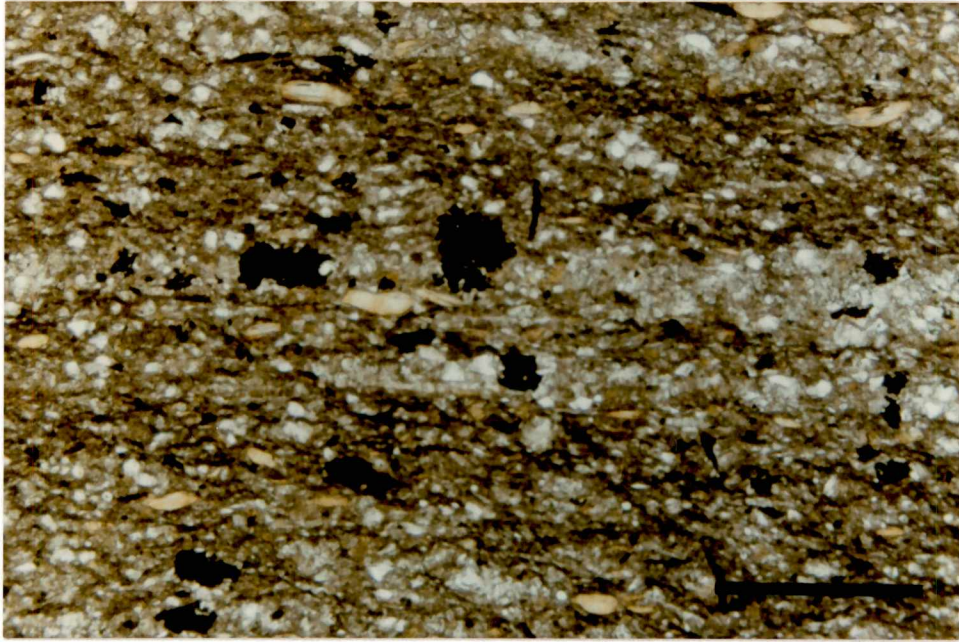
Fig. 5. Photomicrographs of phlogopite zone samples. a) a lower phlogopite zone sample, #86-NP-257, is shown under plane polarized light. Fossil fragments are common and white mica is the most abundant metamorphic mineral. b) shows the same sample under crossed polars. c) shows an upper phlogopite zone sample, #86-NP-302, under plane polarized light. Large phlogopite grains are common and are oriented parallel to bedding. Stylolitization is notable for the first time and the amount of feldspars and quartz has increased dramatically over the lower grade samples. d) shows the same sample rotated 45° and under crossed polars. The bars in a) and c) represent 0.5 mm.



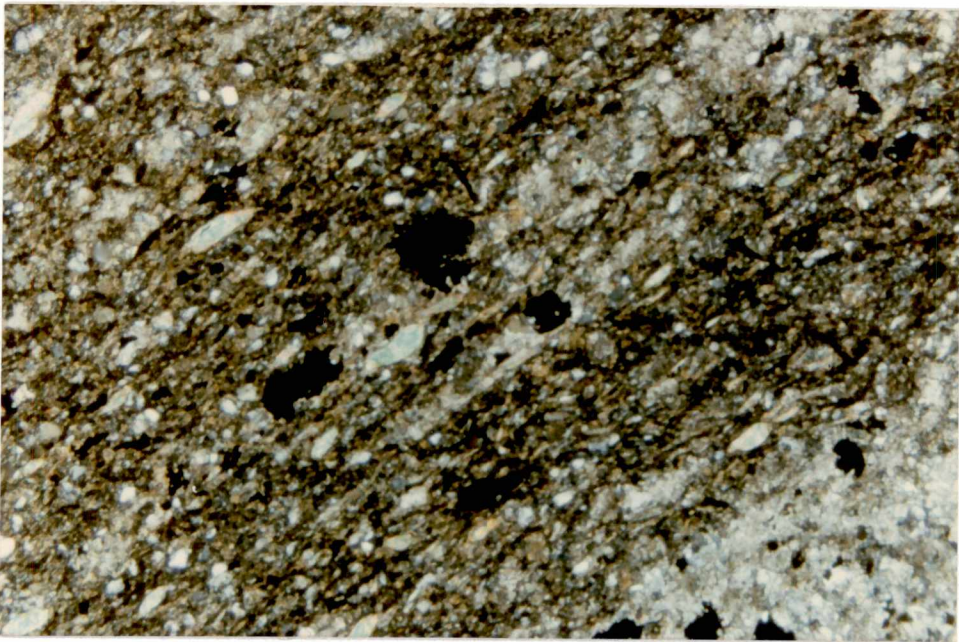
5a)



5b)



5c)



5d)

poorly developed. Fossils have been completely eliminated by metamorphism of these rocks. Pressure solution is extremely well developed in these samples. As in the upper-phlogopite zone samples, tremolite, feldspar, and quartz crystals are more abundant along zones of stylolitization. Photomicrographs of a sample from the tremolite zone are shown in Figure 6.

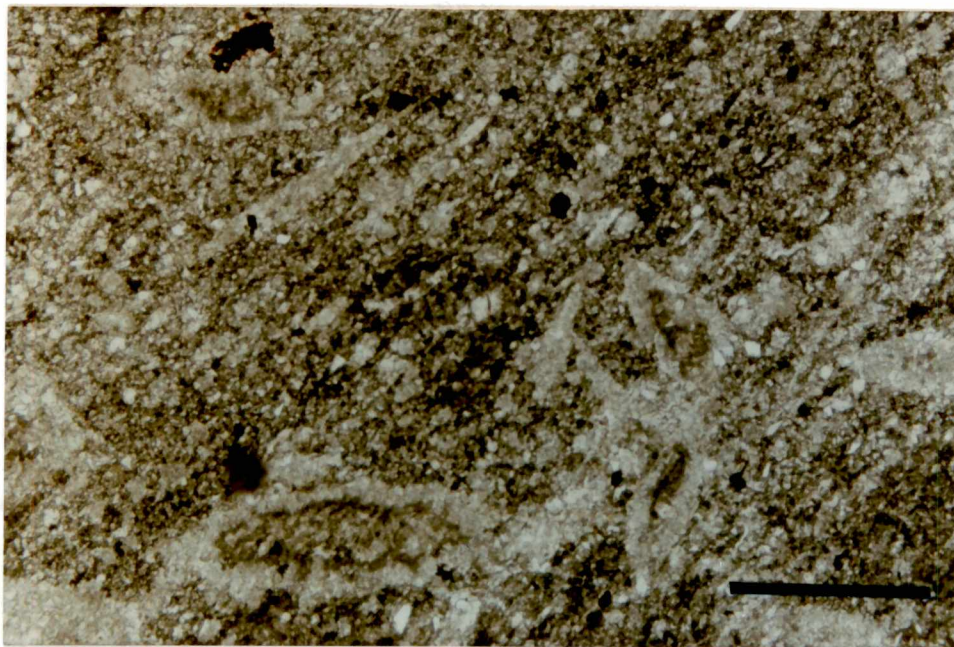
Samples from the diopside zone are the first samples that clearly show the signs of hydrothermal alteration, both in thin section and hand sample. These samples are also the first to contain large, well developed metamorphic minerals. Scapolite grains are as large as 0.5cm in size, commonly euhedral, and generally contain many solid inclusions. Diopside crystals are also large, up to 0.6cm in size; they commonly occur in randomly oriented clusters and locally are rimmed by graphite. Quartz, calcite, K-feldspar, and plagioclase are also abundant in these samples. Photomicrographs of samples from the diopside zone are shown in Figure 7.

The petrography of samples from the wollastonite zone will be discussed in the next chapter.

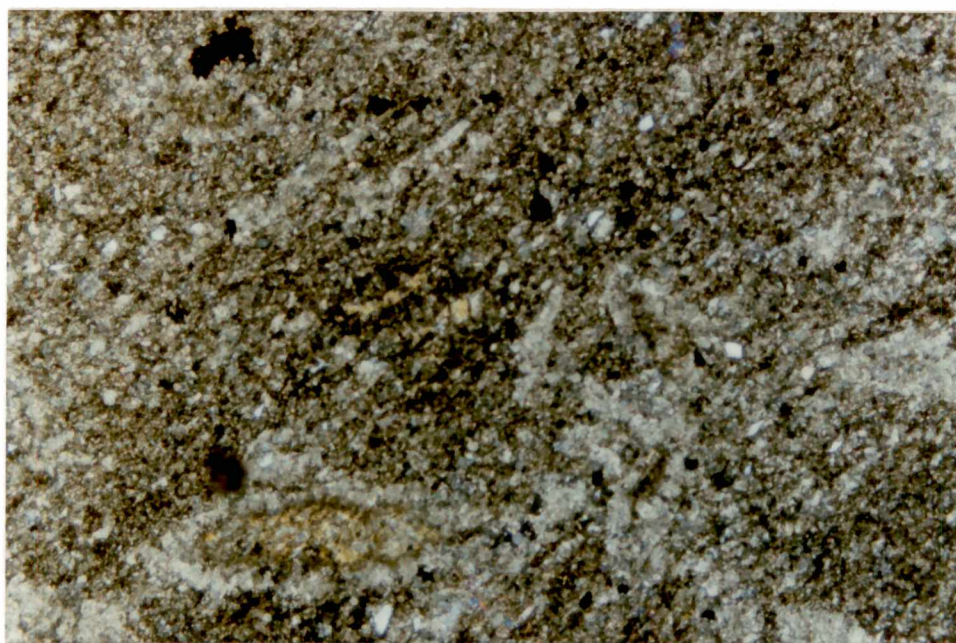
C. MINERAL ASSEMBLAGES AND REACTION RELATIONS

Unmetamorphosed rocks from Notch Peak are typified by the assemblage calcite (Cc) + quartz (Q) + dolomite (Dol) + muscovite (Musc) + plagioclase (Plag) + chlorite

Fig. 6. Photomicrograph of a tremolite zone sample. Sample #86-NP-295. In a) the sample is shown under plane polarized light. Note the "halos" which surround large murky grains, especially to the lower left. In b) which is under crossed polars, these turn out to be large tremolite grains which have replaced fossils. The bar in a) represents 0.5 mm.

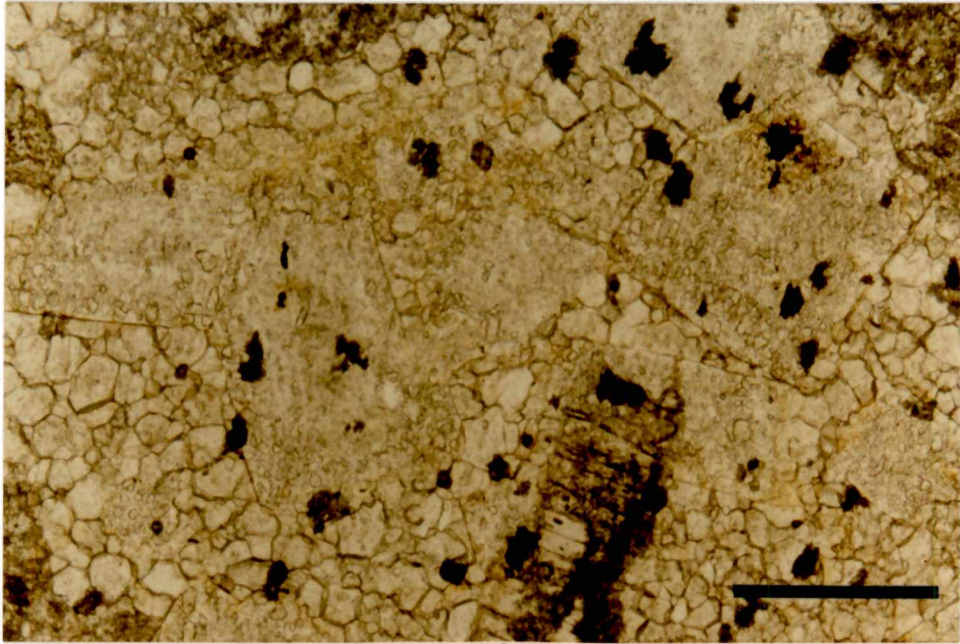


6a)

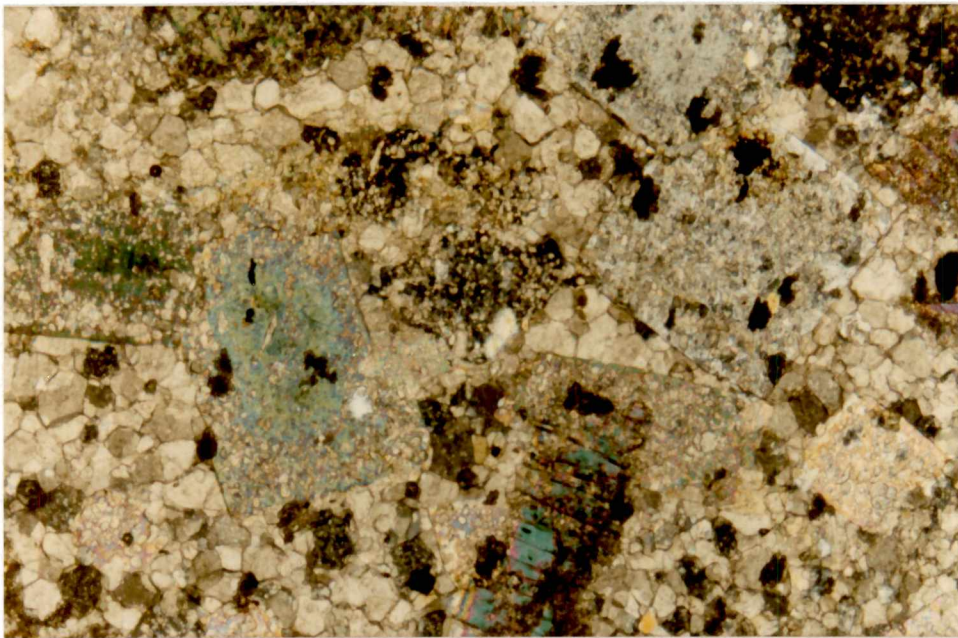


6b)

Fig. 7. Photomicrograph of a diopside zone sample. Sample #86-NP-221. In a) the outlines of large scapolite crystals are notable. The opaque material is probably graphite. In b) the scapolite is the large grey or yellow grains. The green and blue grains are diopside. The small grey grains in the lower right hand corner are probably feldspar. The matrix is calcite. a) was taken in plane polarized light, and b) under crossed polars. The bar in a) is 0.5 mm in length.

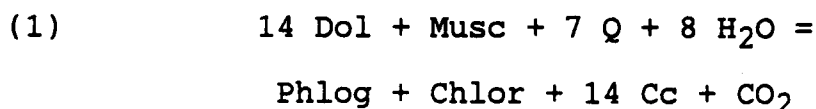


7a)



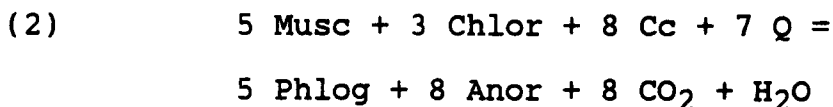
7b)

[metamorphism are encountered when dolomite disappears]
 (Chlor). A typical XRD pattern from the unmetamorphosed rocks is shown in Figure 3 (page 14). The first signs of $\checkmark$ from the rocks, and phlogopite appears in its place. This occurs when the metamorphic conditions reach those of the phlogopite zone. The location of the phlogopite isograd is shown in Figure 1 (page 2). The removal of dolomite from the rocks and the appearance of phlogopite results in the assemblage: calcite + quartz + muscovite + phlogopite (Phlog) + plagioclase + chlorite. This assemblage is typical of rocks in the lower phlogopite zone. A typical XRD pattern from the lower phlogopite zone is shown in Figure 3 (page 14). The reaction that removes dolomite from the rocks at the phlogopite isograd is:



This reaction has been discussed by Ferry (1984).

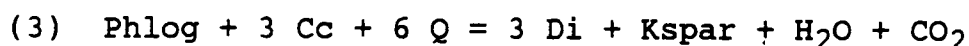
The first major change in the low grade rocks occurs at the muscovite-out isograd where muscovite reacts to form phlogopite by the reaction:



This reaction has been described by de Bethune (1976). The occurrence of this reaction marks the limit of stability of the assemblage muscovite + chlorite +

calcite in these rocks. It also marks the onset of the metamorphic conditions present in the upper part of the phlogopite zone. The location of the upper phlogopite isograd is shown in Figure 1 (page 2). Since the reaction (2) was limited by the amount of muscovite present, it led to the stable assemblage: calcite + quartz + phlogopite + calcic-plagioclase (Anor) + chlorite. A typical XRD pattern from the upper phlogopite zone is shown in Figure 3 (page 14).

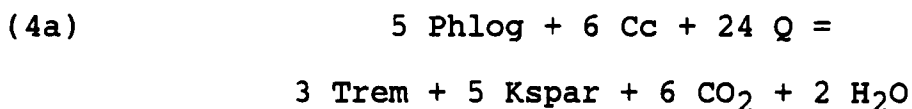
The first appearance of diopside in the rocks signifies the onset of metamorphic conditions present in the diopside zone. The stable assemblage in the diopside zone is diopside (Di) + K-feldspar (Kspar) + plagioclase + calcite + quartz. Closer to the wollastonite isograd, scapolite may also be present. Diopside forms by the reaction:



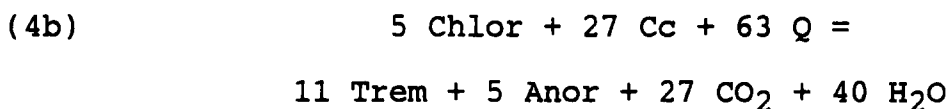
The significance of reaction (3) is discussed, along with the higher grade reactions in Chapter 3. The location of the diopside isograd is shown in Figure 1 (page 2).

In some areas, most notably along the northeast section of the field area, the assemblage calcite + quartz + tremolite (Trem) + plagioclase + K-feldspar has been found. The first occurrence of this assemblage marks the onset of metamorphic conditions present in the

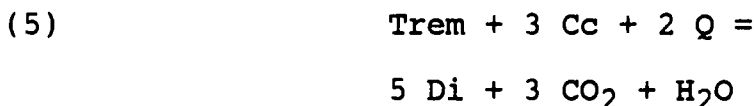
tremolite zone. A typical XRD pattern from the tremolite zone is shown in Figure 3 (page 14). Where found, the tremolite zone is always the smallest of the zones in the metamorphic aureole. Tremolite forms at the tremolite isograd by the reaction:



Tremolite may also form by the reaction:



The reaction (4b) occurs at higher X_{CO_2} where it removes chlorite from the rocks before reaction (4a) occurs. In areas where tremolite is present, the diopside zone is entered when tremolite breaks down by the reaction:



As can be seen in Figure 1 (page 2), all the isograds discussed above (with the exception of the tremolite isograd) are approximately parallel to each other. They are also roughly concentric around the Notch Peak stock, except to the north east where a large salient in the isograds extends out into the Weeks Limestone. A possible reason for the presence of this salient will be discussed in Chapter 3. Tremolite is present only in one small area, near Contact Canyon. The fluid involved in metamorphism in this area probably

had a slightly higher X_{CO_2} than in other areas. The presence of tremolite in these rocks will be discussed later in this Chapter.

D. T- X_{CO_2} CONDITIONS

In Figure 8 the minerals and reactions discussed above are shown plotted on an Al_2O_3 - KAlSi_3O_8 - $\text{MgO}+\text{FeO}$ (AKM) diagram. This diagram is projected from SiO_2 , calcite, and H_2O . It does not distinguish between FeO and MgO and therefore cannot be used to show partitioning of iron and magnesium between coexisting phases. The use of this diagram for the rocks at Notch Peak can be justified by the absence of coexisting phases in which partitioning of iron and magnesium occurred. Minerals plot on this diagram in the following manner: muscovite, which has a chemical formula of $\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$, has one unit of Al_2O_3 and one unit of KAlSi_3O_8 , therefore it plots halfway between the A and the K endpoints. Similarly phlogopite, which is assumed to have the formula $\text{KMg}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$, has three units of MgO and one of KAlSi_3O_8 will plot three quarters of the way to the MgO corner on the MgO - KAlSi_3O_8 side, and chlorite, assumed to have the formula $\text{Mg}_6\text{Al}_3\text{Si}_4\text{O}_{10}(\text{OH})_8$, will do so on the Al_2O_3 - MgO side of the plot. Plagioclase, which has a generalized chemical formula of $(\text{CaAl}_2\text{-NaAlSi})\text{Si}_2\text{O}_8$, would plot at the Al_2O_3

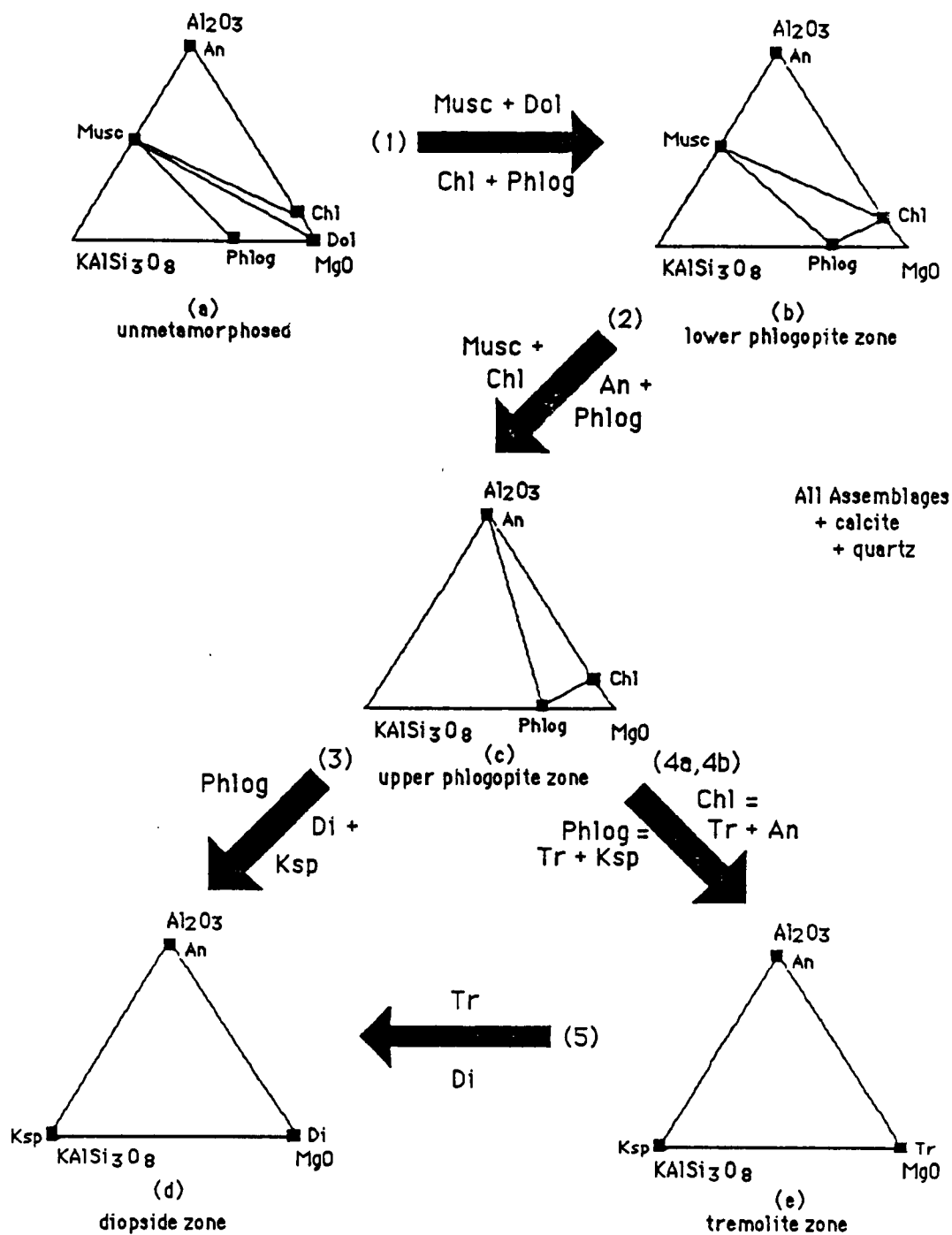


Fig. 8. AKM diagrams showing progressive metamorphism of the low grade rocks at Notch Peak. The reactions are shown between each diagram. Numbers next to each reaction correspond to those in the text. The letters by each diagram also correspond to those in the text.

does have an Al_2O_3 component. It is important to note corner because it has no MgO or KAlSi_3O_8 components, but that this plot does not discriminate between calcic and sodic plagioclase.

The series of reactions described above is shown plotted on AKM diagrams in Figure 8. The unmetamorphosed assemblage is shown in Figure 8a. As the temperature increased, dolomite reacted with muscovite, as described by reaction (1), to form assemblage 8b. As the upper phlogopite isograd was surpassed, muscovite reacted with chlorite, as shown in reaction (2), to form the assemblage shown in Figure 8c. With continued increase in metamorphic grade, diopside formed at the expense of calcite, quartz, and phlogopite as described by reaction (3). The assemblages present in the diopside zone are shown in Figure 8d. Reaction (4a) which formed from calcite, quartz and chlorite are also shown in Figure 8e. At higher grades tremolite will break down to form diopside as described by reaction (5) to result in assemblage 8d.

The sequence of reactions just described is shown on a petrogenetic grid in Figure 9 (after Labotka and Nabelek, 1986). This grid is an isobaric, isothermal diagram that shows μ_{CO_2} versus $\mu_{\text{H}_2\text{O}}$. A reaction will plot in μ - μ space as a line. The slopes of this line

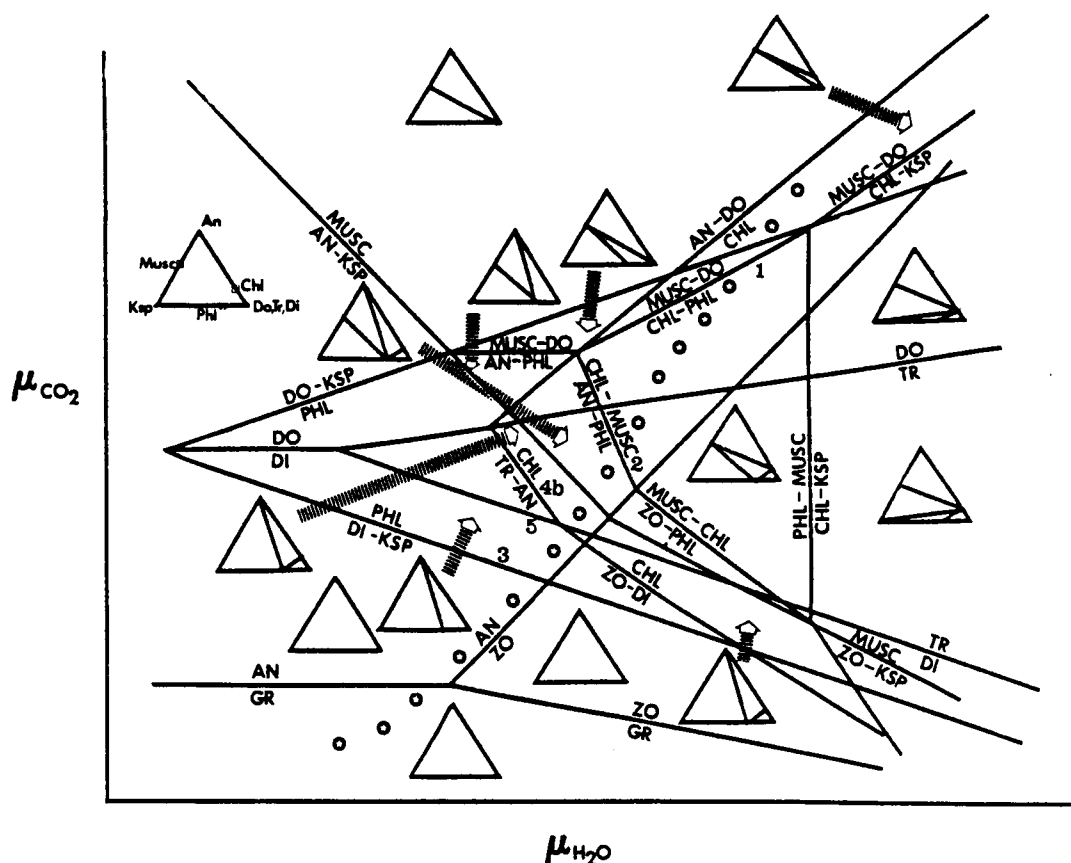


Fig. 9. μ - μ grid for the $\text{CaO-K}_2\text{O-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-NaCl-H}_2\text{O-CO}_2$ system. The grid is isothermal and isobaric. The dotted line is a path which represents the path of metamorphism of the lower grade rocks through μ - μ space. Numbered reactions correspond to those discussed in the text. After Nabelek and Labotka (1986).

may be determined from the balanced reactions by the following relation:

$$d\mu_{\text{CO}_2}/d\mu_{\text{H}_2\text{O}} = -n_{\text{H}_2\text{O}}/n_{\text{CO}_2}$$

where $n_{\text{H}_2\text{O}}$ and n_{CO_2} are the respective stoichiometric coefficients of H_2O and CO_2 from the balanced reaction. The coefficients are defined as positive if they are on the products side and negative if they are on the reactants side of the reaction.

The path of metamorphism for the rocks in μ - μ space is indicated in Figure 9. Each reaction in the text has its corresponding number indicated on the diagram. As can be seen, the reactions described above are a sequence in which CO_2 systematically decreases; however, since this is an isothermal diagram, changes in temperature may also result in the same sequence of reactions. For reasons to be discussed later, reaction (4a) does not plot on this diagram. The presence of tremolite in samples 285, 286, 287 and 307 can be explained by a localized decrease in $\mu_{\text{H}_2\text{O}}$ relative to μ_{CO_2} . This is also true for dolomite, which is present in samples 284 and 295. Local variations in temperature or bulk chemistry of the rocks also may explain the presence of tremolite and dolomite in these samples. The presence of K-feldspar in some of the muscovite + phlogopite zone rocks (i.e. 254, 259 and 262) also can be explained by localized increases in μ_{CO_2} which would

cause phlogopite to break down to form dolomite and K-feldspar. The tremolite present in sample 301 probably is detrital rather than metamorphic in origin.

A schematic version of Labotka and Nabelek's (1986) T-X_{CO2} grid, with modifications after Kerrick et al. (1973), Ferry (1976a), Rice (1977), and Flowers and Helgeson (1983) is shown in Figure 10. A line representing the path of metamorphism is shown on the figure. The reactions (1), (2), (3), (4a), (4b), and (5) proposed for paragenesis at Notch Peak are labeled in this diagram.

The estimated T-X_{CO2} path of metamorphism is indicated in Figure 10. This path reveals that in the bulk of the rocks, the expected reactions with increasing metamorphic grade would be: reaction (1) which would cause the appearance of the assemblage present in the lower phlogopite zone; reaction (2) as the muscovite-out isograd is crossed; and finally reaction (3) leading into the diopside zone. These reactions require that the path of metamorphism represent a sequence in which X_{CO2} decreases systematically while temperature remains relatively constant. An increase in temperature before reaction (3) was crossed would result in the presence of tremolite instead of diopside. Rocks present in the tremolite zone therefore probably represent a localized temperature increase.

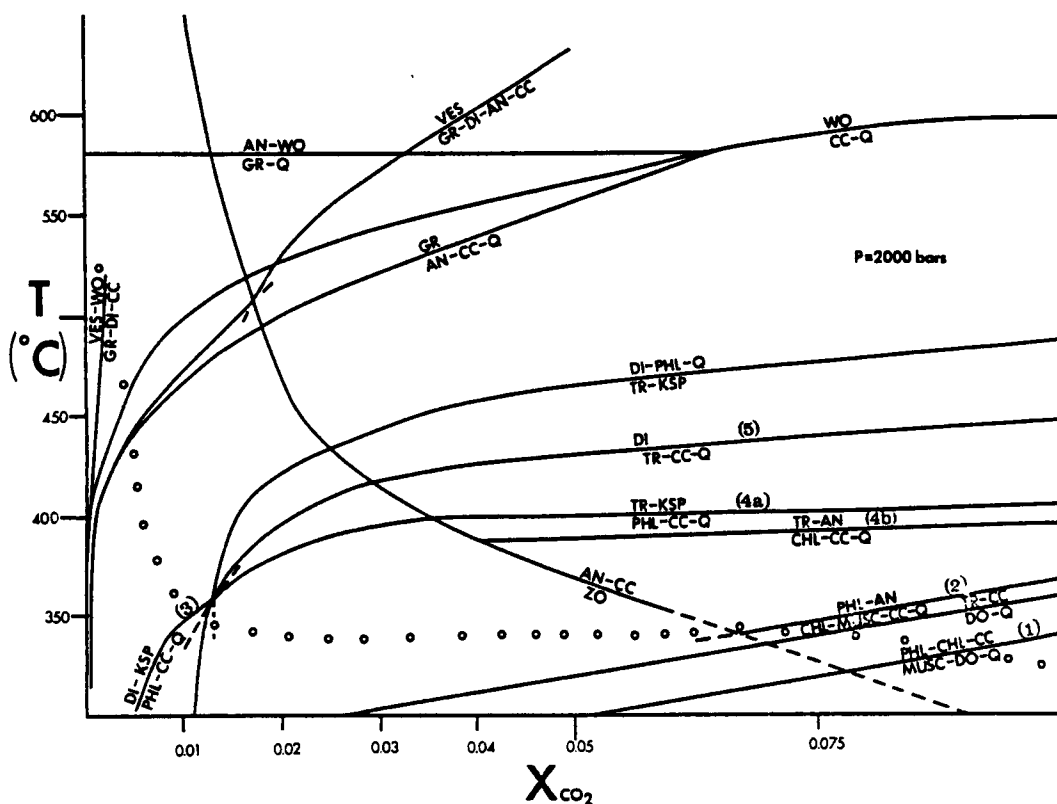


Fig. 10. Schematic T - X_{CO_2} grid for the $\text{CaO-K}_2\text{O-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-NaCl-H}_2\text{O-CO}_2$ system. The grid is isobaric and is shown at 2000 bars. The path indicates the path of metamorphism of the lower grade rocks through T - X_{CO_2} space. Numbered reactions correspond to those discussed in the text. After Labotka and Nabelek (1986) with modifications from Flowers and Helgeson (1983), Ferry (1976) and Nabelek et al. (1983).

After reaction (3) was crossed, the temperature of metamorphism began to increase in accordance with the higher grade reactions that will be discussed later in the text. The presence of the assemblage vesuvianite + diopside + K-feldspar + quartz + calcite in the highest grade rocks suggest peak temperatures of at least 400° C (Olesch, 1978, Valley et al., 1985).

As can be seen in Figure 10, the T- X_{CO_2} path of the rocks at Notch Peak is constrained by reaction (3). Reactions (4a) and (4b) occur at a temperature and X_{CO_2} higher than that at which the diopside forming reaction (3) does. At the temperature and X_{CO_2} present at Notch Peak, the breakdown of tremolite by reaction (5) occurs before the tremolite forming reactions (4a) is reached. This results in diopside being the stable phase before either of the tremolite-producing reactions (4a) and (4b) is crossed. Therefore tremolite is unstable under the conditions present at Notch Peak. Reaction (4a) cannot be represented on a μ - μ diagram at the temperature conditions of Figure 9, because it occurs at a temperature that is considerably higher than represented in Figure 9.

E. SUMMARY

Increasing metamorphic grade at Notch Peak has resulted in the development of the phlogopite isograd by

reaction (1), the muscovite-out isograd by reaction (2), and the diopside isograd by reaction (3). Where tremolite is present, it is formed by reactions (4a) and (4b), and diopside is formed by reaction (5). These reactions have been plotted in T- X_{CO_2} space revealing that the path of metamorphism was initially one in which X_{CO_2} decreased systematically at approximately constant temperature. After the diopside isograd was crossed, the path changed to one in which the temperature increased and X_{CO_2} continued to decrease. The path of metamorphism through T- X_{CO_2} space has revealed that the fluid involved in metamorphism was rich in H_2O . The systematic decrease of X_{CO_2} through T- X_{CO_2} space is consistent with the path of metamorphism through μ - μ space.

CHAPTER 3

FLUID INCLUSIONS

A. INTRODUCTION

Many authors (e.g., Touret, 1977, Hollister & Crawford, 1981, Roedder, 1984, Crawford & Hollister, 1986) have written on the importance of fluid inclusions. Most believe that they are samples of the fluids present at some time during the history of the mineral in which they are trapped. There are three types of fluid inclusions: 1) primary, 2) secondary, and 3) psuedosecondary. Primary inclusions formed as the crystal grew, in which they are trapped. Therefore, they are representative of the fluids present at the time of formation of the mineral. Secondary inclusions, formed where fractures, which already existed in a crystal, were filled. These inclusions contain fluids that were present after the formation of the mineral in which they are trapped and therefore, do not represent fluids present at the time of initial mineral formation. Psuedosecondary inclusions are primary inclusions that occur along fractures and appear to be secondary inclusions. The distinction between the three types of inclusions is not always easy.

The presence of fluid inclusions in a rock indicates that the production of fluid at near

lithostatic pressure was greater than the ability of the rock to release it by grain boundary permeability.

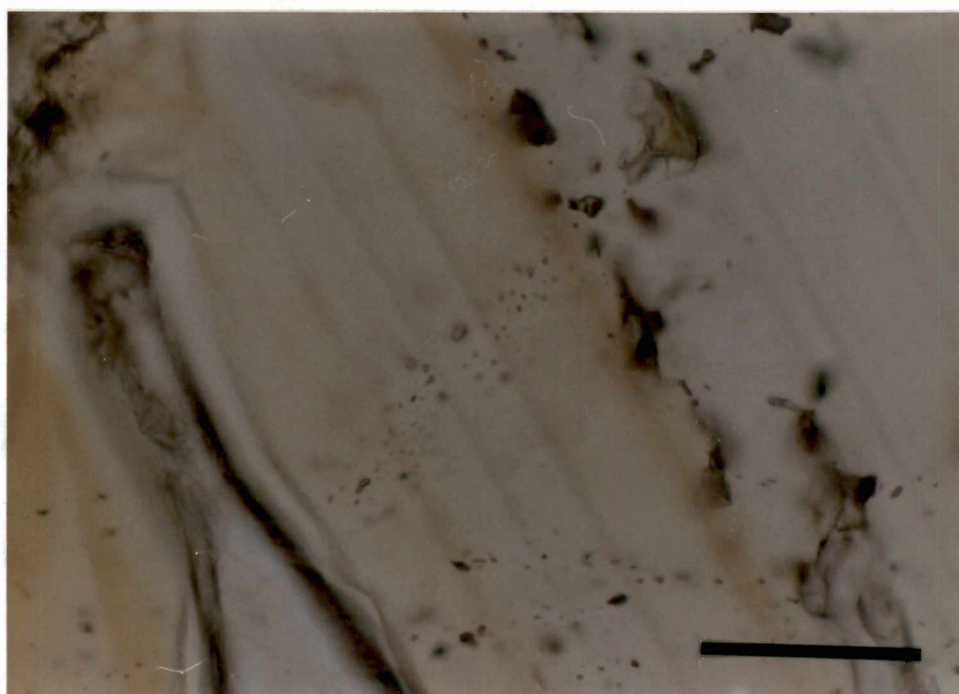
Entrapment of these excess fluids may have occurred along microfractures which were produced by the fluid as it flowed through the rocks, in fractures which already existed, or in irregularities on the surface of a growing crystal (Walther and Wood, 1986). In the case of contact metamorphosed rocks, fluid inclusions probably represent the fluids involved in metamorphism.

By obtaining data about the temperatures at which phase changes occur, compositional information about the fluid contained in fluid inclusions can be determined. If enough data can be obtained, it may be possible to characterize the fluids. It also may be possible to determine changes in the fluid composition which were a result of fluid-rock interactions during metamorphism. More important, fluid inclusions also are useful as geothermometers and geobarometers. Therefore, fluid inclusion data can be very useful in the characterization of fluids and in the constraint of the conditions prevalent at the time of metamorphism.

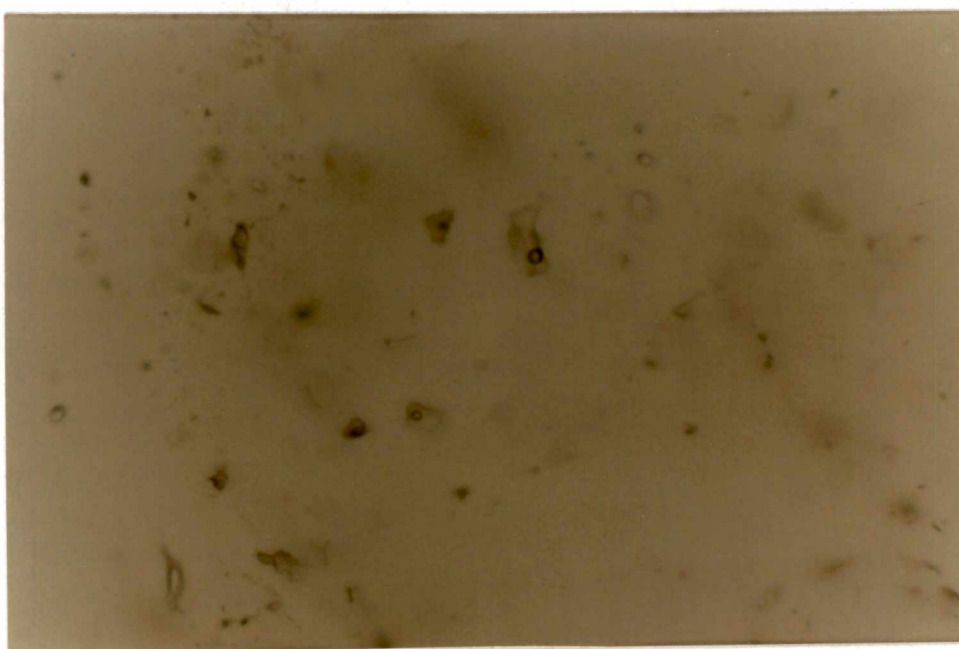
Inclusions, both solid and fluid are widespread in all the minerals present in the rocks of the Weeks Limestone at Notch Peak. Secondary fluid inclusions found in quartz, feldspar, and vesuvianite grains were found to give the most reproducible results. They were

also the easiest minerals to measure the temperatures at which phase changes occurred. Psuedosecondary inclusions were present in planes which cross cut those of secondary nature. Primary inclusions were also present, but they were rare in occurrence. Data from all three types of inclusions was gathered, and the inclusion type was noted. The mineral grains studied for inclusions occurred in three types of rocks: 1) granitic rocks collected from the Notch Peak Stock, 2) rocks collected from skarns adjacent to the stock, and 3) metamorphic rocks collected from the wollastonite zone of the metamorphic aureole. Fluid inclusions found in rocks from lower grades were too small to determine the temperatures at which phase changes occurred. Photomicrographs of fluid inclusions from the skarns are shown in Figure 11. The granite samples were studied in order to determine if CO_2 was present in the fluids expelled from the stock. Skarn samples were examined in order to determine the compositions of fluids after the peak of metamorphism (the skarns appear to be a result of retrograde metamorphism). The metamorphic samples were studied in order to determine the fluid composition and the temperatures of entrapment of inclusions formed at the peak of metamorphism. This information was gathered so that the evolution of the fluid composition as well as conditions of metamorphism could be examined

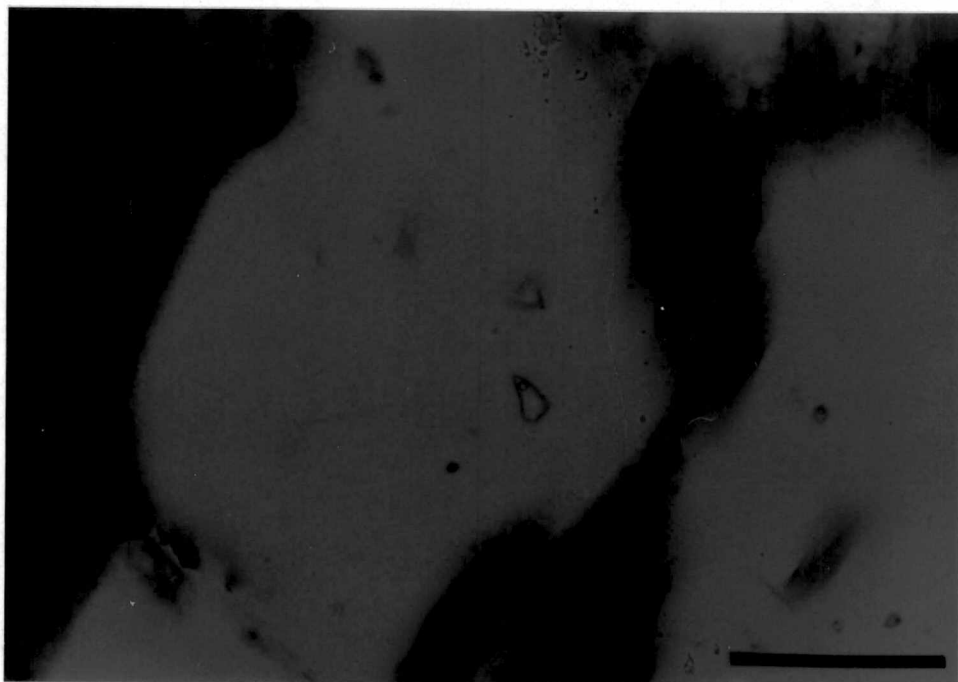
Fig. 11. Photomicrograph of fluid inclusions. In a) and b) inclusions from sample #80-NP-8P1 are shown. a) secondary inclusions are shown cross cutting zonations in a garnet. These inclusions are typical of the size of most of the fluid inclusions present in the Notch Peak samples. In b) primary inclusions in quartz are shown. Most of the inclusions contain a liquid with a vapor bubble. c) shows psuedosecondary inclusions in quartz from sample #80-NP-165-2. The psuedosecondary nature of these inclusions is not apparent from this photomicrograph. These inclusions also contain a liquid with a vapor bubble. The bars in a) and c) represent 50 μ .



11a)



11b)



11c)

and related to the development of the isograds. Determination of melting temperatures and homogenization temperatures was done on a fluid inclusion adapted U.S.G.S. gas-flow heating/freezing stage. The unit was checked against a known standard for reliability several times during the course of this study. Readings for the standard remained consistent through out the entire study. Calculation of salinities and isochores was done using Nicholls and Crawford's (1985) FORTRAN program HALWAT with the corrections described by Brown and Lamb (1986). Given the melting temperature and homogenization temperature of a fluid in a fluid inclusion, HALWAT will calculate the salinity and fluid density of the fluid using equations of state at the temperatures at which the fluid inclusion measurements were made. Isochores are calculated using both Redlich-Kwong and modified Redlich-Kwong equations of state. Due to a lack of available data most equations of state are extrapolated at pressures higher than 2000 bars. Trapping temperatures were calculated using a pressure of 2000 bars as estimated from the overburden present at the time of emplacement of the stock (Hover et al., 1981). Values for trapping temperatures were then checked using the temperature correction tables generated by Potter (1977). Potter generated these tables by compiling volumetric data from

aqueous sodium chloride solutions and evaluating them by a weighted least-squares regression. He then plotted the data in Temperature correction versus homogenization temperature tables and contoured the tables for pressure. Both resulting values are reported in the following section.

B. RESULTS

A phase diagram of the H_2O - NaCl system is shown in Figure 12. This diagram shows all the temperatures important to fluid inclusion studies. T_e is the eutectic temperature of the system. At this temperature the first drop of liquid forms from a solid when it is melted. The eutectic temperature is constant for any given system and is different for each aqueous species. For example, the eutectic for the H_2O - NaCl system is -20.8°C . For the H_2O - KCl system the eutectic is at -10.6°C . Therefore, determination of the eutectic temperature will allow an educated guess to be made regarding the salt species present in the fluid inclusion (unless there is more than one type of salt present). The melting temperature, T_m , for a fluid inclusion is the temperature at which the frozen fluid melts congruently to form a liquid and a gas. If the melting temperature of a fluid inclusion is known, it is possible to calculate the equivalent weight percent NaCl

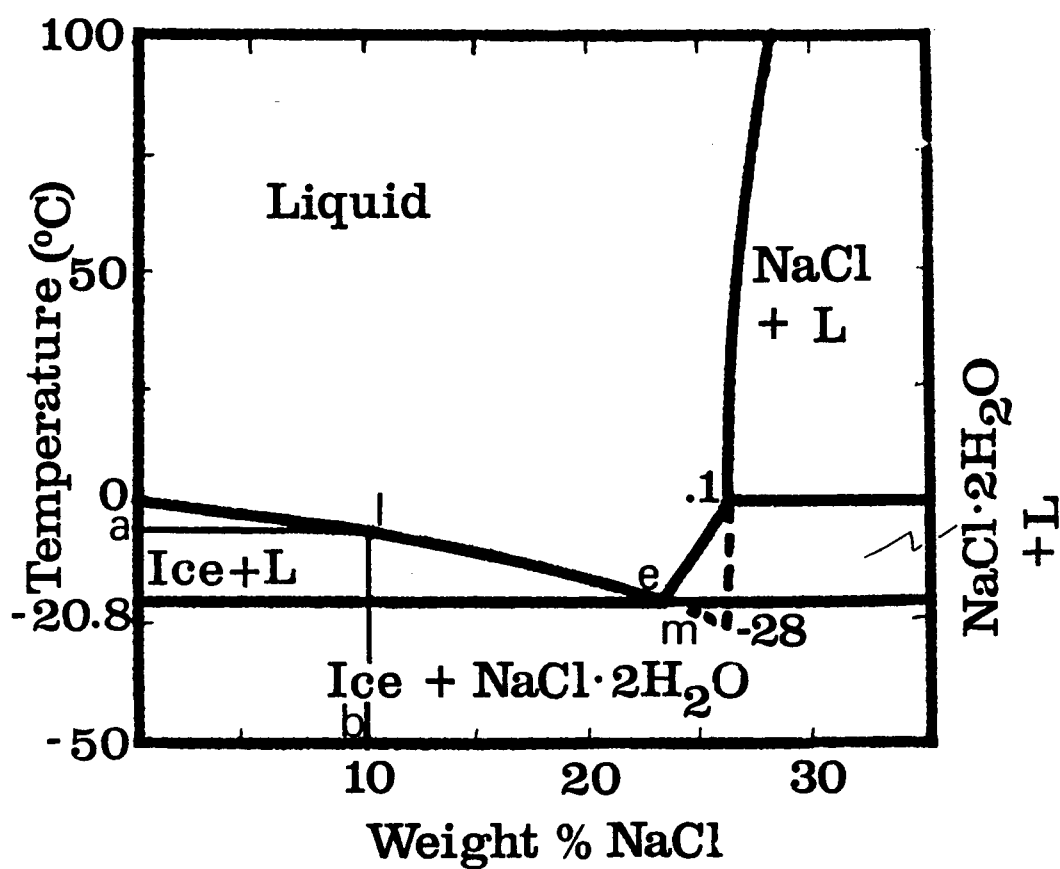


Fig. 12. Phase diagram of the H₂O-NaCl system. Point e is the eutectic, m, is a metastable eutectic, a, l, and b are discussed in the text. Modified after Hollister and Crawford (1981).

in the solution using equations such as those given by Roedder (1984) and Nicholls and Crawford (1985). For example, the following are characteristics of an inclusion which has the melting temperature shown as 'a' in Figure 12. A line can be drawn from point 'a' parallel to the weight percent NaCl axis. This line will intersect the liquidus at point 'l'. The weight percent NaCl present in the fluid corresponds to point 'l'; it can be read off the weight percent NaCl axis at point 'b'. Point 'e' on Figure 12 is the eutectic of the H₂O-NaCl system. Point 'm' is a metastable eutectic for the system. In real system, all salinities are reported as equivalent weight percent NaCl by convention. The homogenization temperature, T_h , of a fluid inclusion is the temperature at which the liquid and gas phases present in the inclusion homogenize to form one fluid. In the H₂O-CO₂ system, there are two homogenization temperatures. One of them represents the temperature at which H₂O and CO₂ become miscible. The second homogenization temperature represents the temperature at which the clathrate compound breaks down to its H₂O and CO₂ components and "homogenizes" with the surrounding liquid and gas phases. Along with the melting temperature of the fluid inclusion and the H₂O/CO₂ ratio, this temperature is necessary to calculate the density of the fluid. Once the fluid

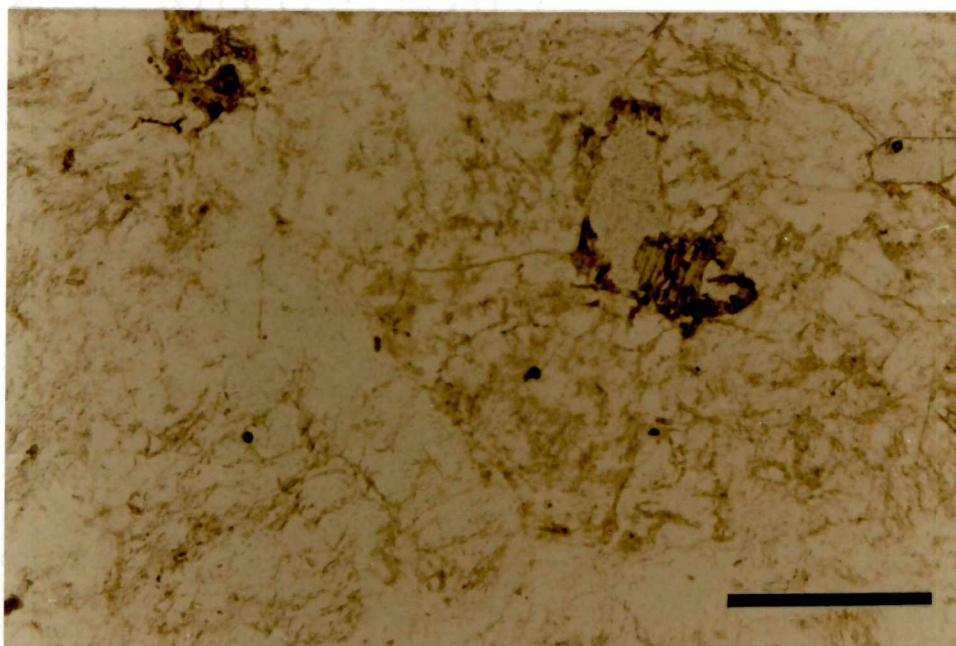
density is known, it is possible to calculate the isochore for the fluid. The isochore is a line through P-T space along which the density of the fluid is constant. Calculation of the fluid density and the isochore has been discussed above. Once the isochore has been calculated, it is possible to determine the temperature or pressure of entrapment of the inclusion if either of the two is already known. Some examples of isochores are shown in Figs. 15, 19 and 23.

Data from Granite Samples

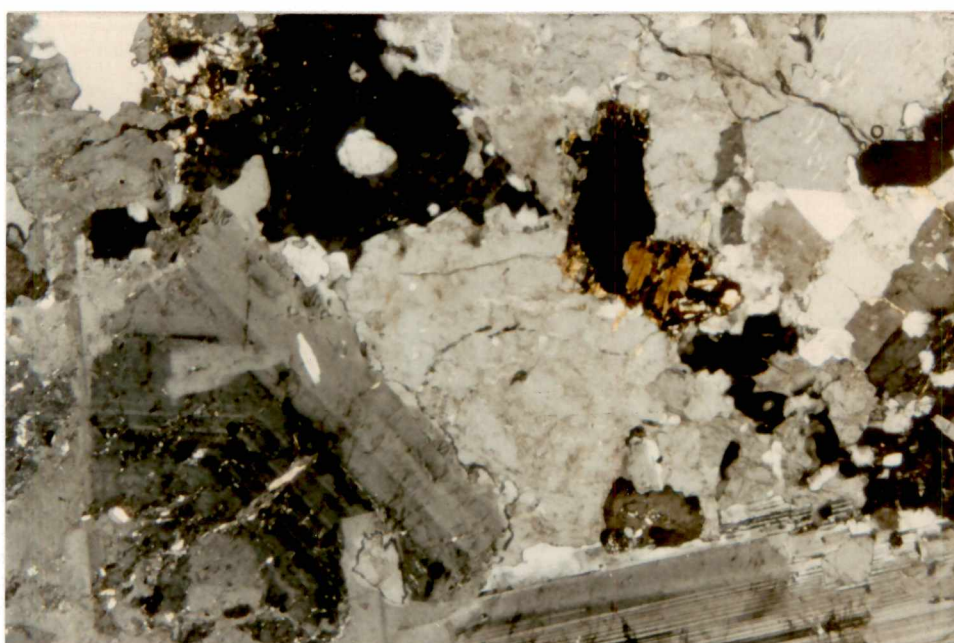
The Notch Peak Stock is a reversely zoned granite porphyry containing subequal amounts of quartz, perthitic alkali feldspar, and zoned plagioclase. The stock has been extensively studied by Nabelek et al. (1981, 1983, 1984, 1986a, 1986b) in order to determine the petrogenesis and origin of the zoning. A photomicrograph of the granite is shown in Figure 13.

Fluid inclusion data were collected from quartz grains in samples 80-NP-159-1 and 80-NP-165-2 collected from the Notch Peak stock (see Figure 1, page 3 for sample locations). Fluid inclusions in these samples are secondary and contain no daughter crystals. Data collected from these samples are given in Appendix 2. Eutectic temperatures ranged from -5° to -21° C. These data indicate that sodium chloride and potassium chloride are probably both present in fluid inclusions.

Fig. 13. Photomicrograph of a granite sample. Sample 80-NP-165. In b) large zoned plagioclase crystals, K-feldspar and quartz crystals are present with small amounts of biotite and sphene (upper right). a) is in plane polarized light, b) is under crossed nicols. The bar in a) is 0.5 mm in length.



13a)



13b)

Eutectic temperatures, along with the absence of clathrate formation implies low to no CO₂. As shown in Figure 14, the melting temperatures of inclusions are clustered around 0° to -5° C with another set of values clustered around -15° to -20° C. These data give salinities in the range of 0 to 25 equivalent weight percent NaCl. The distribution of homogenization temperatures is shown in Figure 15. The data range from 130° to 210° C. Construction of the isochores and extrapolation of data indicate approximate trapping temperatures for these data are in the range of 300° to 400° C. The method of Potter (1977) gave trapping temperature values in the range of 300° to 370° C. Plots of some of the isochores are shown in Figure 16.

Data from Skarn Samples

Skarns at Notch Peak generally occur near the margin of the intrusion. The samples collected from these rocks are characterized by the presence of large euhedral grossular garnets. In one skarn, the garnets make up 75% of the sample. These garnets typically contain large, solid inclusions and show well developed zoning (notable in thin section). Also typical of the skarn deposits is the presence of diopside, tremolite, and/or hornblende, as well as minor occurrences of vesuvianite, rutile, chlorite, and ilmenite. Quartz and calcite are present, filling spaces between garnets.

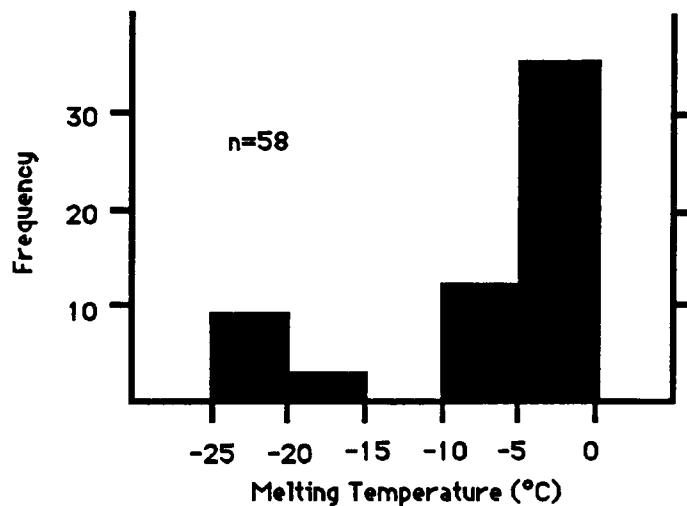


Fig. 14 Histogram showing the melting temperatures of fluid inclusions in the granite samples. The fluid inclusions are secondary and occur in quartz grains in samples 80-NP-159-1 and 80-NP-165-2.

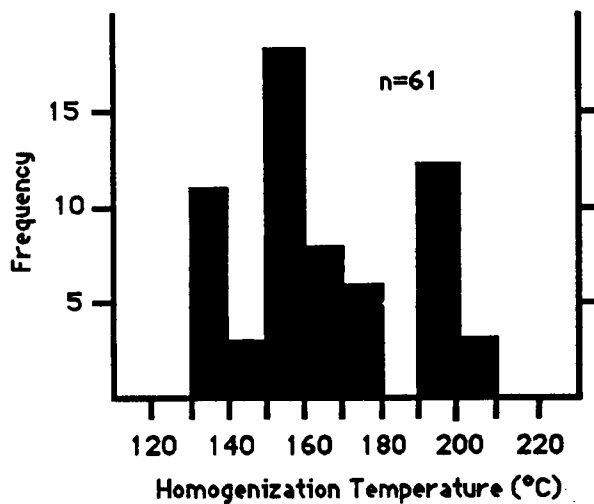


Fig. 15. Histogram showing the homogenization temperatures of fluid inclusions in the granite samples. The fluid inclusions are secondary and occur in quartz grains in samples 80-NP-159-1 and 80-165-2.

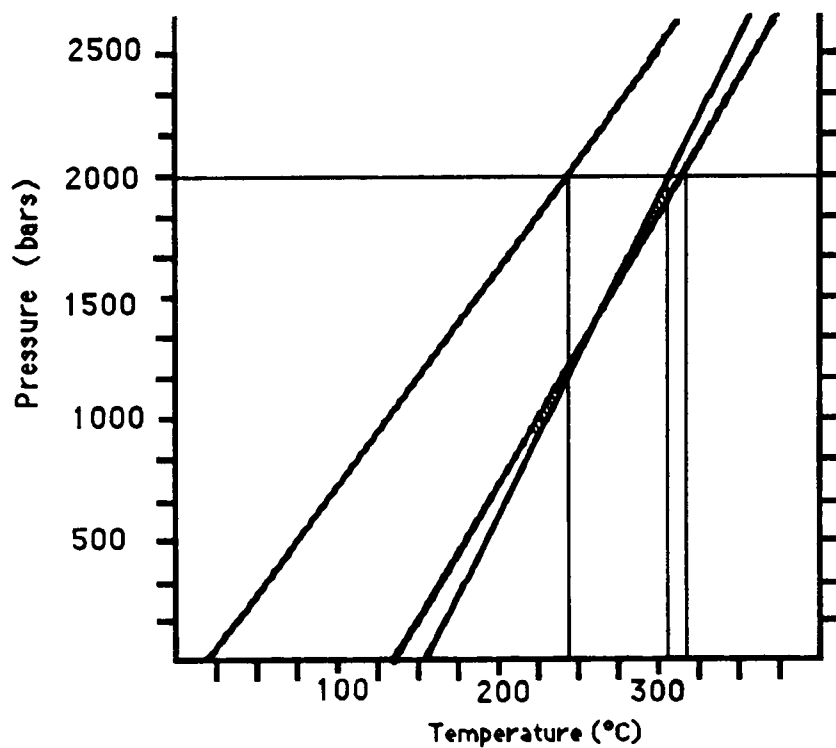
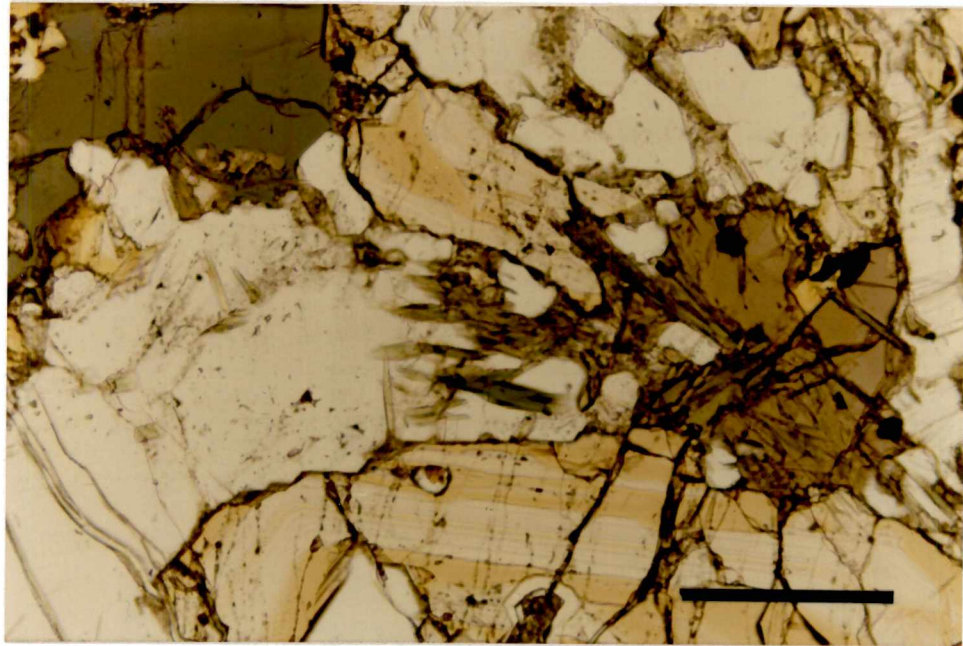


Fig. 16. Examples of isochores determined from fluid inclusion data from the granite samples. The fluid inclusions are secondary and occur in quartz grains.

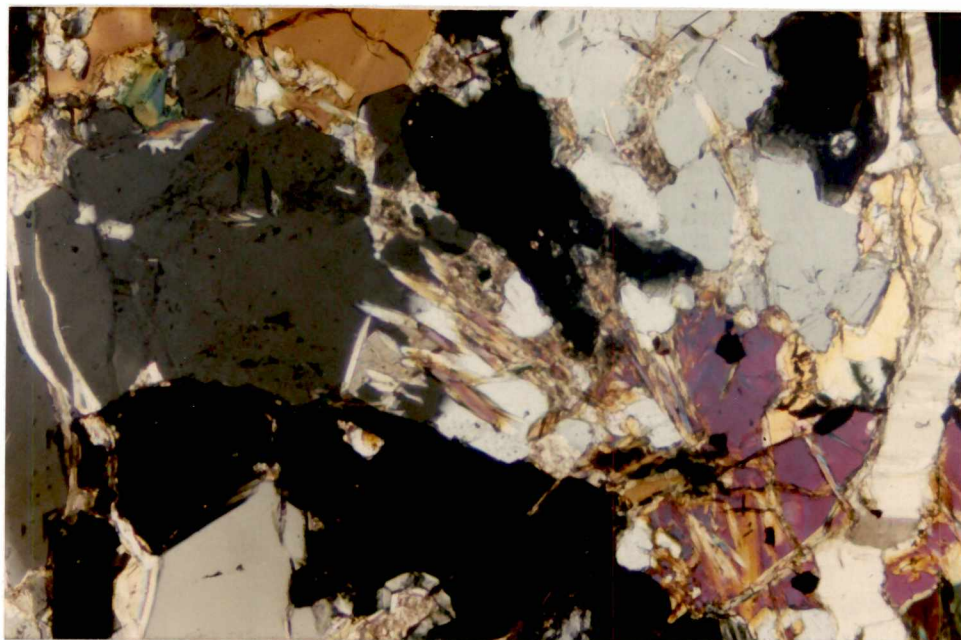
Quartz grains in these samples contain well-developed planes of large, secondary inclusions. A photomicrograph of a skarn is shown in Figure 17.

A complete list of data from fluid inclusions found in the skarn samples is given in Appendix 2. Data were collected from quartz grains in samples 80-NP-8P-1, 86-NP-205a, and 86-NP-205b (see locations on map, Figure 1, page 3). Fluid inclusions are secondary and contain no daughter crystals. The eutectic temperatures ranged from -20° to -38° C. These data indicate that sodium chloride, along with other salt species (calcium and/or magnesium chloride?) are present in the inclusions. Once again eutectic temperatures and the absence of clathrate compounds implies that CO_2 values were low. A histogram of the melting temperatures of fluid inclusions in the skarn samples is shown in Figure 18. Melting temperatures are in the range of 0° to -20° C giving salinity values of 0 to 25 equivalent weight percent NaCl, which is similar to those from the granite. Homogenization temperatures for skarn samples fell in the range of 130° to 260° C. A histogram showing homogenization temperatures from the skarn samples is shown in Figure 19. The isochores determined from HALWAT are shown in Figure 20. Trapping temperatures are estimated to be 250° to 430° C.

Fig. 17. Photomicrograph of a skarn sample. Sample 80-NP-8P1. In a) the yellow, zoned crystals are garnets, green, fibrous crystals are tremolite, and brighter yellow crystals are vesuvianite. The massive brown crystal near the center is probably pyroxene. Quartz and calcite make up the remainder of the sample. a) is in plane polarized light, b) is under crossed nicols. The bar in a) is 0.5 mm in length.



17a)



17b)

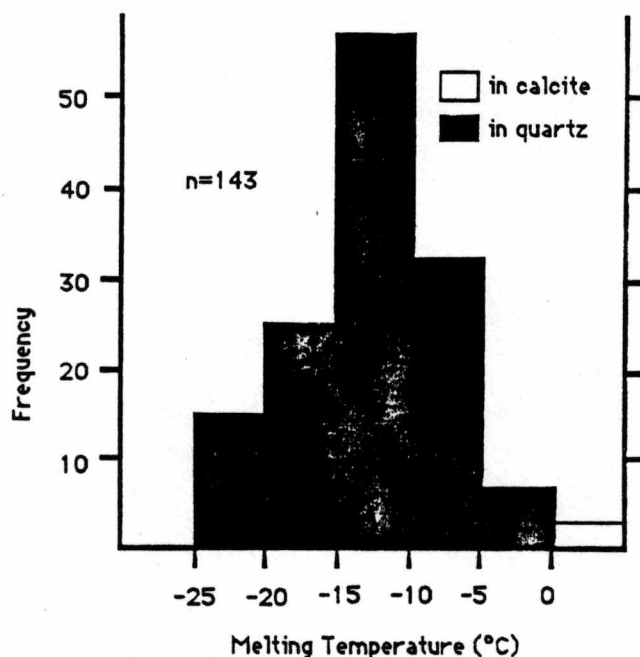


Fig. 18. Histogram showing the melting temperatures of fluid inclusions in the skarn samples. The fluid inclusions are secondary and occur in quartz and calcite grains in samples 80-NP-8P1, 86-NP-205a and 86-NP-205b.

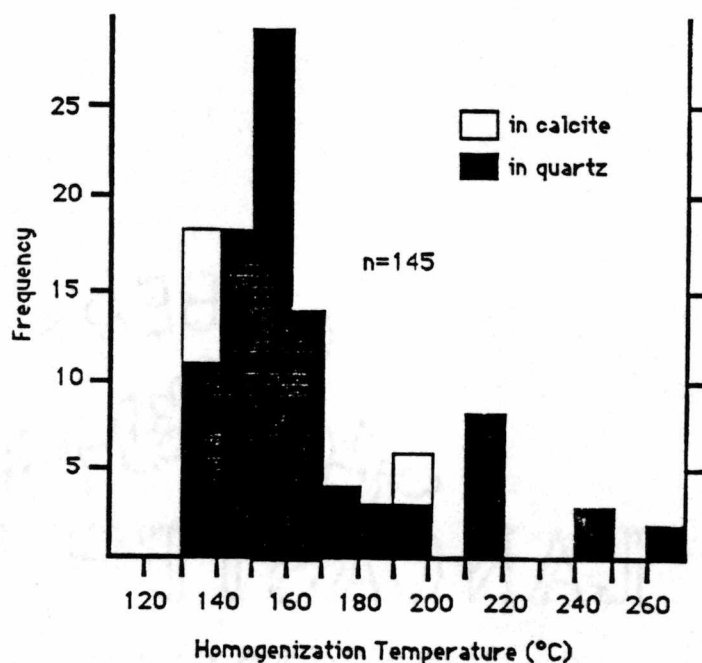


Fig. 19. Histogram showing the homogenization temperatures of fluid inclusions in the skarn samples. The fluid inclusions are secondary and occur in quartz and calcite grains in samples 80-NP-8P1, 86-NP-205a and 86-NP-205b.

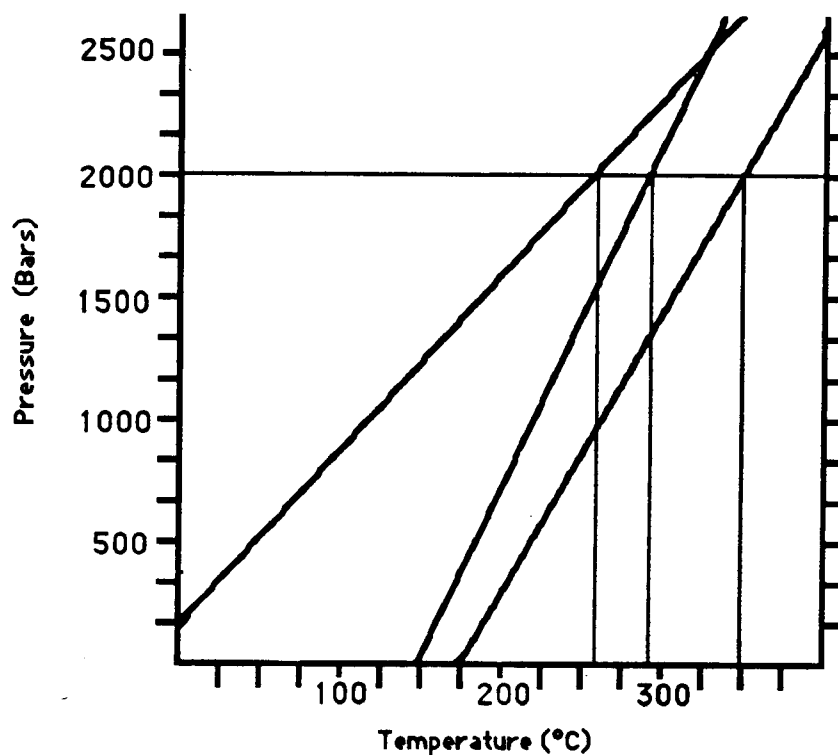


Fig. 20. Examples of isochores determined from fluid inclusion data from the skarn samples. The fluid inclusions are secondary and occur in quartz grains.

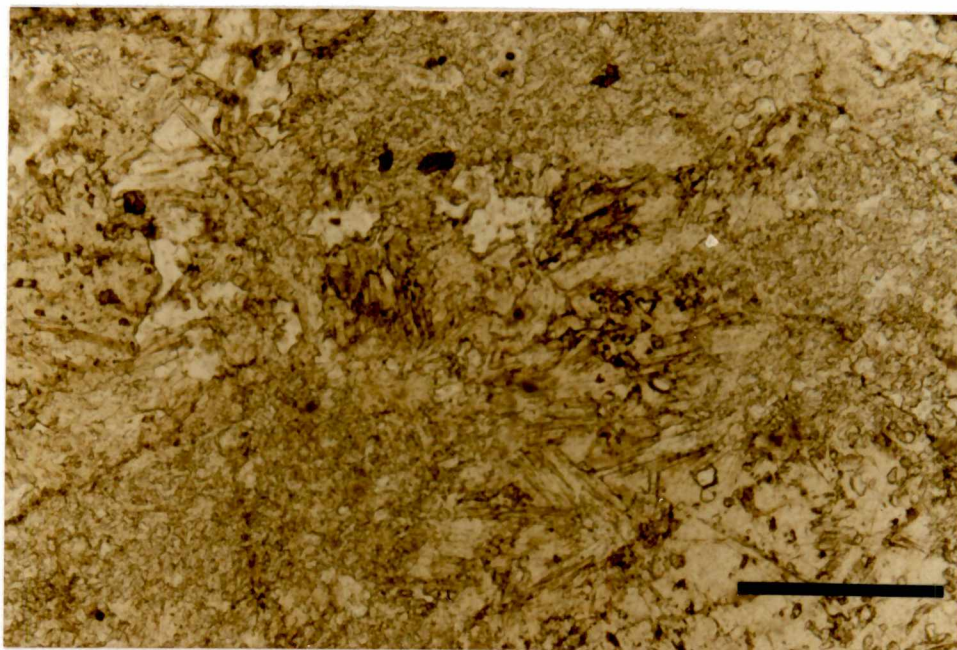
Potter's (1977) method gave trapping temperatures of 300° to 440° C.

Data from Wollastonite Zone Samples

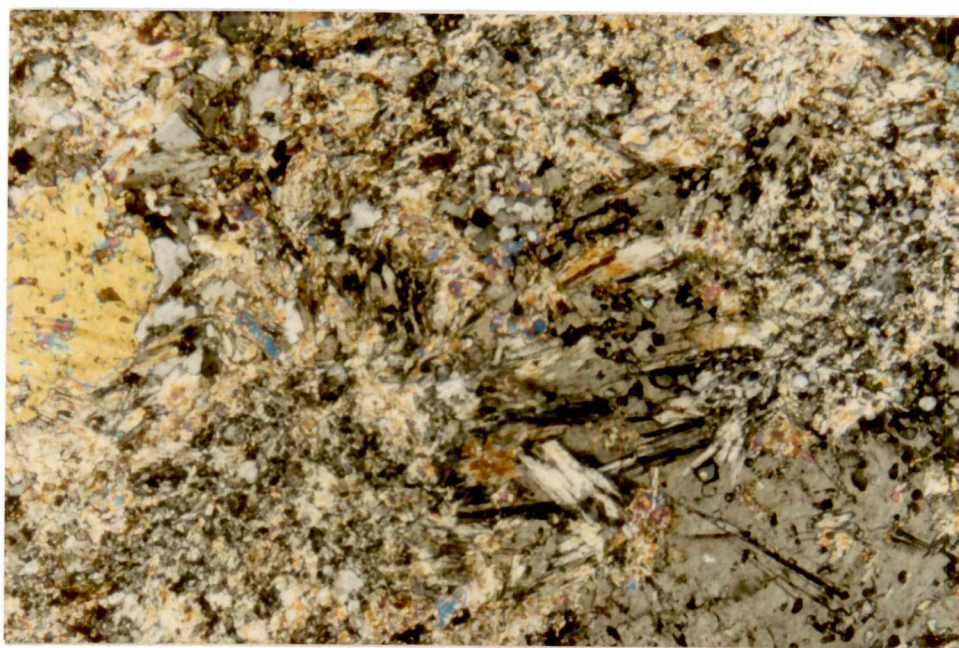
The wollastonite zone samples are characterized by vesuvianite, wollastonite, diopside, and scapolite. These critical minerals are typically set in a fine grained calcite and feldspar matrix. Chlorite and garnet may be present; however, they are generally rare in occurrence. The samples from these zones typically contain interlayered diopside, calcite, and feldspar and vesuvianite, wollastonite, and feldspar. Scapolite and diopside also may be present in vesuvianite layers. The diopside layers typically contain highly altered crystals of diopside in a fine-grained matrix of calcite and feldspar. Vesuvianite occurs as large crystals (centimeters in size) rimmed by wollastonite, diopside, and rare scapolite. When scapolite crystals are found, they generally contain many solid inclusions. Vesuvianite-bearing layers tend to lack calcite and are coarser-grained than diopside-bearing layers. A photomicrograph of a typical wollastonite-zone sample is shown in Figure 21.

A complete list of fluid inclusion data collected from the wollastonite zone samples is given in Appendix 2. Inclusion data were collected largely from feldspar and vesuvianite grains in samples 86-NP-195, 86-NP-207a,

Fig. 21. Photomicrograph of a wollastonite zone sample. Sample 86-NP-199. In b) the large gray crystal in the lower right corner is vesuvianite, the large yellow crystal to the left as well as other high birefringence crystals are diopside, the low birefringence, fibrous mineral is wollastonite, and the pore filling first order grey mineral is feldspar. a) is in plane polarized light, b) is under crossed nicols. The bar in a) is 0.5 mm in length.



21a)



21b)

86-NP-208a, 86-NP-211, 86-NP-212, 86-NP-226b, and 86-NP229b (see locations on map, Figure 1, page 3). Fluid inclusions are secondary and contain no daughter crystals. Eutectic temperatures generally were between -28° and -38° C, however, values as high as -20° C and as low as -50° C were observed. These data indicate that sodium chloride along with other salt species (calcium and/or magnesium chloride?) are present in the fluid inclusions. The absence of clathrates implies low CO_2 values. Figure 22 is a histogram that shows the melting temperatures of the fluid inclusions. Melting temperatures range from 0.5° to -28° C. Salinities in these, samples ranged from 0 to 28 equivalent weight percent NaCl. Figure 23 shows the frequency of homogenization temperatures of fluid inclusions in the wollastonite-zone samples. These temperatures range from 115° to 280° C. Some representative isochores calculated for the data from these samples indicate trapping temperatures of 250° to 475° C. The isochores are plotted in Figure 24. Potter's (1977) method for values of 265° to 460° C.

C. DISCUSSION AND SUMMARY OF DATA

The study of these inclusions has revealed that they contain an H_2O -rich fluid (low to no CO_2). Most of the fluid inclusions were secondary. They yielded

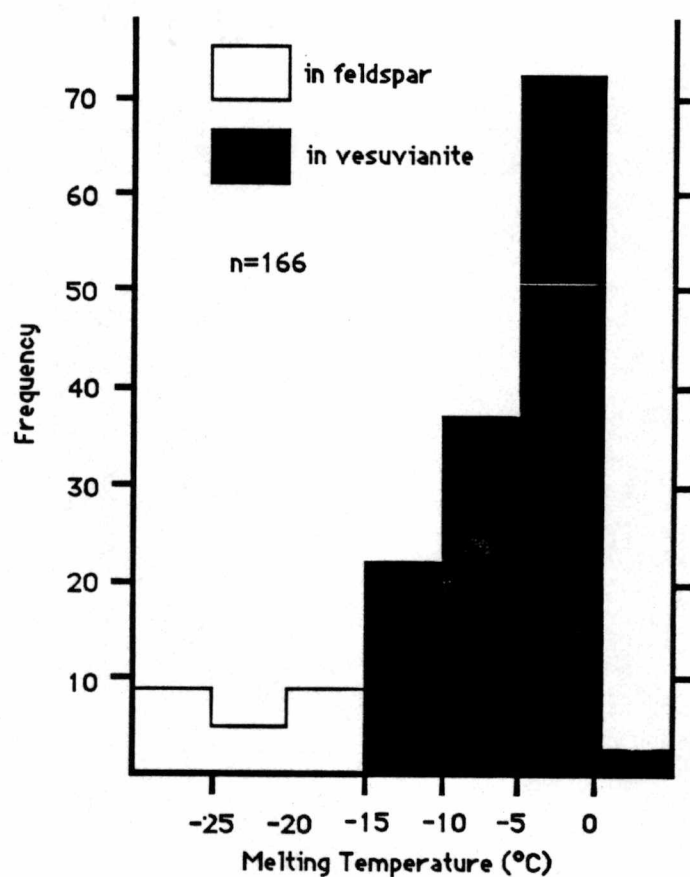


Fig. 22. Histogram showing melting temperatures of fluid inclusions in the wollastonite zone samples. The fluid inclusions are secondary and occur in feldspar and vesuvianite grains in samples 86-NP-195, 86-NP-207a, 86-NP-208a, 86-NP-212, 86-NP-226b and 86-NP-229b.

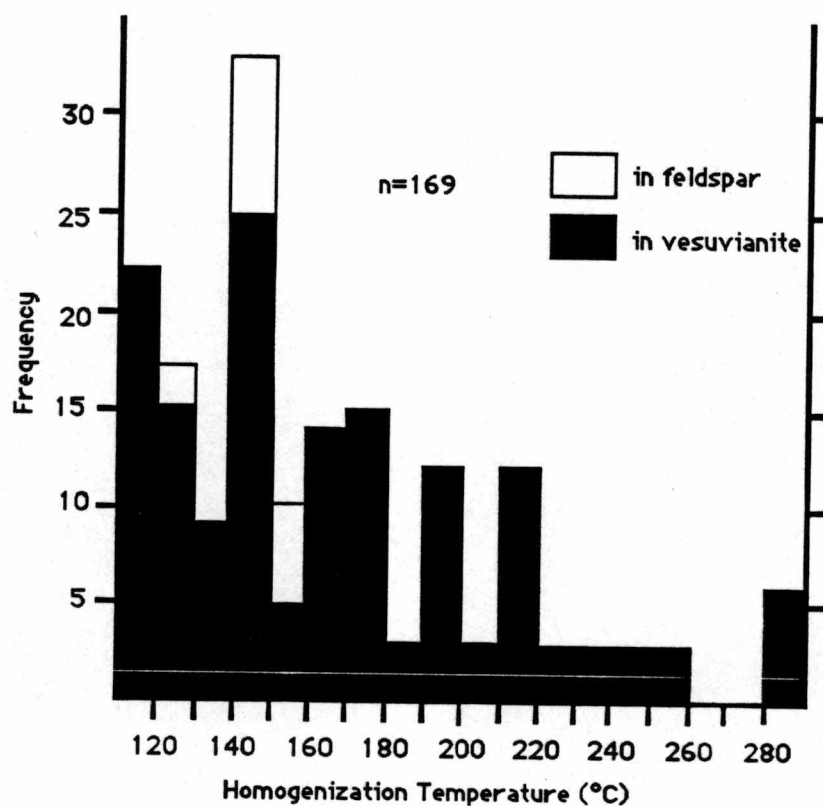


Fig. 23. Histogram showing the homogenization temperatures of fluid inclusions in the wollastonite zone samples. The fluid inclusions are secondary and occur in feldspar and vesuvianite grains in samples 86-NP-195, 86-NP-207a, 86-NP-208a, 86-NP-211, 86-NP-212, 86-NP-226b and 86-NP-229b.

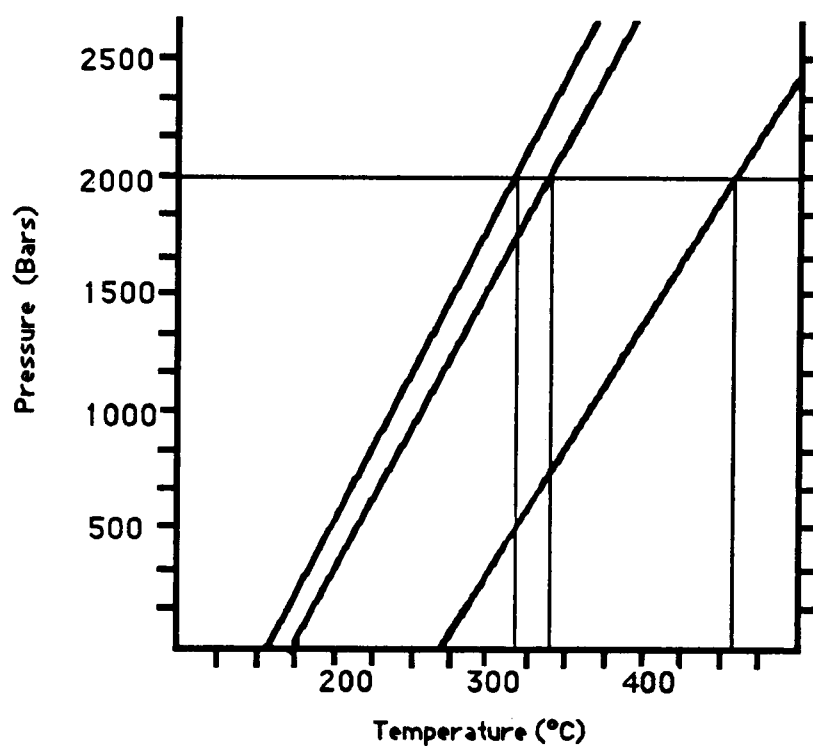


Fig. 24. Examples of isochores determined from fluid inclusion data in the wollastonite zone samples. The fluid inclusions are secondary and occur in feldspar and vesuvianite grains.

moderate to high salinities ranging from 5 to 28 equivalent weight percent NaCl. Daughter crystals were determining trapping temperatures yielded the similar not observed in any of the samples. Salinity values in the granite samples clustered around 5 to 10 equivalent weight percent NaCl while those from the skarn samples clustered around the slightly higher values of 10 to 15 equivalent weight percent NaCl. Salinity values in the wollastonite zone samples clustered around 5 to 15 equivalent weight percent NaCl. Values for eutectic temperatures usually ranged between -20°C and -38°C . Homogenization temperatures of 130° to 210°C were typical for the granite samples, 130° to 270°C for the skarns, and 115° to 280°C in the wollastonite-zone rocks. Homogenization temperatures clustered around 140° to 160°C for all of the samples. Isochores constructed using Nicholls and Crawford's (1985) HALWAT indicate trapping temperatures in the range of 300° to 400°C for the granites, 250° to 475° for the wollastonite-zone samples and 250° to 430°C for the skarns.

Inclusions found in the metamorphic minerals were clearly associated with mineralization (e.g., secondary planes of inclusions can be seen originating and terminating within individual garnets in the skarns). The fluids in these inclusions were found to be similar

in composition to other inclusions which were studied. Despite these facts, a comparison of trapping temperatures calculated for the inclusions with temperatures from mineral equilibria has revealed that the fluids in the inclusions are not representative of those from the peak of metamorphism. This eliminated the possibility of studying the evolution of the fluid composition through time. Isochores, constructed from data on a large number of inclusions indicate trapping temperatures of 250° to 475° C, while peak temperatures, constrained by the assemblage vesuvianite + diopside + grossular in the skarns have been estimated to be 400° C to 500° C (discussed in chap. 2, see Figure 10, page 35).

Summary diagrams for each of the sample types are shown in Figures 25, 26 and 27. These diagrams show homogenization temperature versus melting temperature for each of the inclusions studied. The distribution of data points for the granite samples (Figure 25) reveals that the inclusions have a wide range of salinity and homogenization temperatures. The distribution of the data in the granite samples is similar to that of the skarn samples (Figure 26), and to that of the wollastonite zone samples (Figure 27).

The wide range of homogenization temperatures for inclusions is consistent with ranges of data reported by

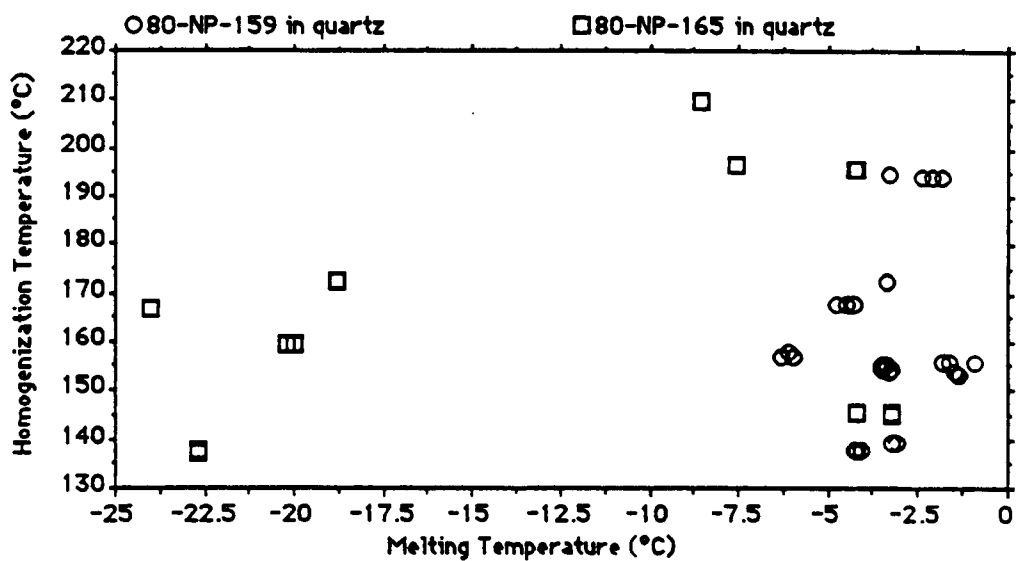


Fig. 25. T_h versus T_m diagram for the granite samples. Fluid inclusions are secondary and occur in quartz grains. The symbols are defined in the figure.

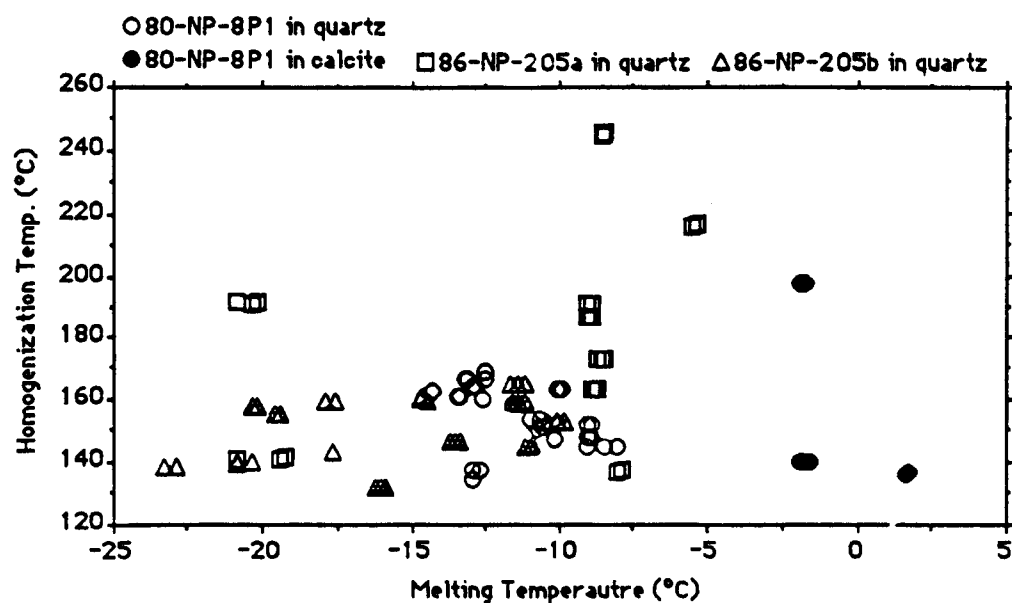


Fig. 26. T_h versus T_m diagram for the skarn samples. Fluid inclusions are secondary and occur in quartz and calcite grains. The symbols are defined in the figure.

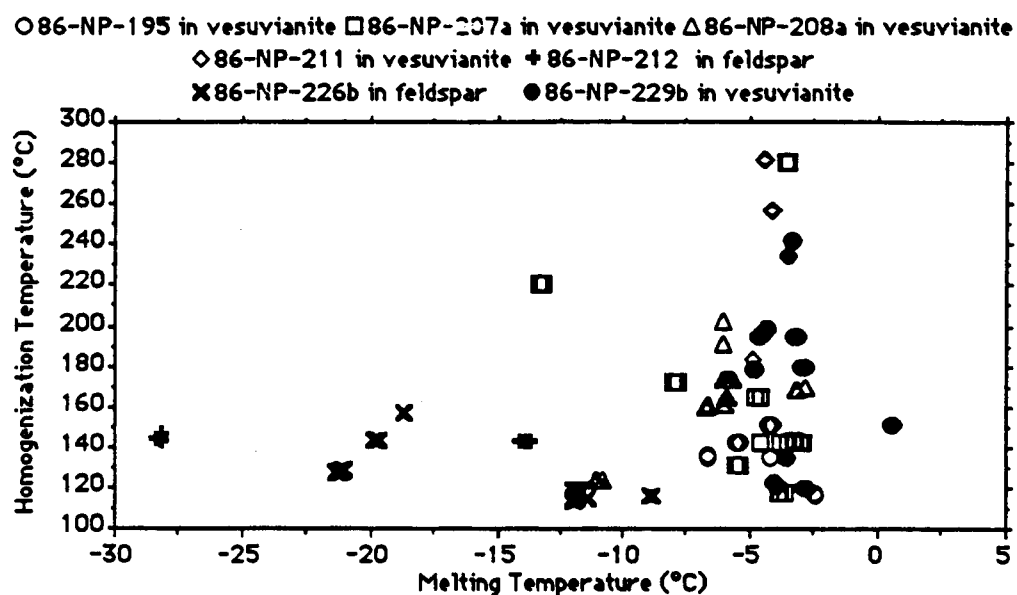


Fig. 27. T_h versus T_m diagram for the wollastonite zone samples. Fluid inclusions are secondary and occur in feldspar and vesuvianite grains. The symbols are defined in the figure.

Harris and Einaudi (1982) and in most of the porphyry copper studies listed by Roedder (1984). The wide range of trapping temperatures probably reflects the capture of inclusions over a long period of time. During this period of time, the temperature of metamorphism can be expected to have slowly decreased due to cooling of the pluton.

The study by Harris and Einaudi (1982) and the reports listed by Roedder (1984) reveal that a narrow range in salinities is typical of porphyry copper deposits. For the wollastonite-zone samples, if the data from the inclusions present in feldspar grains is removed, then the range of salinities is relatively narrow (between 5 and 10 equivalent weight percent NaCl), however; all of the sample groups show a wide spread in salinities. There are several possible reasons for the distribution of salinities. The first, and most likely of these, is a direct result of interaction of the metamorphic fluid with the rocks. This model suggests that the change in salinity may be due to a direct molar exchange of sodium from the fluid with potassium or calcium from the rocks. Figure 28 shows the NaCl-CaCl₂-H₂O ternary. Given point 'a' or 'b' as the initial fluid composition, line 'ab' on this diagram represents a line along which any fluid composition resulting from a direct molar cation

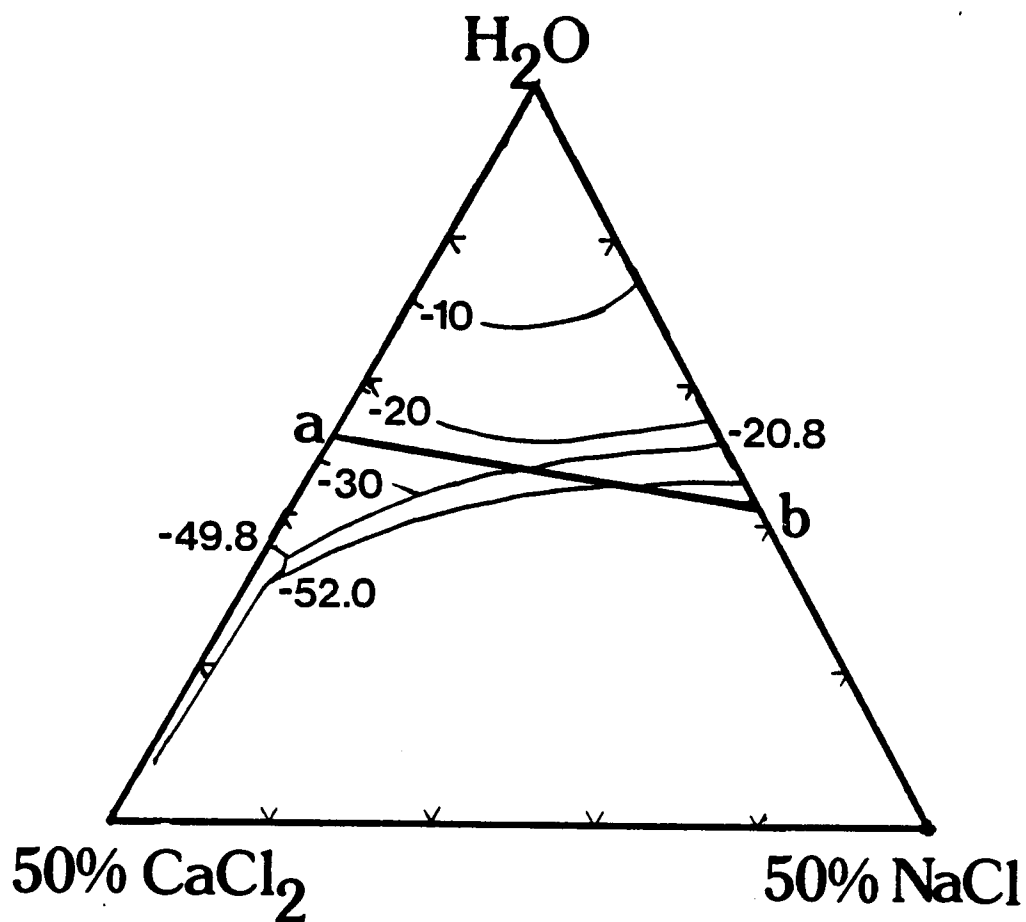


Fig. 28. Top half of the NaCl-CaCl₂-H₂O ternary. Eutectic temperatures for the NaCl-H₂O, CaCl₂-H₂O and the NaCl-CaCl₂-H₂O systems are indicated. The diagram is contoured for temperature. Line 'ab' represents a line along which molar cation exchange occurs. Modified after Hollister and Crawford (1981).

exchange would plot. As is apparent from this diagram, for a fluid of a composition falling on the line 'ab' (but not at point 'b'), the NaCl equivalent salinity would appear to be higher than it actually is. Since this is true, then a molar cation exchange occurring between the fluid and rocks involved in metamorphism could change the melting temperature of the fluid in fluid inclusions without actually changing the salinity of the fluid. In the second model, the increase in the salinity of the fluids would be caused by fluid "boiling" (as discussed by Trommsdorff and Skippen, 1986). This suggestion has been rejected for reasons that will be discussed later. The third model suggests that mixing of the metamorphic fluids with more saline connate fluids occurred. This model can be rejected on two grounds. First, isotope data suggests that fluid mixing did not occur (Labotka and Nabelek, 1987). Second, as will also be discussed later, the rocks at Notch Peak are believed to have equilibrated with a body of fluid that would have been large enough to cause the effects of fluid mixing to have been minimal. The fourth and final model suggests that a late pulse of more saline fluid was involved in the formation of the skarns. Unfortunately, this model cannot be tested without further knowledge of the history of the fluid.

The presence of an H₂O-NaCl-rich fluid in the higher-grade rocks is supported by the presence of scapolite which indicates moderately saline solutions (Labotka and Nabelek, 1986). Fluid inclusion data yielding salinity values as high as 27 to 28 equivalent weight percent NaCl confirm this. At salinity values greater than that of the eutectic of the H₂O-NaCl the presence of daughter crystals in the inclusions is expected. Since the eutectic of the H₂O-NaCl system is at 23.3 weight percent NaCl (Roedder, 1984), salinity values of 27 to 28 weight percent NaCl should result in the occurrence of daughter crystals in the inclusions; however, none were observed. This indicates that the salts percent in the fluids that passed through these rocks contained NaCl and/or other salts. This also agrees with the suggestion that apparent enrichment of salinities occurred due to a molar exchange between sodium in the fluids and potassium or calcium in the rocks.

Hendel and Hollister (1982) have determined the solvus for H₂O-CO₂ solutions that contain small amounts of NaCl. They state that the solvus is raised by as much as 70° C by 2.6 weight percent NaCl. Because of this they conclude that at salinities typical of metamorphic fluids (30 to 40 equivalent weight percent NaCl), the H₂O-CO₂ solvus may be raised to temperatures

typical of greenschist or even amphibolite facies. At Notch Peak, salinity values were as high as 28 equivalent weight percent NaCl. Under these conditions it is likely that H₂O present in the fluids evolved from the Notch Peak Stock, and CO₂ liberated by devolatilization reactions in the metamorphic rocks was immiscible at temperatures much higher than that at which the fluid inclusions were filled.

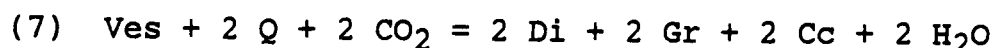
Selective removal of the lower density (i. e. CO₂-rich) fluid after immiscibility occurred has been suggested as a method of concentrating salts in a water-rich fluid. This phenomenon has been referred to as fluid phase separation or "boiling". If the fluids accompanying the intrusion became immiscible (i. e. they "boiled") before the inclusions were filled, it is to be expected that two types of inclusions would be found: 1) an H₂O-NaCl-rich group, and 2) a CO₂-rich group. The densities for the H₂O-NaCl-rich fluid have been calculated by Nicholls and Crawford's (1985) HALWAT. These densities are in the range of 0.80 to 1.15 grams per cubic centimeter. Comparison of these values with isochores for the CO₂ system as generated by Swanenberg (1979) have shown that the conditions necessary for fluid phase separation probably were present at the peak of metamorphism at Notch Peak; however, due to the lack of a CO₂-rich group of inclusions, as well as a lack of

other evidence, fluid boiling probably did not occur and hence was cannot be used as a mechanism for enrichment of salinities in the metamorphic fluid.

The breakdown of diopside, wollastonite (Wo), and grossular (Gr) to form vesuvianite (Ves) is discussed by Valley et al. (1985). The reaction:



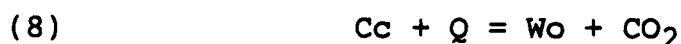
occurs at about 400° C and $X_{\text{CO}_2} < 0.025$. This agrees with low CO_2 values from the fluid inclusion data. This reaction results in the assemblages seen in the highest grade metamorphic rocks present at Notch Peak. Olesch (1979) has described the reaction:



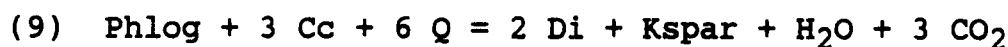
This assemblage is seen in the skarns at Notch Peak where the vesuvianite has broken down to form large amounts of grossular garnet and diopside. The presence of calcite and quartz in the skarns along the margin of the Notch Peak stock suggests that the skarns may have formed at a slightly lower $P_{\text{H}_2\text{O}}$ than in the wollastonite-zone rocks. The fact that these two reactions occur at very low X_{CO_2} is confirmed by Labotka et al. (1984) who claim that the presence of vesuvianite suggests an $X_{\text{CO}_2} \leq 0.05$. Hochella et al. (1982) also claim that vesuvianite is unstable in The presence of CO_2 , however, they list $X_{\text{CO}_2} \leq 0.015$ as its stability region. As can be seen, the mineral equilibria is in

agreement with the fluid inclusion data in suggesting that an H₂O-rich fluid was involved in metamorphism.

Inclusions studied from the Notch Peak granite have revealed that CO₂ was probably not present in the fluids released from the stock. In any event, the lack of CO₂-rich inclusions is somewhat surprising because the carbonates surrounding the Notch Peak Stock have undergone extensive decarbonation. Labotka and Nabelek (1986) have calculated a 23% loss by weight of CO₂ during metamorphism. Other authors have shown that the formation of metamorphic minerals by decarbonation may result in the evolution of considerable amounts of CO₂. For example, in controlled experiments Jacobs and Kerrick (1981) found that the reaction:



released enough CO₂ to change the fluid composition of a closed system from $X_{\text{CO}_2} = 0.500 \pm 0.01$ to $X_{\text{CO}_2} = 0.885 \pm 0.01$ at 880° C and 6 Kbar. At temperatures and pressures closer to the peak conditions of metamorphism at Notch Peak, values on the order of 60% X_{CO_2} would still be produced. As is apparent, this reaction, as well as diopside forming reaction:



(and the other reactions discussed in Chapter 2) produce a considerable amount of CO₂. Considering this, one would expect to see CO₂-bearing inclusions in the rocks,

however, evidence from fluid inclusion data and mineral equilibria have revealed that this is not the case.

The low CO_2 values in fluid inclusions from Notch Peak probably is a result in an H_2O -rich fluid being exsolved from the Notch Peak stock upon its crystallization. The lack of CO_2 -rich inclusions, even though significant decarbonation has occurred suggests that the amount of H_2O expelled by the granite was so great that the CO_2 liberated by the wollastonite, diopside, and other decarbonation reactions was diluted to amounts that are so low that they cannot be seen. Nabelek et al. (1983, 1986) have stated that upon crystallization, the intrusion exsolved tremendous amounts of water so that the rocks of the Weeks Formation may have seen as much as 9 rock volumes of water during metamorphism, possibly more (Labotka and Nabelek, 1986). Labotka and Nabelek (1986) have also postulated that this was the reason that most of the rocks have undergone extensive decarbonation. Continuous addition of water to the system would drive decarbonation reactions to maintain equilibrium. Labotka and Nabelek (1986) have shown that in this way the wollastonite-zone rocks may have lost as much as 23 weight percent CO_2 .

The presence of a large salient in the isograds in the Weeks Limestone (see Figure 1, page 2) probably

reflects a channel through which the convecting fluids escaped. The channel is a fault which exists in the area, its location is shown in Figure 1 (page 2). This channel may be the reason why so much fluid passed through the rocks. As discussed above, the low CO₂ content in fluid inclusions also supports this conclusion. The presence of a fluid conduit implies that the Notch Peak stock was intruded into relatively impermeable rocks. If the Weeks Limestone was relatively permeable then a large portion of the fluids would flow out through it. The large amount of water pumped through the system could conceivably have diluted the amount of CO₂ in the fluids and hence in the fluid inclusions to very low concentrations. This conclusion is somewhat different from that of Hover-Granath et al. (1983), in which the argillaceous units of the Big Horse Limestone acted as metamorphic aquifers for the magmatic fluids during metamorphism because the limestones were relatively, impermeable to fluid flow.

CHAPTER 4

CONCLUSIONS

Fluid inclusions in quartz, feldspar and vesuvianite grains from rocks of the Weeks Limestone at Notch Peak, Utah have revealed the presence of an H₂O-rich fluid. Inclusions from three types of rocks were studied. The rock types examined are: 1) the Notch Peak granite, 2) skarns found adjacent to the granite, and 3) the wollastonite-zone rocks. Inclusions in granites from the Notch Peak stock have melting temperatures of 0° to -20° C giving salinity values of 5 to 25 equivalent weight percent NaCl. Homogenization temperatures of 170°±40° C imply filling temperatures of 300°±100° C. Melting temperatures from skarn samples are -10°±10° C yielding values for salinity of 8 to 25 equivalent weight percent NaCl. Homogenization temperatures of 140° to 270° C give filling temperatures of 200° to 350° C. In the wollastonite-zone rocks, inclusion melting temperatures ranged from -2.5° to -28° C, yielding salinities of 5 to 28 equivalent weight percent NaCl. The homogenization temperatures were 115° to 280° C giving filling temperatures of 250° to 475° C. In all cases fluid inclusion data indicate low X_{CO2}.

Comparison of filling temperatures from fluid inclusions with indications of peak temperatures from

mineral equilibria indicate that the fluids contained in the fluid inclusions are not representative of those from the peak of metamorphism (this study). Isochores indicate filling temperatures for the inclusions of 250° to 475°, while temperatures, constrained by the assemblage vesuvianite + wollastonite + diopside + K-feldspar at high grades are estimated to be 400° to 500° C. The presence of salinities that are higher than that of the H₂O-NaCl eutectic and the lack of daughter crystals in the inclusions implies that the salts present in the fluids that passed through these rocks must have contained salts other than NaCl (this study).

Mass-balance calculations reveal that high grade rocks may have lost 23% by weight CO₂ due to decarbonation reactions during metamorphism (Labotka and Nabelek, 1986). Despite this, CO₂-rich inclusions are lacking, and the mineral equilibria indicate conditions of low X_{CO2} during metamorphism. Evidence for "boiling" of fluids at the time of trapping of the inclusions is not present (this study). This implies that CO₂ was diluted by an H₂O rich fluid exsolved by the Notch Peak stock during crystallization. The presence of a large salient in the isograds indicates that the Weeks Limestone may have acted as a conduit for fluid flow due to the relative impermeability of the other limestone units surrounding the Notch Peak Stock. Because of this

the rocks of the Weeks Limestone may have seen as much as 22.5 ± 9 rock volumes of fluid during metamorphism.

The reactions leading up to the higher grade assemblages have been determined and described. The initial affect of metamorphism was the replacement of dolomite and muscovite by phlogopite and chlorite at the phlogopite isograd. This was followed by the reaction of muscovite and chlorite to form anorthite and phlogopite. At higher grades diopside and K-feldspar were formed when phlogopite broke down at the diopside isograd. In areas where X_{CO_2} was slightly higher than the norm, tremolite and feldspar were formed by the break down of phlogopite and also of chlorite. Diopside was formed in these areas by the breakdown of tremolite.

Reactions in the diopside and wollastonite zones occur over much wider geographic areas than those in the lower grade rocks. The wollastonite isograd seems to mark the limit of massive infiltration of hydrothermal fluids (see Tracy et al., 1983). As a result, it is inferred that fluid buffering would have been of more importance where the rocks equilibrated with a smaller fluid reservoir (i.e. the lower grade rocks) than in the diopside and wollastonite zones. This implies that the fluid generated by the rocks was more important in controlling the fluid compositions in the low grade rocks than in the high grade rocks.

Reaction relations are significantly affected by the presence of fluids. The amount and composition of the fluids is also of importance. In fluid dominated rock-fluid environments such as those present in the wollastonite- and diopside-zones at Notch Peak, externally derived fluids may be important in the control of fluid compositions. In rock dominated systems similar to those in the lower grade rocks at Notch Peak, fluid compositions may be controlled by the fluid released from the rocks. This factor alone may significantly affect the development and relative positioning of isograds. For these reasons it is important to know the fluid-rock relations in any study of metamorphic rocks.

LIST OF REFERENCES

LIST OF REFERENCES

- Berry, L. G. (ed). (1974) Selected Powder Diffraction Data for Minerals. The Joint Committee on Powder Diffraction Standards: Swarthmore, Penn., 833p.
- Bethune, S. de. (1976) Formation of Metamorphic Biotite by Decarbonation. *Lithos* 9, 309-318.
- Bowers, T. S. and H. C. Helgeson. (1983a) Calculation of the Thermodynamic and Geochemical Consequences of Nonideal Mixing in the System H_2O-CO_2-NaCl on Phase Relations in Geologic Systems: Equation of State for H_2O-CO_2-NaCl Fluids at High Pressures and Temperatures. *Geochimica et Cosmochimica Acta* 47, 1247-1275.
- Bowers, T. S. and H. C. Helgeson. (1983) Calculation of the Thermodynamic and Geochemical Consequences of Nonideal Mixing in the System H_2O-CO_2-NaCl on Phase Relations in Geologic Systems: Metamorphic Equilibria at High Pressures and Temperatures. *American Mineralogist* 68, 1059-1075.
- Brown, P. E. and W. M. Lamb. (1986) Mixing of H_2O-CO_2 in Fluid Inclusions; Geobarometry and Archean Gold Deposits. *Geochimica et Cosmochimica Acta* 50, 841-852.
- Collins, P. L. F. (1979) Gas Hydrates in CO_2 -Bearing Fluid Inclusions and the Use of Freezing Data for Estimation of Salinity. *Economic Geology* 74, 1435-1444.
- Crawford, M. L. and L. S. Hollister. (1986) Metamorphic Fluids: the Evidence from Fluid Inclusions. in J. V. Walther and B. J. Wood (eds) *Fluid - Rock Interactions During Metamorphism*. (New York, Springer - Verlag) *Advances in Physical Geochemistry*, Vol. 5, 1-35.
- Crawford, M. L., D. W. Kraus and L. S. Hollister. (1979) Petrologic and Fluid Inclusion Study of Calc-Silicate Rocks, Prince Rupert, British Columbia. *American Journal of Science* 9, 1135-1159.
- Feldman, M. D. and J. J. Papike. (1981) Metamorphic Fluid Compositions from the Notch Peak Aureole, Utah. abstract EOS [transactions of the American Geophysical Union] 62, #17, 435.

- Ferry, J. M. (1976a) Metamorphism of Calcareous sediments in the Waterville-Vassalboro Area, South Central Maine: Mineral Reactions and Graphical Analysis. American Journal of Science 276, 841-882.
- Ferry, J. M. (1976b) P, T, f_{CO_2} , f_{H_2O} during metamorphism of calcareous sediments in the Waterville-Vassalboro area, South Central Maine. Contributions to Mineralogy and Petrology 57, 119-143.
- Ferry, J. M. (1978) Fluid Interaction Between Granite and Sediment During Metamorphism, South Central Maine. American Journal of Science 278, 1025-1056.
- Ferry, J. M. (1984) A Biotite Isograd in South Central Maine, U. S. A.: Mineral Reactions, Fluid Transfer, and Heat Transfer. Journal of Petrology 25, 871-893.
- Flowers, G. C. and H. C. Helgeson. (1983) Equilibrium and mass Transfer During Metamorphism of Siliceous Dolomites. American Journal of Science 283, 230-286.
- Geheman, H. M. (1958) Notch Peak Intrusive, Millard Co., Utah, Geology, Petrogenesis and Economic Deposits. Utah Geologic and Mineralogic Survey Bulletin 62, 1-50.
- Hanks, K. L. (1962) Geology of the Central House Range, Millard Co., Utah. BYU Geology Studies 9, pt. 2, 115-136.
- Harris, N. B. and M. T. Einaudi. (1982) Skarn Deposits in the Yerrington District, Nevada: Metasomatic Skarn Evolution near Ludwig. Economic Geology 77, 877-898.
- Hendel, E. M. and L. S. Hollister. (1981) An Empirical Solvus for CO_2 - H_2O -2.6 wt.% Salt. Geochimica et Cosmochimica Acta 45, 225-228.
- Hewitt, D. A. (1975) Stability of Phlogopite-Calcite-Quartz. American Mineralogist 60, 391-397.
- Hintze, Lehi F. (1974) Preliminary Map of the Notch Peak Quadrangle, Millard Co., Utah. USGS Misc. Field Studies Map MF-636.
- Hintze, L. F. and A. R. Palmer. (1976) Upper Cambrian Orr Formation. It's Subdivisions and Correlatives in Western Utah. USGS Bulletin 1405-G, 1-25.

- Hintze, Lehi F. and Robison, Richard A. (1975) Middle Cambrian Stratigraphy of the House, Wah Wah and Adjacent Ranges in Western Utah. GSA Bull 86, 881-891.
- Hochella, M. F., Jr., J. G. Liou, M. J. Keskinen, and H. S. Kim. (1982) Synthesis and Stability Relations of Magnesium Idocrase. Economic Geology 77, 798-808.
- Hollister, L. S. and M. L. Crawford (eds). (1981) Fluid Inclusions: Applications to Petrology. (Calgary, Mineralogical Association of Canada) Short Course Handbook, Vol. 6, 305p.
- Hover, V. C. (1981) The Notch Peak Metamorphic Aureole, Utah; Mineralogy, Petrology and Geochemistry of the Big Horse Canyon Member of the Orr Formation. MS Thesis, State University of New York at Stony Brook.
- Hover, V. C., J. J. Papike, P. I. Nabelek and J. C. Laul. (1981) The Notch Peak Contact Metamorphic Aureole, Utah. abstract EOS [transactions of the American Geophysical Union] 62, #17, 434-435.
- Hover-Granath, V. C., J. J. Papike and T. C. Labotka. (1983) The Notch Peak Contact Metamorphic Aureole, Utah: Petrology of the Big Horse Limestone Member of the Orr Formation. GSA Bull 94, 889-906.
- Jacobs, G. K. and D. M. Kerrick. (1981) Devolatilization equilibria in H_2O-CO_2 and H_2O-CO_2-NaCl Fluids: an Experimental and Thermodynamic Evaluation at Elevated Pressures and Temperatures. American Mineralogist 66, 1135-1153.
- Kerrick, D. M., K. E. Crawford and A. F. Randazzo. (1973) Metamorphism of Calcareous Rocks in Three Roof Pendants in the Sierra-Nevada, California. Journal of Petrology 14, 303-325.
- Labotka, T.C. and P. I. Nabelek. (1987) The Water/Rock Ratio and Fluid Infiltration in the Contact-Metamorphic Aureole of the Notch Peak Stock, Utah. Abstract to talk given at AGU west, San Francisco, Dec. 1987.
- Labotka, T. C. and P. I. Nabelek. (1987) Isotopic Exchange and the Fluid/Rock Ratio in Contact - Metamorphosed Calc-Argillites from Notch Peak, Utah. GSA abstracts with programs 99, 741.

- Labotka, Theodore C. and Peter I. Nabelek. (1986)
Petrology of the Contact Metamorphosed Weeks
Formation Notch Peak, Utah. abstract, International
Mineralogical Association, Stanford Ca., July, 1986.
- Nabelek, P. I., J. J. Papike and J. C. Laul. (1986) The
Notch Peak Granitic Stock, Utah: Origin of Reverse
Zoning and Petrogenesis. Journal of Petrology 27,
1035-1069.
- Nabelek, P. I., T. C. Labotka and M. G. Glascock. (1986)
Chemical Changes During Contact Metamorphism of the
Weeks Formation at the Notch Peak Complex, Utah.
abstract, International Mineralogical Association,
Stanford, Ca., July 1986.
- Nabelek, P. I., T. C. Labotka, J. R. O'Neill and J. J.
Papike. (1984) Contrasting Fluid/Rock Interaction
Between the Notch Peak Granitic Intrusion and
Argillites and Limestones in Western Utah: Evidence
from Stable Isotopes and Phase Assemblages.
Contributions to Mineralogy and Petrology 86, 25-34.
- Nabelek, P. I., J. R. O'Neill and J. J. Papike. (1983)
Vapor Phase Exsolution as a Controlling Factor in H
Isotope Variation in Granitic Rocks in the Notch
Peak Granitic Stock, Utah. Earth Planetary Sciences
Letters 66, 137-150.
- Nabelek, P. I., J. J. Papike, C. White and J. C. Laul.
(1981) The Geochemical Evolution of the Notch Peak
Granitic Stock. abstract EOS [transactions of the
American Geophysical Union] 62, #17, 435.
- Nicholls, J. and M. L. Crawford. (1985) FORTRAN Programs
for Calculation of Fluid Properties from
Microthermometric Data of Fluid Inclusions.
Computers and Geosciences 11, 619-645.
- Olesch, M. (1978) Obere Thermische Stabilität von
Vesuvian (Idocras) bis 2 Kbar und Vesuvian + Quartz
bis 5 Kbar im system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$. (abs)
Fortschritte Der Mineralogie 56, b. 1, 99.
- Potter, R. W. (1977) Pressure Corrections for Fluid -
Inclusion Homogenization Temperatures Based on the
Volumetric Properties of the System $\text{NaCl-H}_2\text{O}$.
Journal of Research, U. S. Geological Survey 5,
603-607.

- Powell, D. K. (1959) Geology of the Southern House Range, Millard Co., Utah. BYU Research Studies, Geology Series, 6, #1, 49p.
- Ribbe, P. H., ed. (1983) Feldspar Mineralogy. (Washington D. C., Mineralogical Society of America) Reviews in Mineralogy, Vol. 2, 360p.
- Rice, J. M. (1977) Progressive Metamorphism of Impure Dolomitic Limestone in the Marysville Aureole, Montana. American Journal of Science 277, 1-24.
- Roedder, E. (1984) Fluid Inclusions. (Washington D. C., Mineralogical Society of America) Reviews in Mineralogy, Vol. 12, 644p.
- Sisson, V. B., M. L. Crawford and P. H. Thompson. (1981) CO₂-Brine Immiscibility at High Temperatures, Evidence from Calcareous Metasedimentary Rocks. Contributions to Mineralogy and Petrology 78, 371-378.
- Sourirajan, S. and G. C. Kennedy. (1962) The System H₂O-NaCl at Elevated Temperatures and Pressures. American Journal of Science 200, 115-141.
- Swanenberg, H. E. C. (1979) Phase Equilibria in Carbonic Systems, and Their Application to Freezing Studies of Fluid Inclusions. Contributions to Mineralogy and Petrology 68, 303-306.
- Touret, J. (1977) The Significance of Fluid Inclusions in Metamorphic Rocks. in D. G. Fraser (ed) Thermodynamics in Geology, 203-227.
- Tracy, R. J., D. M. Rye, D. A. Hewitt and C. M. Schiffries. (1983) Petrologic and Stable-Isotope Studies of Fluid-Rock Interactions, South-Central Connecticut: I. The Role of Infiltration in Producing Metamorphic Reaction Assemblages in Impure Marbles. American Journal of Science 283-A, 589-616.
- Trommsdorff, V. and G. Skippen. (1986) Vapour loss ("Boiling") as a Mechanism for Fluid Evolution in Metamorphic Rocks. Contributions to Mineralogy and Petrology 94, 317-322.
- Valley, J. W. and E. J. Essene. (1980) Calc-Silicate Reactions in Adirondack Marbles: The Role of Fluids and Solid Solutions: Summary. Geological Society of America Bulletin 91, 114-117.

- Valley, J. W., D. R. Peacor, J. R. Bowman, E. J. Essene and M. J. Allard. (1985) Crystal Chemistry of a Mg-Vesuvianite and implications of phase equilibria in the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O-CO}_2$. Journal of Metamorphic Petrology 3, 137-153.
- Walker, J. R. (1986) Compositional Trends in Chlorite from Low - Grade Metamorphic Rocks in Northern Maine. Abstracts with Programs, 1986, Geological Society of America 99, 780.
- Walther, J. V. and B. J. Wood. (1986) Fluid - Rock Interactions during Metamorphism. Advances in Physical Geochemistry, Vol. 5 (New York, Springer-Verlag) 224p.
- Wheeler, H. E. and Grant Steels. (1951) Cambrian Sequence of the House Range, Utah. Intermountain Association of Petroleum Geologists Guide Book 6, 29-39.

APPENDICES

Appendix 1: Mineral Assemblages as Determined from
X-ray Diffraction

<u>SAMPLE #</u>	<u>ASSEMBLAGE</u>
86-NP-253	CC+Q+DO+MUSC+CHL+PLAG
86-NP-254	CC+Q+DO+MUSC+KSP
86-NP-255	CC+Q+MUSC+CHL+PLAG
86-NP-256	CC+Q+PHLOG+MUSC+CHL+PLAG
86-NP-257	CC+Q+PHLOG+MUSC+CHL+PLAG
86-NP-258	CC+Q+PHLOG+MUSC+CHL+PLAG
86-NP-259	CC+Q+CHL+OR+PLAG
86-NP-260	CC+Q+CHL
86-NP-261	CC+Q+DO+MUSC
86-NP-262	CC+Q+PHLOG+MUSC+CHL+KSP+PLAG
86-NP-263	CC+Q+PHLOG+PLAG
86-NP-264	CC+Q+PHLOG+CHL+PLAG
86-NP-265	CC+Q+CHL
86-NP-266	CC+Q+CHL
86-NP-267	CC+Q+PHLOG+CHL+PLAG
86-NP-284	CC+Q+DO+TREM+KSP+PLAG
86-NP-285	CC+Q+PHLOG+CHL+TREM+KSP+PLAG
86-NP-286	CC+Q+PHLOG+CHL+KSP+PLAG
86-NP-287	CC+Q+PHLOG+CHL+TREM+PLAG
86-NP-288	CC+Q+PHLOG+PLAG
86-NP-289	CC+Q+CHL+PLAG
86-NP-290	CC+Q+PHLOG+CHL+KSP+PLAG
86-NP-294	CC+Q+KSP
86-NP-295	CC+Q+DO+CHL+KSP+PLAG
86-NP-298	CC+Q+DO+MUSC
86-NP-299	CC+Q+DO+MUSC+CHL+PLAG
86-NP-300	CC+Q+DO+MUSC+CHL
86-NP-301	CC+Q+MUSC+TREM+KSP+PLAG
86-NP-302	CC+Q+PHLOG+PLAG
86-NP-303	CC+Q+PHLOG+PLAG
86-NP-304a	CC+Q+PHLOG+CHL+PLAG
86-NP-304b	CC+Q+PHLOG+CHL+PLAG
86-NP-305	CC+Q+PHLOG+CHL+PLAG
86-NP-306	CC+Q+CHL+PLAG
86-NP-307a	CC+Q+PHLOG+CHL+TREM+KSP+PLAG
86-NP-307b	CC+Q+PHLOG+CHL+TREM+PLAG
86-NP-308	CC+Q+TREM+KSP+PLAG
86-NP-309	CC+Q+DO+MUSC+CHL
86-NP-310	CC+Q+DO+MUSC+CHL+PLAG
86-NP-311a	CC+Q
86-NP-311b	CC+Q+MUSC
86-NP-312a	CC+Q+DO+MUSC+CHL
86-NP-312b	CC+Q+DO+CHL
86-NP-312c	CC+Q+DO+MUSC+CHL
86-NP-312d	CC+Q+DO+MUSC

Appendix 2: Fluid Inclusion Data

The following list contains the notations that are used in this appendix.

- T_m Melting temperature of fluid inclusion.
- T_h Homogenization temperature of fluid inclusion.
- T_e Eutectic temperature of fluid inclusion, determined or approximated when possible.
- a Fluid inclusions from granite and skarn samples are secondary and from quartz grains.
- b The numbers in parenthesis represent 1s standard deviations for three replicate analyses in terms of the last digit cited for the value to their immediate left, thus -4.3(0) indicates a standard deviation of 0.1.
- c Total number of inclusions analyzed for the sample.
- d Fluid inclusions from this sample are secondary and found in vesuvianite unless indicated otherwise.
- e Fluid inclusions from this sample are secondary and found in feldspar unless indicated otherwise.
- f Fluid inclusion data are from diopside, they are secondary in occurrence.
- g Salinities measured in equivalent weight percent NaCl. Values were calculated using Nicholls and Crawford's (1985) program HALWAT.
- h Salinities were not calculated for inclusions that had a melting temperature above 0 °C or decrepitated before freezing runs were performed.
- * Inclusion decrepitated or leaked before replicate analyses were performed.

=====

Fluid inclusion data

sample type & number	T_m	T_h	T_e	salinity _g
Granite samples ^a				
80-NP-159-1	-3.4(0) ^b	172.3(0)	-6.6	5.55
n = 37 ^c	-4.5(3)	167.8(0)		7.15
	-4.8(3)	167.8(0)		7.57
	-4.3(3)	167.8(0)		6.89
	-0.9(5)	155.9(0)		1.55
	-1.6(5)	155.9(0)		2.72
	-3.4(0)	172.3(0)		5.55
	-1.8(5)	155.9(0)		3.05
	-3.3(0)	194.6(1)		5.40
	-3.3(0)	194.7(1)		5.40
	-2.1(3)	194.3(1)	-7.8	3.53
	-3.4(0)	172.3(0)		5.55
	-1.8(3)	194.2(1)		3.05
	-2.4(3)	194.2(1)		4.01

-3.1(1)	139.5(1)		5.09
-3.2(1)	139.5(1)		5.25
*	139.4(1)		h
-3.3(0)	194.7(1)		5.40
*	147.0(*)		h
*	167.6(*)		h
-3.4(1)	155.1(0)		5.55
-3.5(1)	155.1(0)		5.70
-3.3(2)	154.0(1)	-20	5.40
-3.2(2)	154.2(1)		5.25
-3.5(2)	154.1(1)		5.70
*	162.3(*)	-6.6	h
-1.4(1)	153.5(1)		2.40
-6.3(2)	156.9(1)		9.60
-1.5(1)	153.6(1)		2.56
-1.3(1)	153.4(1)		2.23
-6.0(2)	157.1(1)		9.21
-4.3(1)	138.0(1)		6.87
-6.1(2)	158.0(1)		9.34
*	133.9(9)		h
*	135.1(9)		h
-4.2(1)	137.8(1)		6.72
-4.1(1)	137.9(1)		6.58

80-NP-165-2
n = 27

-24.0(0)	166.5(0)		25.35
-18.8(0)	172.3(2)		21.79
-20.2(1)	159.7(0)		22.80
-24.0(0)	166.5(0)		25.35
-22.7(0)	137.3(2)		24.50
-24.0(0)	166.5(0)		25.35
-18.8(0)	172.3(2)		21.79
-20.0(1)	159.7(0)		22.66
-22.7(0)	137.6(2)		24.50
-20.2(1)	159.7(0)		22.80
-22.7(0)	137.6(2)		24.50
-18.8(0)	172.5(2)		21.79
-8.6(0)	209.9(2)		12.42
-7.6(0)	196.7(1)		11.23
-8.6(0)	209.6(2)		12.42
-7.2(1)	*		10.74
-8.6(0)	209.7(2)		12.42
-7.6(0)	196.6(1)		11.23
-4.2(1)	195.9(0)		6.72
-7.6(0)	196.6(1)		11.23
-7.2(1)	*		10.74
-7.3(1)	*		10.86
-3.2(0)	145.4(1)		5.25
-4.2(1)	145.4(1)		6.72
-3.2(0)	145.2(1)		5.25
-4.2(1)	195.9(0)		6.72
-4.3(1)	195.9(0)		6.87

Skarn samples^a

80-NP-8P1

n = 61

-14.3(0)	162.7(1)	-20.8	18.18
-9.1(1)	152.4(1)		12.99
-8.9(1)	148.2(2)		12.76
-9.0(1)	148.3(2)	-20.8	12.88
-14.3(0)	162.5(1)		18.18
-14.3(0)	162.6(1)		18.18
-9.1(1)	148.5(2)		12.99
-8.9(1)	152.4(1)	-20.8	12.76
-8.9(1)	152.3(1)		12.76
-10.6(1)	151.2(2)		14.62
-10.8(1)	150.9(2)		14.83
-10.6(1)	151.1(2)		14.62
1.6(1)	136.3(4)		h
-10.2(0)	147.1(1)		14.20
1.6(1)	135.8(4)		h
-14.1(0)	*		18.00
1.7(1)	136.5(4)		h
-14.1(0)	*		18.00
-14.1(0)	*	-20.8	18.00
-13.4(*)	*		17.37
-1.9(2)	140.0(1)		3.21
-1.6(2)	139.8(1)		2.72
-1.8(2)	139.9(1)		3.05
-1.7(1)	197.6(1)		2.89
-10.2(0)	147.2(1)		14.20
-1.9(1)	197.4(1)		3.21
-10.2(0)	147.2(1)	<-30	14.20
-1.7(1)	197.6(1)		2.89
-8.1(5)	144.6(1)		11.83
-8.5(5)	144.8(1)	<-30	12.30
-9.1(5)	144.8(1)		12.99
-11.6(2)	158.8(2)		12.65
-11.0(1)	153.6(1)		15.04
-11.3(2)	159.0(2)	<-30	15.35
-10.5(1)	151.3(1)		14.52
-10.1(0)	152.1(1)		14.09
-11.4(2)	158.8(2)		15.45
-11.0(1)	153.7(1)	-38	15.04
-10.1(0)	152.2(1)		14.09
-10.7(1)	153.7(1)	-38	14.73
-10.5(1)	151.3(1)		14.52
-10.6(1)	151.4(1)		14.62
-10.1(0)	152.2(1)		14.09
-10.1(1)	163.2(1)	<-30	14.09
-10.0(1)	163.3(1)		13.99
-9.9(1)	163.3(1)		13.88
-11.4(1)	152.6(0)	-38	15.44
-12.7(1)	136.4(1)	-20	16.74
-12.4(2)	148.0(1)		16.54
-12.2(2)	153.6(0)	<-30	16.24

86-NP-205a
n = 39

-11.4(3)	160.2(1)		15.44
-11.9(3)	160.3(1)		15.95
-12.4(2)	153.7(0)		16.54
-12.3(2)	148.0(1)		16.34
*	136.6(1)		h
-11.7(3)	152.7(0)		15.74
-12.4(3)	152.6(0)		16.24
*	136.6(1)		h
-12.1(2)	148.3(1)		16.14
-12.5(2)	153.0(0)		16.64
-11.4(3)	160.4(1)		15.44
-14.9(2)	*		18.70
-15.3(2)	*		19.04
-20.9(9)	141.3(3)	-36.6	23.29
-19.4(9)	141.2(3)		22.23
-16.0(2)	*		19.62
-19.3(9)	141.7(3)		22.16
-16.2(2)	*		19.79
-20.9(4)	191.5(2)		23.29
-20.2(4)	191.4(2)		22.80
-22.4(6)	*		24.30
-15.1(2)	*		18.88
-23.5(6)	*	-23.2	25.02
-20.4(4)	191.2(2)		22.94
-7.9(1)	137.3(1)		11.59
-15.9(2)	*		19.54
-22.4(6)	*		24.30
-8.1(1)	137.2(1)		11.83
-8.9(1)	163.1(0)		12.76
-8.8(1)	163.1(0)		12.65
-8.1(1)	137.2(1)		11.83
-8.7(1)	163.1(0)		12.53
-9.1(1)	190.6(1)	-23.0	12.99
-8.9(1)	190.7(1)	-23.1	12.76
-9.1(1)	190.7(1)		12.99
-8.6(1)	245.0(1)	-22.7	12.42
-8.5(1)	245.2(1)	-22.9	12.30
-9.1(1)	186.9(1)	-20.0	12.99
-9.0(1)	186.9(1)	-22.2	12.88
-8.9(1)	187.1(1)		12.76
-8.6(1)	245.2(1)	-22.9	12.42
*	176.8(*)		h
-5.4(1)	216.2(2)		8.40
-5.5(1)	215.9(2)	-22.0	8.54
-5.5(1)	215.9(2)		8.54
-8.7(1)	173.1(1)	-23.1	12.53
*	266.5(1)		h
-8.6(1)	173.2(1)		12.42
-8.5(1)	173.1(1)		12.30
*	266.6(1)		h

86-NP-205b n = 48	-16.1(2)	132.0(2)	19.71
	-15.9(2)	132.2(2)	19.54
	-11.2(2)	145.3(1)	15.24
	-16.2(2)	132.3(2)	19.79
	-17.9(2)	159.2(0)	21.12
	-17.6(2)	159.2(0)	20.89
	-11.0(2)	145.3(1)	15.03
	-10.9(2)	145.4(1)	14.94
	-15.3(7)	*	19.04
	-15.3(7)	*	19.04
	-17.9(2)	159.2(0)	21.12
	-16.5(7)	*	20.02
	-13.5(2)	146.6(1)	17.46
	-11.4(2)	159.6(2)	15.44
	-13.4(2)	146.7(1)	17.37
	-13.7(2)	146.8(1)	17.64
	-11.2(2)	159.5(2)	15.24
	-11.4(3)	164.8(1)	15.45
	-11.7(3)	164.9(1)	15.74
	-14.7(1)	160.5(7)	18.53
	-11.6(2)	159.8(2)	15.65
	-14.5(1)	159.5(7)	18.36
	-14.6(1)	160.8(7)	18.44
	-10.1(3)	153.2(1)	14.09
	-9.8(3)	153.2(1)	13.77
	-11.2(3)	164.9(1)	15.24
	-10.4(3)	153.3(1)	14.41
	-12.2(2)	*	16.24
	-12.0(2)	*	16.04
	-19.4(1)	155.6(1)	22.23
	-20.2(1)	157.5(1)	22.80
	-20.4(1)	157.5(1)	22.94
	-23.3(2)	138.5(1)	24.89
	-19.6(1)	155.8(1)	22.38
	-17.7(1)	*	20.97
	-23.3(2)	138.6(1)	24.90
	-22.9(2)	138.6(1)	24.63
	-12.3(2)	*	16.34
	-20.9(3)	139.7(1)	23.29
	-20.4(3)	139.8(1)	22.94
	-17.7(0)	143.2(2)	20.97
	-17.7(0)	143.4(2)	20.97
	-19.6(1)	155.6(1)	22.38
	-20.9(3)	139.8(1)	23.29
	-20.2(1)	157.5(2)	22.80
	-17.9(1)	*	21.12
	-17.7(0)	143.5(2)	20.97
	-17.9(1)	*	21.12
<-30			
Metamorphic samples 86-NP-195 ^d n = 21	-4.2(0)	134.6(1)	6.72
	-6.7(0)	135.5(1)	10.11

	-4.2(0)	134.6(1)	6.72
	-2.5(0)	116.7(1)	4.17
	-6.7(0)	135.6(1)	10.11
	-4.2(1)	151.1(2)	6.72
	-2.5(0)	116.7(1)	4.17
	-6.7(0)	135.4(1)	10.11
	*	170.5(1)	h
	-4.1(1)	122.6(0)	6.58
	-4.0(1)	122.6(0)	6.43
	-4.2(0)	134.5(1)	6.72
	-5.5(1)	141.8(1)	8.54
	-4.1(1)	150.8(2)	6.58
	-4.3(1)	151.0(2)	6.87
	-5.6(1)	141.9(1)	8.67
	-5.4(1)	141.8(1)	8.40
	*	170.5(1)	h
	*	170.4(1)	h
	-2.5(0)	116.8(1)	4.17
	-4.1(1)	122.6(0)	6.58
86-NP-207a ^d	-8.1(1)	172.3(1)	11.83
n = 30	-3.6(1)	280.0(1)	5.85
	-13.3(1)	221.1(1)	17.28
	-8.0(1)	172.4(1)	11.71
	-7.9(1)	172.3(1)	11.59
	-13.2(1)	221.0(1)	17.19
	-3.7(1)	279.9(1)	5.99
	-13.2(1)	221.0(1)	17.27
	-3.7(1)	279.9(1)	5.99
	-4.8(1)	164.6(2)	7.58
	-4.6(0)	141.7(1)	7.29
	-3.4(1)	143.1(0)	5.55
	-5.6(1)	130.9(1)	8.67
	-4.6(1)	164.5(2)	7.29
	-5.5(1)	130.8(1)	8.54
	-3.3(1)	143.1(0)	5.40
	-5.4(1)	130.7(1)	8.40
	-4.6(0)	141.8(1)	7.29
	-4.8(1)	164.3(2)	7.58
	-3.4(1)	143.1(0)	5.55
	-4.6(0)	141.9(1)	7.29
	-3.8(1)	117.8(1)	6.14
	-3.0(1)	142.1(1)	4.94
	-3.7(1)	117.8(1)	5.99
	-3.6(1)	142.5(1)	5.84
	-3.8(1)	142.5(1)	6.14
	-3.1(1)	142.3(1)	5.09
	-3.9(1)	117.7(1)	6.29
	-3.1(1)	142.2(1)	5.09
86-NP-208a ^d	-2.9(2)	169.0(3)	4.79
n = 27	-3.3(2)	168.6(3)	5.40

<-30

	-5.9(1)	164.5(2)		9.07
	-6.7(1)	159.9(2)		10.11
	-6.1(0)	191.2(1)	<-30	9.34
	-6.1(1)	160.5(2)		9.34
	-6.0(1)	160.8(2)		9.21
	-6.1(0)	191.3(1)		9.34
	-6.1(0)	191.2(1)		9.34
	-6.1(1)	160.7(2)		9.34
	-6.0(1)	164.2(2)		9.21
	-5.9(1)	164.4(2)		9.07
	-3.2(2)	168.6(3)		5.25
	-6.7(1)	160.3(2)		10.11
	-5.8(1)	172.7(1)		8.94
	-6.8(1)	160.2(2)		10.24
	-5.9(1)	172.8(1)		9.07
	-6.1(1)	173.1(1)		9.34
	-6.1(0)	201.8(1)		9.34
	-5.7(1)	172.9(1)		8.81
	-6.1(1)	173.1(1)		9.34
	-6.0(1)	173.2(1)		9.21
	-6.1(0)	201.9(1)		9.34
	-6.1(0)	201.8(1)		9.34
	-10.8(2)	123.9(1)		14.83
	-11.0(2)	123.8(1)		15.04
	-11.1(2) ^f	123.7(1) ^f		15.14
86-NP-211 ^d n = 9	-4.1(1)	256.2(1)		6.58
	-4.9(0)	183.5(1)		7.72
	-4.5(1)	280.9(0)		7.15
	-4.1(1)	256.4(1)		6.58
	-4.9(0)	183.3(1)		7.72
	-4.2(1)	256.3(1)		6.72
	-4.5(1)	280.9(0)		7.15
	-4.9(0)	183.3(1)		7.72
	-4.4(1)	280.9(0)		7.01
86-NP-212 ^e n = 12	-28.1(1)	143.4(0)		27.96
	-14.1(2)	141.8(1)		18.00
	-28.3(1)	143.3(0)	<-50	28.09
	-28.1(0)	141.7(0)		27.97
	-28.1(0)	146.3(0)		27.97
	-28.1(1)	143.3(0)		27.97
	-13.7(2)	142.0(1)	<-20	17.65
	-28.1(0)	141.7(0)	<-50	27.97
	-28.1(0)	146.3(0)		27.97
	-13.9(2)	141.8(1)		17.83
	-28.1(0)	141.7(0)		27.97
	-28.1(0)	146.3(0)		27.97
86-NP-226b ^e n = 30	-21.2(1)	128.7(2)	<-40	23.49
	-8.9(1)	116.3(0)		12.76
	-21.1(1)	129.0(2)		23.43

-21.3(1)	127.5(1)		23.56
-19.7(1)	143.1(2)		22.44
-19.8(1)	143.2(2)		22.52
-21.2(1)	127.6(1)		23.49
-19.8(1)	143.4(2)		22.52
-19.9(1)	143.1(1)		22.59
-19.8(1)	142.9(1)		22.52
-21.3(1)	127.4(1)		23.56
-12.0(0)	115.3(1)	<-20	16.04
-19.9(1)	143.1(1)		22.59
-12.0(1)	113.9(1)		16.04
-11.9(1)	113.8(1)		15.95
-18.7(0)	156.8(1)		21.72
-11.9(1)	113.9(1)		15.95
-18.7(0)	156.9(1)		21.72
-18.7(0)	156.8(1)		21.72
-9.0(1)	116.3(0)		12.88
-21.1(1)	129.0(2)		23.43
-8.9(1)	116.3(0)		12.76
-12.0(2)	118.3(1)		16.04
-11.7(2)	118.2(1)		15.75
-12.0(0)	115.2(1)		16.04
-11.8(3)	115.3(2)	<-20	15.85
-12.0(0)	115.4(1)		16.04
-11.8(2)	118.2(1)		15.85
-11.4(3)	115.1(2)		15.45
-11.9(3)	115.4(2)		15.95

86-NP-229^b
n = 30

-4.0(1)	120.9(1)		6.43
-4.8(1)	178.6(1)		7.58
-4.4(1)	198.5(3)		7.01
-4.8(1)	178.4(1)		7.58
-4.0(1)	120.8(1)		6.43
-3.9(1)	121.0(1)		6.29
-4.4(1)	198.0(3)		7.01
-4.3(1)	198.4(3)		6.87
-4.9(1)	178.5(1)		7.71
-4.9(1)	194.2(1)		7.44
-2.9(1)	179.4(4)		4.79
-2.8(1)	120.1(2)		4.63
-3.0(1)	179.3(4)		4.94
-3.1(1)	180.0(4)		5.01
-4.7(1)	194.3(1)		7.44
-4.6(1)	194.4(1)		7.29
-3.0(1)	119.8(2)		4.94
-3.2(1)	194.3(1)		5.25
-3.6(1)	234.4(1)		5.85
-3.5(1)	241.5(2)		5.70
0.6(1)	150.8(1)		h
-3.4(1)	194.1(1)		5.55
-2.9(1)	120.2(2)		4.79
-3.7(1)	234.2(1)		5.99

-3.6(1)	234.3(1)	5.85
-3.2(1)	194.2(1)	5.25
0.5(1)	150.8(1)	h
-3.4(1)	241.6(2)	5.55
-3.5(1)	241.3(2)	5.70
0.6(1)	150.9(1)	h

VITA

Jonathan S. Novick was born in New York City, New York. He graduated from Ann Arbor Huron High School in Ann Arbor, Michigan in June of 1981. He then attended the University of Wisconsin - Madison where he received a Bachelor of Science degree in Geology in August of 1985. In September of that same year he entered the University of Tennessee, Knoxville. He received a Master of Science in Geology in March of 1987.