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Robert M. Bond
Lehigh University

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CONDITIONS OF QUARTZ MINERALIZATION IN THE MARTINSBURG FORMATION , EASTERN PENNSYLVANIA AND NEW JERSEY

by

ROBERT M. BOND

A Thesis
Presented to the Graduate Committee
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in Candidacy for the Degree of
Master of Science
in
Geology

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1985

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 22, 1985
(date)

Dale R.
Professor in Charge

Charles B.
Chairman of Department

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ABSTRACT

The Martinsburg formation in the Lehigh and Kittatinny Valleys is a part of the Paleozoic rock sequence repeated in the complex nappe system of the Great Valley. The area has been deformed by the Taconic orogeny and the Alleghanian orogeny. Assigning major structures to a particular orogenic event has been the subject of much debate. This study has employed an integrated approach for determining the histories of fault and fracture systems by analyzing the mineral assemblages deposited in them. Specifically, fluid inclusions in the quartz veins were examined to ascertain the temperature of mineralization and consequently the host rock temperature during the faulting and fracturing event. Two main orogenic pulses during the Paleozoic are recorded by the temperature of mineralization of the quartz veins of the Martinsburg formation. Structures containing exclusively the regionally pervasive low temperature quartz mineralization (100 - 150°C) are Alleghanian features. Quartz containing the high temperature inclusion group (200 - 350°C) is older than Alleghanian and therefore records an earlier Paleozoic event. The metamorphic grade was imprinted on the rocks during this earlier event.

Chapter 1
Introduction

1.1 General Statement

The purpose of this study was to assess the regional tectonic relations, metamorphic grade and trends of the Martinsburg formation in the Musconetcong nappe system in eastern Pennsylvania and New Jersey. To establish these relationships, fluid inclusions in quartz veins occupying known structural settings were used to determine the thermobarogeochemical conditions of vein formation.

The Martinsburg formation in the Lehigh and Kittatinny Valleys is a part of the Paleozoic rock sequence repeated in the complex nappe system of the Great Valley. Current structural interpretation places most of these Paleozoic rocks that are exposed in surface outcrop and the Precambrian rocks of the Reading Prong within the Musconetcong nappe system. The area has been deformed by the Taconic orogeny, Alleghanian orogeny, and possibly by Acadian and Triassic events.

1.2 Statement of the Problem

Major thrust faults involving Paleozoic and Precambrian rocks have been mapped in the Lehigh and Kittatiny Valleys. Most of these faults define the borders between regional nappes or thrust sheets. Assigning these structures to a particular orogenic event has been a major problem in Appalachian geology. The relative importance of the Taconic, Acadian, and Alleghanian orogenies in this area is the subject of much debate.

Rocks of the Martinsburg formation have been deformed and recrystallized.

However, the lack of sensitive mineral indicators of low-grade regional metamorphism in the Martinsburg formation and the neighboring Paleozoic carbonates has precluded determination of the thermal conditions to which the rocks have been subjected. It is important that the thermal history be determined as it has a bearing on hydrocarbon exploration. regional tectonic relations, and the origin of the regional cleavage. This study addresses these problems of regional tectonic relations and metamorphic grade using an integrated geochemical-structural approach.

1.3 Approach to the Problem

Structural features for dating faults, fractures, and cleavages in the Martinsburg, such as crosscutting relations, commonly are lacking. The effects of pressure shadow on cleavage are very similar to refraction effects and to fault drag of cleavage and therefore interpretation is difficult. This study employs an integrated approach for determining the histories of fault and fracture systems by analyzing the mineral assemblages deposited in them. This approach has been successfully applied to the northern Appalachian basin of New York and the Triassic - Jurassic Newark basin of New York, New Jersey, and Pennsylvania (Tillman and Barnes,1979,1983). Specifically, fluid inclusions in the quartz veins were examined to ascertain the temperature of mineralization. It is assumed that during periods of faulting and fracturing the permeability and consequently the access of the rock to mineralizing solutions is enhanced. Hence the entrapment temperature of the fluid inclusions will approximate the host rock temperature during the faulting and fracturing event. This data was used for relative dating because in the study area the host rock temperature at the time of fracture filling was predominantly a function of depth of burial.

The use of inclusions for the determination of the temperature at the time of formation requires that they be of the two phase, liquid - vapor type. Primary and secondary inclusions in quartz were both used from various quartz - calcite veins. Primary inclusions are those initially entrapped in the growing crystal, and secondary inclusions are those trapped in healing fractures at some later date. Both types of inclusions are important to this study since each records a geologic event.

Samples were taken from numerous and different faults and fractures occupying known structural settings. The inclusion data was correlated with the structural setting to develop a faulting, fracturing, and folding history for the lower Paleozoic rocks of the Lehigh and Kittatinny Valleys of Pennsylvania and New Jersey.

Chapter 2
Geologic Setting

2.1 Introduction

The Martinsburg formation is part of a belt of the lower Paleozoic sedimentary rocks and underlying Precambrian basement that is exposed throughout eastern Pennsylvania and northern New Jersey. Regionally this belt is generally referred to as the Reading Prong and lies in the Great Valley physiographic province of the central Appalachians. The southern boundary of the belt is defined by the Triassic border fault and the northern boundary by younger (Silurian) rocks of the ridge-forming Shawangunk or Tuscarora formations. The northern boundary is a Taconic unconformity that was subsequently reactivated as a fault (Epstein and Epstein,1969). (see figure 2-1).

2.2 Stratigraphy

This study is centered on the middle to late Ordovician Martinsburg formation, a thick sequence of rhythmically bedded shale and graywacke. The present thickness averages about 11,000 feet (3,350 m) and consists of three distinct members (Drake,1969; Epstein,1969,1980). The upper Pen Argyl member and the lower Bushkill member are principally slate and bracket the graywacke-rich Ramseyburg member. All contacts in the Martinsburg are gradational. The general characteristics of all the formations important in this study are given in Tables 2-1 and 2-2.

The rock sequences that are of concern are the direct result of Ordovician Taconic tectonism. The uplands that formed as a result of the Taconic orogeny shed sediment to the northwest into a deepening basin. Early Ordovician rocks

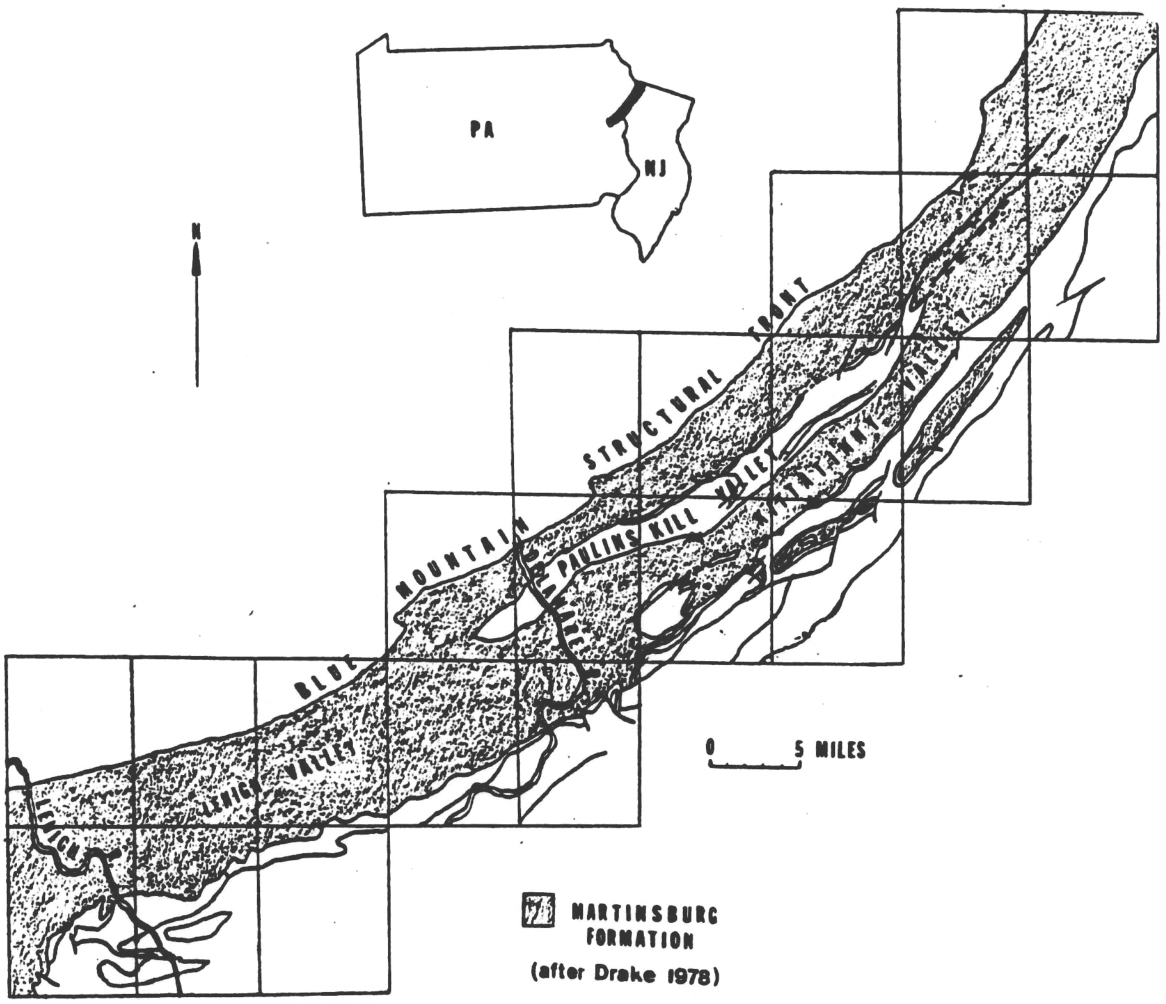

Figure 2-1: Geologic Setting of Study Area

are interpreted as orthoquartzite - carbonate shelf deposits. As the basin deepened in the middle Ordovician the Jacksonburg limestone was deposited. This formation is a deep water neritic carbonate deposit and is gradational into the Martinsburg flysch deposit. The coarse graywacke-rich Ramseyburg member is thought to represent the peak of Taconic activity (Drake,1969). The overlying Silurian rocks represent braided stream deposits and transitional continental-shallow marine deposits (Epstein,1980).

2.3 Structural Geology

To explain the structural geology of this area and the Great Valley - Reading Prong segment of the Appalachians in general an Alpine-type nappe theory has been developed . Seismic surveys have determined the depth to basement beneath the Great Valley near the Blue Mountain structural front to be 30,000 to 45,000 feet. Aeromagnetic studies in the valley near Blue Mountain suggest a depth of greater than 25,000 feet (Drake,1970). Such depths cannot be accounted for by the thickness of the Paleozoic sequence. This basement depth requires a double to triple thickness of the Paleozoic sequence which can only be obtained by the stacking of nappes and thrust sheets. The megasystem of nappes as proposed by Drake(1978) is complicated. It is thought to contain nappes, thrust sheets, and steep ramp faults of both Taconic and Alleghanian ages. Subsequent events during the Acadian orogeny and Triassic period may have also affected the area. The basic tectonic relationships between the nappes in the study area, which belong to the Reading Prong megasystem of nappes, are presented in Drake (1978). Samples for this particular study were collected entirely within the Musconetcong nappe system, with the exception of several samples from sites north of the Blue Mountain

Silurian Stratigraphy
(after Epstein and Epstein , 1969)

Bloomsburg Red Beds	1,500 feet	Very fine to coarse-grained red and green sandstones with siltstone and shale beds.
Shawangunk Conglomerate	Quartzite - argillite facies 1,225 feet	Gray to greenish gray very fine to medium grained quartzite
	Quartzite - Conglomerate facies 200-300 feet	Gray to greenish gray medium to very coarse grained quartzite
	Conglomerate 0-225 feet	Gray quartz , chert , quartzite, argillite pebble conglomerate and conglomeratic quartzite

Table 2-1: Stratigraphy

Ordovician Stratigraphy
(after Drake, 1969)

Martinsburg	Pen Argyl member 3000 - 6000 feet	Thick bedded clay stone slate, upper contact with Silurian is a major unconformity.
	Ramseyburg member 2800 feet	Slate with 20 - 30 % interbedded graywacke. Overlain conformably by the Pen Argyl member.
	Bushkill member 4000 feet	Thin bedded slate commonly with interbedded limestone or graywacke. Overlain conformably by Ramseyburg.
Jacksonburg	Cement rock facies 300-1000feet	Fine-grained argillaceous limestone with a strong slaty cleavage. Gradational into the Martinsburg.
	Cement limestone facies 200-400 feet	Coarsely crystalline limestone, generally thick bedded. Gradational into cement rock.
Beekmantown	Epler 800 feet	Interbedded dolomites and limestones with bedded and nodular chert. Contact with Jacksonburg unconformable.
	Rickenbach 635 feet	Thin to massive bedded coarsely crystalline dolomite with nodular and bedded chert. Gradational into Epler.

Table 2-2: Stratigraphy

structural front. This sampled nappe system contains the Lyon Station - Paulins Kill nappe and Musconetcong nappe. In Pennsylvania the South Mountain nappe and Applebutter Thrust Sheet also are included within this nappe system and in New Jersey the Allamuchy nappe and the Jenny Jump Thrust Sheet are considered to be part of the system. To the west near Reading, Pennsylvania the Lebanon Valley nappe system overlies the Musconetcong system.

Folding in the Martinsburg is disharmonic and of many types. Fold sizes vary from small crinkles to regional synclines. Folding mechanisms range from flexural slip and flow through passive slip and flow (Epstein and Epstein,1969). In the Lehigh Valley and Kittatinny Valley three distinct axial directions representing three distinct folding epidodes have been found (Drake,1969,1978; Drake and Lyttle,1980). Relative ages have been determined for these folding events in New Jersey. The direction of the earliest folding event is east-northeast and the regional slaty cleavage is parallel to the axial surfaces of these folds. Before the next folding event there was a period of major thrust faulting whose structures postdate the slaty cleavage and are deformed by the next two phases of folding (Drake,1978). Following the thrusting, northeast trending folds developed and produced the locally penetrative strain-slip cleavage. The last folding phase is nearly east trending.

Penetrative slaty cleavage is the dominant planar structure in the Martinsburg and Jacksonburg formations. This regional cleavage generally parallels the axial surfaces of major folds. It is represented by a spaced cleavage in the non-pelitic rocks . A slip cleavage may be present and may be locally penetrative but is not widespread. It parallels the axial surfaces of a fold phase that deforms the slaty cleavage. The Martinsburg cleavage problem is centered on the dichotomy of ages for the regional slaty cleavage. Drake and Lyttle (1980) have found that the regional cleavage in New Jersey preceded major thrust faulting which they consider to be the first phase of the Alleghanian orogenic pulse. They also point out that cleaved Martinsburg fragments have been found in the Ordovician Beemerville diatreme of New Jersey and conclude that the regional slaty cleavage is probably Taconic in age. In Pennsylvania Epstein (1969,1980) has convincingly shown that the cleavage in the Pen Argyl member is related to the folds that deform the Silurian and Devonian rocks. Therefore the regional cleavage in that area would appear to be Alleghanian and not Taconic. This dichotomy of ages may or may not be real and will be addressed in the discussion of results.

2.4 Metamorphic Grade

Previous estimates of the metamorphic grade of the rocks in the Lehigh and Kittatiny Valleys were attempted from the minerals in the Martinsburg formation. However, these pelites, and the neighboring carbonate rocks lack mineral indicators of low-grade regional metamorphism. As a result, the possible thermal range is very broad. The narrowing of this range is important to the interpretations of cleavage genesis, regional tectonic relations, and hydrocarbon exploration.

Evidence supporting a low-grade metamorphism is the presence of the 2M polymorph of muscovite, porphyroblasts of chlorite, and spindled quartz grains with a length to width ratio of up to 5:1 (Epstein and Epstein,1969). In the Martinsburg formation there are bedding-plane slickensides which are deformed by the regional slaty cleavage. This demonstrates that the shale was competent when the cleavage formed and that flexural slip preceded passive deformation (Epstein and Epstein,1969). Macroscopic evidence of recrystallization in the Martinsburg and Jacksonburg formations consists of veins of quartz and calcite which are parallel to cleavage and faults. They are intraformational in origin and generally found only in areas of strong deformation (Drake,1969;Cameron,1977). Less deformed rocks of the area contain open voids that are not mineralized; hence, the veins are considered to have been formed by recrystallization under directed stresses of regional metamorphism (Drake,1969). Cameron (1977) found that the primary fluid inclusions in veins in the Jacksonburg formation indicated that they formed in a temperature range from 135 to 150°C. Later, an extensive conodont study which included the area under investigation was published (Epstein,Epstein,and Harris,1977). The authors used the conodont color alteration index (CAI) to determine the level of organic metamorphism . The CAI data indicates that the rocks of the Lehigh and Kittatiny Valleys have been exposed to temperatures greater than 300°C. This dichotomy of temperatures given by two different geothermometers seems to be real and will be discussed later in this report.

2.5 Summary

Field mapping by many authors, aeromagnetic interpretations and drill hole data support the theory that the Great Valley is composed of a system of eroded portions of nappes and thrust sheets that represent portions of former complete nappes. The large amount of sediments shed from the ancient Taconic highlands testify to the orogeny's great intensity. The Alleghanian orogeny was also intense, but whether or not the major structural features observed in this area were produced during this event is unknown. This study endeavors to address this problem of tectonic relations and to ascertain the actual metamorphic grade and any trends, if any, which may exist.

2.6 Sample Locations

Samples were collected from seven formations in the Paleozoic sequence of the Lehigh - Kittatinny Valleys. Extensive sampling parallel to strike was confined to the Martinsburg formation. To the west the study area is bordered by the Lehigh River and extends along the strike of the formations to the New Jersey - New York border (see figure 2-2). The youngest rocks sampled were of the Silurian Bloomsburg redbeds. Specimens taken were from veins in bedding faults, wedge faults and fractured fold hinges. Mineralized bedding faults were also sampled in the Lizard Creek and Minsi members of the Silurian Shawangunk conglomerate. Slickensided samples were taken from the Blue Mountain detachment zone separating the Silurian and Ordovician rocks. All three members of the autochthonous Ordovician Martinsburg sequence were sampled perpendicular and parallel to formation strike. Sampled veins were parallel and subparallel to bedding faults, thrust faults and cleavage. The sampled veins in the Jacksonburg formation had the same mode of occurrence. Near major thrust faults, veins in the Ordovician Ontelaunee and Epler formations of the Beekmantown group were sampled. Finally, samples of quartz mineralization in ore from the Friedensville zinc mine, located in the Ordovician Rickenbach formation of the Saucon Valley were also collected.

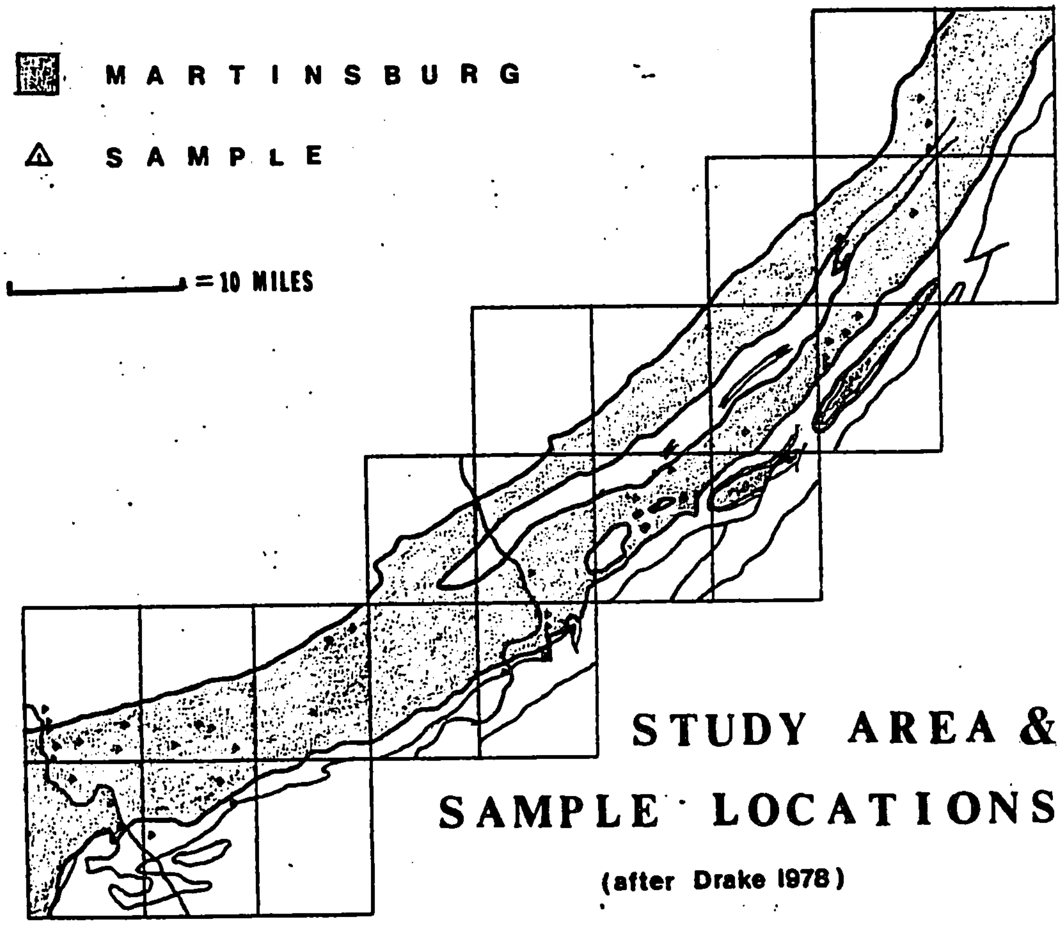

Figure 2-2: Sample Locations

Chapter 3
Fluid Inclusions

3.1 General Statement

The use of fluid inclusions in this investigation requires the remobilization and crystallization of quartz during deformational events. The Martinsburg and Jacksonburg formations are extensively veined with quartz and calcite. Most of the veins are parallel or subparallel to the regional slaty cleavage. Discordant veins are associated with fault related fracture systems. Veining is most commonly concentrated in areas of strong deformation; usually in fold hinge zones and near major faults. Cameron (1977) found a mineralogical trend in the Jacksonburg limestone as a vein was approached. The acid insoluble residue steadily increases within a few tens of centimeters of the vein. The columnar vein quartz and calcite therefore appear to be intraformationally derived by pressure solution. During deformational events, locally opened voids or zones of low pressure were mineralized. Fluid inclusion geothermometry should therefore approximate host rock temperatures during periods of strong deformation.

3.2 Principles

Any mineral recrystallizing in a fluid medium will trap some of that fluid in crystal defects and irregularities. If these fluids are sealed into the crystal during its growth they are defined as primary fluid inclusions. Later mineralization which heals fractures in the crystal produce secondary inclusions. To be useful as geothermometers, the inclusions must be of the two phase liquid - vapor type. It is assumed that upon entrapment the inclusion contained one homogeneous fluid phase, and a vapor bubble developed upon cooling and contraction of the fluid. Reheating the inclusion to the point of homogenization will closely approximate the temperature of entrapment.

Sorby (1858) was the first to propose the use of fluid inclusions as geothermometers. He correctly recognized that the two phase liquid - vapor inclusions originated from differential shrinkage during cooling and that this reversible phase change could be used as a viable thermometer. Fluid inclusion geothermometry does have many limitations and one must be careful to recognize these in order to estimate errors. The following five underlying assumptions pertaining to the use of inclusions as geothermometers and indicators of fluid chemistry are given by Roedder (1979).

1. The fluid was a single, homogeneous phase upon trapping. To make this assumption the volumetric ratio of liquid to vapor of many inclusions must be determined to be the same. If the hydrothermal system was heterogeneous at the time of entrapment, as would occur with a boiling solution, then different phase ratios would be trapped and the resulting temperature data would be erroneous. Variable phase ratios can also result from several episodes of mineralization at different P-T conditions and by the processes of leaking. Some inclusions may be deformed and recrystallize as two inclusions. This is known as necking down, and it may result in a segregation of liquid and vapor. Some of these features may be recognized by microscopy, and different episodes should result in distinct populations of inclusions with different liquid - vapor ratios.

2. The volume of the fluid inclusion does not change after sealing. Most mechanisms affecting volume change during cooling are reversed and cancelled upon reheating to homogenization. Dilational changes from internal or external

pressures can have an effect but are small and usually ignored. Inclusions trapped at elevated pressures and brought to the earth's surface develop relatively high internal pressures and expand. During reheating to homogenization the internal pressure climbs even higher because it is unbalanced externally. The effect actually is insignificant because the compressibility of most minerals is very small.

3. After trapping there is nothing added or lost from the inclusion. Leakage of fluid inclusions has been experimentally evaluated by Roedder (1977,1979) and Roedder and Skinner (1968). They found that leakage is very rare and only occurs when the sample has been exposed to severe crushing, deformation, or very high pressure gradients.

4. The effects of pressure are known or are insignificant. Ideally a fluid inclusion will be trapped near or along the boiling curve. In this case the homogenization temperature will be equal to the trapping temperature. Commonly the inclusion is trapped at a P-T condition which places it above the boiling curve. In this case a vapor bubble will not cavitate until the inclusion has cooled to the boiling curve. This temperature difference is the pressure correction and is added to the homogenization temperature to obtain the trapping temperature. To calculate the correction the fluid salinity and pressure must be approximated. The pressure can be estimated by geologic field evidence and the salinity by freezing experiments.

5. The origin of the inclusion is known. This assumption is concerned with the primary and secondary classification of inclusions. Both types are used in this study since each records a geologic event. The separation of the different types can be important in studies of fluid chemistry and ore genesis

but is not of great concern to this study. The main interest in this investigation is to recognize deformational events. The primary inclusions will preserve the conditions of the first event while the secondary inclusions will record later events. If later deformations open voids in previously formed veins, the fractures and openings may heal giving more secondary inclusions and neomineralization with a second generation of primary inclusions. This study therefore relies on the grouping of inclusion populations to define events.

The homogeneity of the mineralizing fluid, leakage, and distinction between primary and secondary inclusions can be recognized by microscopy and pose no significant problems to this study. Volumetric changes of the inclusion can be ignored since the host mineral used was quartz. The greatest potential source of error to this investigation is the pressure correction.

3.3 Method of Study

Inclusion homogenization and freezing experiments were performed on a SGE Model IV heating - freezing stage. This stage was originally developed by Werre, Bodnar, Bethke, and Barton (1979) and uses externally heated and cooled gas to heat and cool specimens mounted in the sample chamber. Air was employed in all experiments and heated by an electric resistance heater called a flameless electric torch. Temperatures required for freezing runs were obtained by passing dried air through liquid nitrogen.

Standard fluid inclusion studies have always employed doubly polished thick thin-sections. This type of sample provides the excellent optics needed to observe the minute changes in inclusions and is stable at high temperatures. Disadvantages to this method are the high cost and lengthy time of preparation. In this investigation a new method suggested by Dale Simpson of Lehigh

University was tested and used successfully. Quartz from the veins was carefully crushed to diameters between 150 and 300 micrometers. The grains were mounted between glass cover slips in an epoxy glue with a refractive index close to that of quartz. The mount is similiar to an oil immersion mount as used in optical microscopy. Because the method is effective, rapid, and inexpensive, the number of samples examined is limited by observational time and not sample preparation time. For comparison, a limited number of standard doubly polished slabs were used and yielded identical results to grain mounts of the same specimens. The limitation of this method is one of temperature; the epoxy carbonizes and boils near temperatures of 400°C. This was not a problem in this investigation since such temperatures were never encountered in the study. Consistency and close groupings of the data in conjuction with polished slab comparisons proves that very little to no leakage occurred during sample preparation. Quartz was used exclusively because it is a "hard" mineral, lacks cleavage, and contained larger inclusions than the coexisting calcite.

Accurate calibration of the equipment was essential in order to obtain useable results. This was achieved by using several standards and calibrating every hour. The boiling and freezing points of water were used in conjunction with a 20 - 30°C water bath measured with a precision thermometer. Melting point standards were made of Bismuth (271.3°C) and Lead (327.3°C) to calibrate the system at higher temperatures. In addition, homogenization temperatures of inclusions in the Gonzales, New Mexico fluorite from another study and laboratory (University of Arizona, Tucson) were accurately reproduced with the equipment used in this investigation (SGE,1980).

In order to check reproducibility each inclusion was examined over at least two heating and cooling cycles. Leakage during runs was found to be very rare and the variation in temperature measurements in successive runs was equal to or less than 0.5°C. Temperature measurements of particular inclusions after the sample had been removed and run again at a later time gave an experimental precision of +- 1.0°C. Temperature gradients within the sample chamber were minimized by using a high gas flow rate. At 40 standard cubic feet per hour (SCFH) the gradient in the cell from center to edge never exceeded 0.5°C and was usually less in the 0 to 200°C range.

3.4 Results

All of the sampled veins which contained quartz had useable inclusions. Extremely milky quartz had a very high inclusion density, and was more difficult to work with than the clearer samples. Generally, the size distribution of useable inclusions was from 5 to 30 micrometers in diameter. The most common shapes used were sharp and rounded negative crystals.

The inclusions fell into two main populations from the homogenization data. These populations will be referred to as the low and high temperature groups. The low temperature group is bracketed within the range of 100 to 150°C and the high temperature group from 200 to 350°C. The low temperature group is the more common and constitutes 85 percent of the collected specimens. The rare, high temperature group was found only in a few bedding-slip faults. Most of the mineralizations containing the high temperature group also contained the lower group. The details of all the experimental results on both groups are presented separately.

3.4.1 Low Temperature Group

The majority of the quartz veins collected from the seven sampled formations fall into the low temperature group. The only exceptions were found in bedding-slip faults within the Martinsburg formation of New Jersey. The common type of veining, which has been designated as the low temperature group by this study, found in the Jacksonburg and Martinsburg formations has been determined to have formed intraformationally by pressure solution (Drake,1969; Cameron,1977). In this study fluid inclusions were homogenized along perpendicular traverses across polished slabs of veins. Inclusions located 15 micrometers from the vein - host rock boundary gave the same temperatures as all other inclusions from the traverse. This demonstrates that the vein lacks a chilled margin; and it indicates that the host rock and mineralizing fluid had similiar temperatures at the time and site of mineralization. Pressure solution is the likely mechanism for charging the mineralizing liquor.

Useable inclusions ranged from 5 to 30 micrometers in diameter, the average being 15 micrometers. The vapor bubble occupies approximately 5 percent of the inclusion volume at room temperature. The most common shape taken is that of a rounded negative crystal. No daughter crystals were observed in any of the inclusions studied. Typical inclusions of the low temperature group are shown in plate 3-1.

The inclusions have been characterized by the homogenization and freezing methods. The homogenization temperatures range from 100 to 150°C. In any one sample a plethora of data shows a spread of 20 to 30°C. This 20 to 30°C temperature spread is not an experimental artifact. Within this range the inclusions form two to four distinct populations. When 40 inclusions per sample are determined these populations become clearly defined. In some cases the populations can be correlative among samples and trend defined. The implications of this will be discussed later. Figures 3-1,3-2, and 3-3 are histogram plots of samples taken from three cross-sections.

Samples taken from the Martinsburg in a traverse normal to the strike of the formatiom show a trend. On a traverse from either edge of the strike belt to its center the temperatures drop by approximately 25°C. The entire 20 to 30°C temperature spread moves, the end points defining a relatively smooth curve. In general, the edge temperature range is from 130 to 150°C and the center from 100 to 120°C. This temperature trend is the same for cross-sections taken at any point in the study area, with slight changes occurring only in its shape. There is no detectable low temperature trend parallel to the strike of the Martinsburg formation from the Lehigh River to the New Jersey - New York border.

The results of the freezing experiments indicate the presence of a salinity trend perpendicular to strike. Due to limited data this trend is not as well defined as the homogenization temperature trend. However the freezing point depression results suggest that there is a slight increase in salinity towards the center of the Martinsburg formation from either edge (see figure 3-4). The actual weight percent of NaCl present may be approximated by comparing the data with the freezing point depression of pure NaCl solutions (Roedder,1962,1971). The estimated salinities resulting from this comparison are low, ranging from 2 to 6 weight percent NaCl.

During the homogenization and freezing experiments it was observed that all the inclusions showed significant degrees of metastability. New phases failed

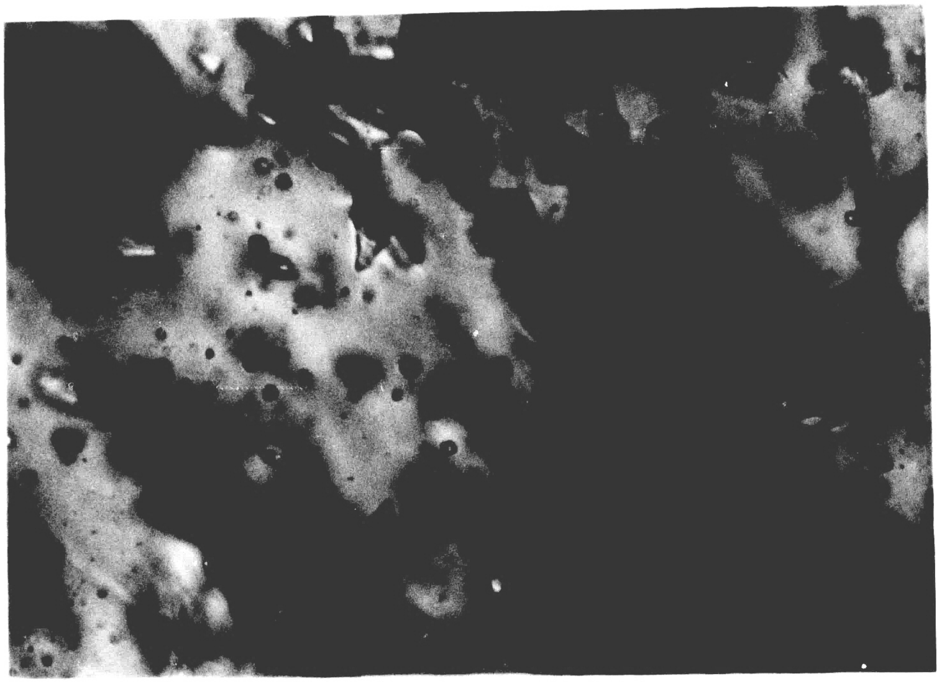

PLATE 3-1 : Typical inclusions of the low temperature group appear in the top right corner of the photomicrograph.

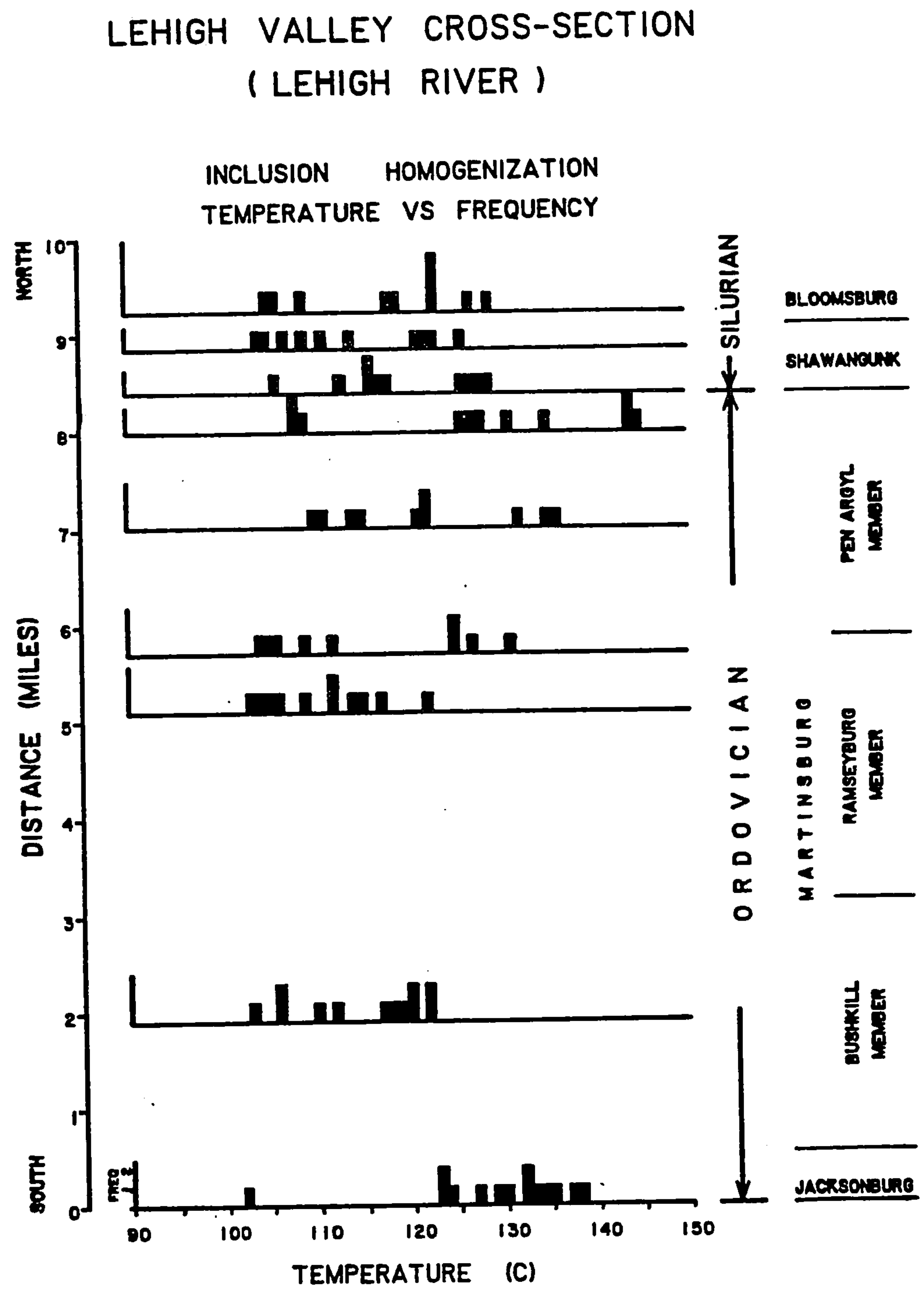

Figure 3-1: Lehigh Valley Cross-Section; Lehigh River

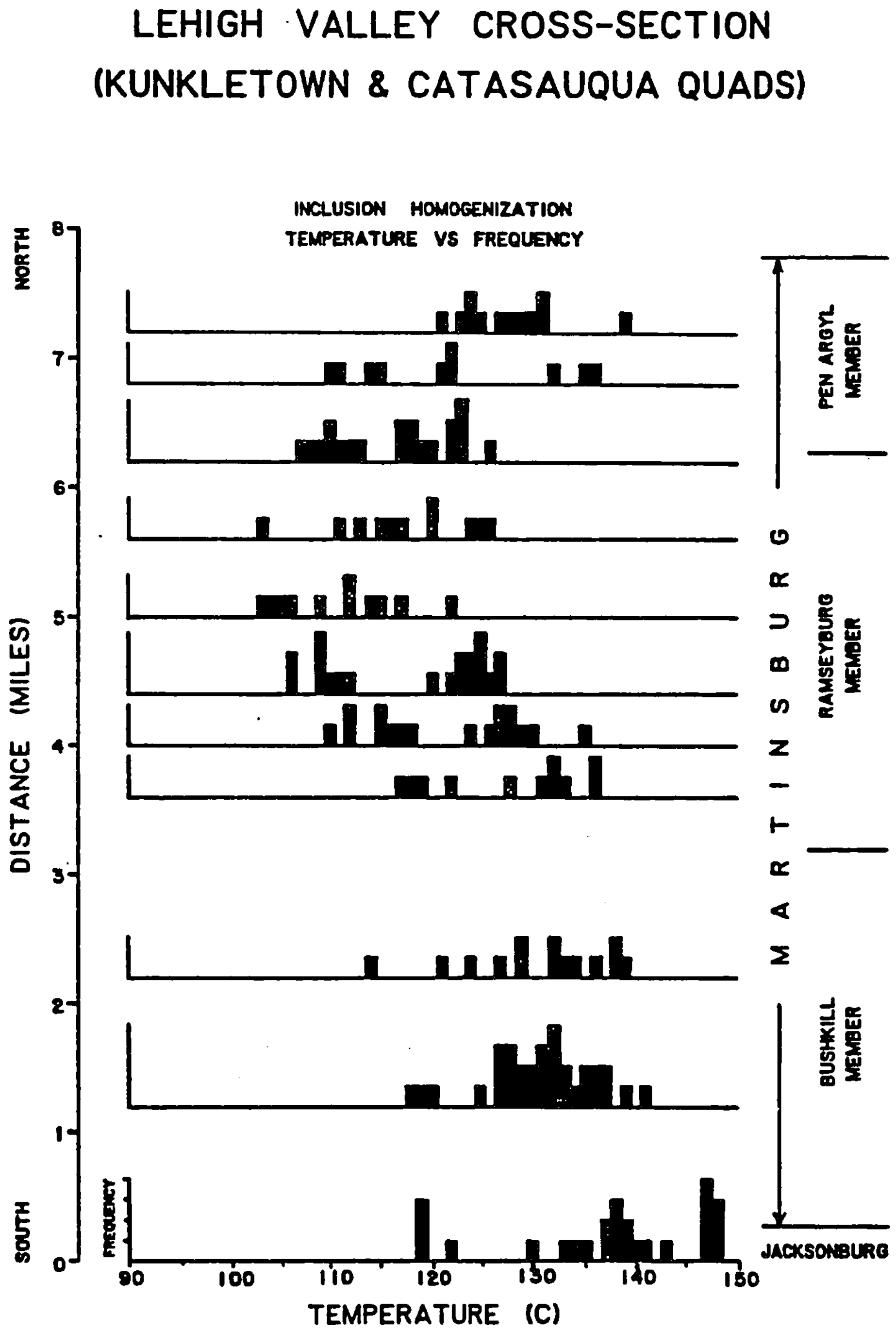

Figure 3-2: Lehigh Valley Cross-Section

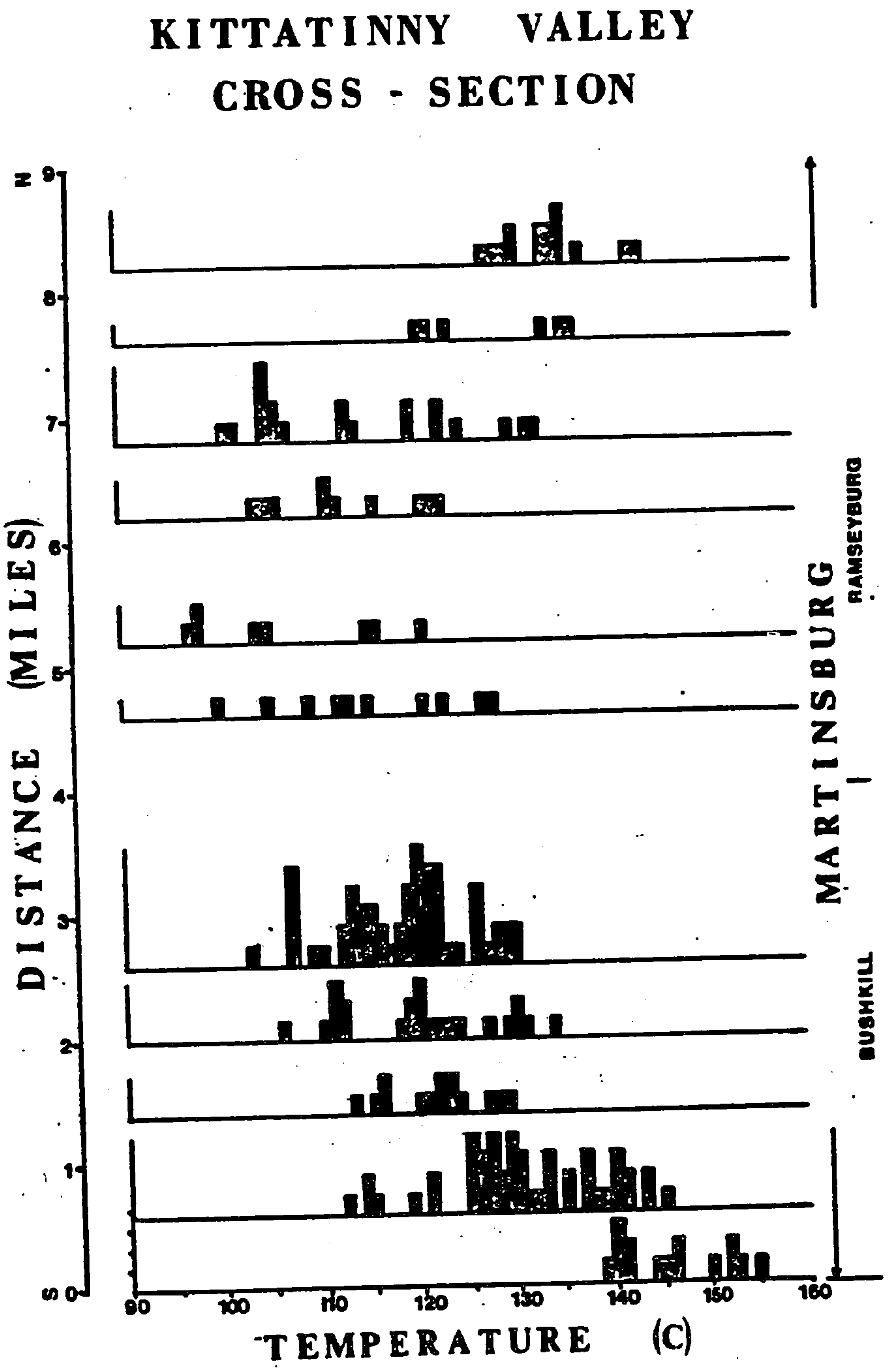

Figure 3-3: Kittatinny Valley Cross-Section

to nucleate when conditions were such that they should have been stable. Upon cooling of homogenized inclusions the nucleation of vapor bubbles did not take place at the temperature of homogenization. For the low temperature group the temperature of nucleation ranged from 120 to 25°C. Some inclusions never renucleated a bubble after being held at room temperature for 24 hours. Roedder(1967,1977) suggests that this phenomenom partially results from the fluid lacking spurious nuclei.

It was found in this study that the nucleation temperature of a single inclusion may vary randomly over a 30°C range or remain constant to within a degree. This metastability proved to be very useful in the following way. Commonly a shrinking vapor bubble will become obscured by shadows as it moves around an inclusion. The actual point of homogenization can therefore be difficult to pin-point. Metastable renucleation does not occur until an inclusion is cooled at least 20°C below its homogenization temperature. When a bubble became obscured the temperature was raised by one degree increments with a cooling period after each elevation. If a bubble became immediately visible upon dropping the temperature a few degrees then homogenization had not been achieved. When the inclusion had become a single phase the characteristic metastability was observed on cooling. This helped to increase the accuracy of the experiments.

Failure to nucleate ice crystals at stable conditions was also observed in freezing runs. The temperatures of metastable ice nucleation ranged from -25 to -40°C. No correlation with the salinity trend was observed. This phenomenon was of no consequence since the freezing point is taken as the temperature at which the last piece of ice melts. The freezing point depressions ranged from

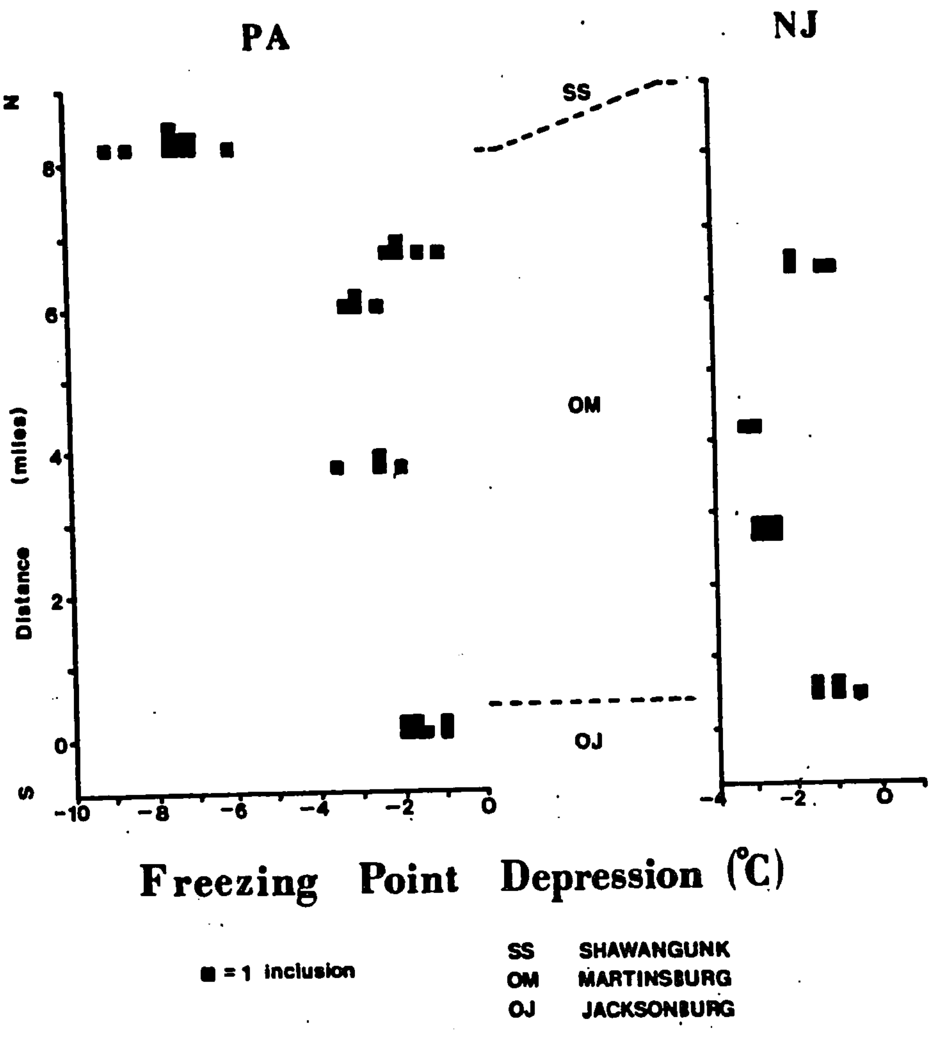

Figure 3-4: Salinity Cross-Sections

-0.5 to -3.5°C.

Quartz veins from the Silurian Shawangunk and Bloomsburg formations gave homogenization temperatures of 105 to 130°C with no trend parallel or perpendicular to the strike (see figure 3-1). No freezing experiments were run on the samples from the Silurian rocks.

Four samples were examined from the Friedensville zinc deposit in the Ordovician Rickenbach formation. Quartz mineralization in the actual ore body contains very few usable inclusions; their small size being inhibitive. The underlying Evans Marker contained somewhat larger inclusions. The temperature range found was 137 to 167°C. One of the ore samples also had a grouping from 175 to 184°C. Secondary mineralization from the 500 foot level of the Ueberroth Mine yielded temperatures around 85°C (see figure 3-5). Three freezing runs were made and the resulting depressions were -7.25, -10.00, and -14.00°C. Roedder(1971) published data on nine inclusions from Friedensville quartz samples. Eight of the inclusions were depressed to -12°C and one to -26°C. This compares reasonably well with the data obtained in this study. There are no published homogenization temperatures for this ore body. Most of the inclusions are so small (< 5 microns) that they never nucleate gas bubbles and exist metastably under negative pressures as a liquid. Determinations in this study were possible because in the course of mining an unusually coarse grained veining material was found in the Evans Marker.

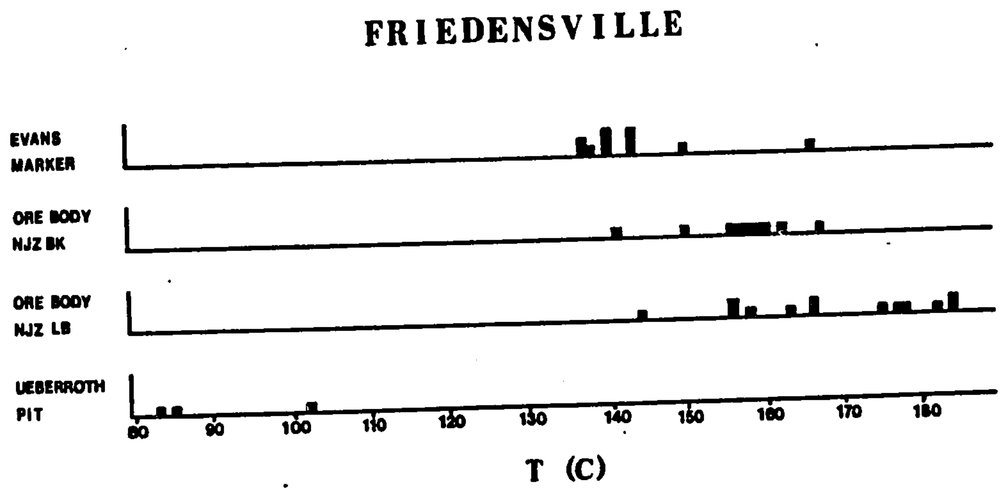

Figure 3-5: Friedensville Zinc Mine

3.4.2 High Temperature Group

Samples were placed into the high temperature group when they contained inclusion populations which homogenized at much greater temperatures than the common low temperature group. The two groups can be distinguished. The low temperature group never exceeds 170°C and the high temperature group is only found above 200°C. Most of the samples containing the high temperature group also contain the low temperature inclusions. The size and shape of the inclusions are very similiar to those of the low temperature group. The vapor bubble is slightly larger in the very high temperature populations (see plate 3-2).

High temperature populations were found in several bedding-slip structures. The Blue Mountain and Portland faults also contain high temperature homogenizing inclusions but these will be discussed separately. Samples from the bedding-slip faults were taken from vugs,breccias , and fractures directly associated with the faults. These bedding-slip structures had an opposite sense of slip than the thrust faults of the area. Adjacent beds occasionally showed slightly different slip directions. This suggests that the high temperature group is associated with a folding event.

The temperature spread in the high temperature group is large, ranging from 50 to 100°C. Histograms of three New Jersey bedding-slip faults are shown in figure 3-6. Also shown is the data from a fault of unknown structural setting found in a Pen Argyl, PA slate quarry.

The inclusions from the Blue Mountain fault homogenized from 250 to 400°C. The samples were taken from the actual mineralized and slickensided

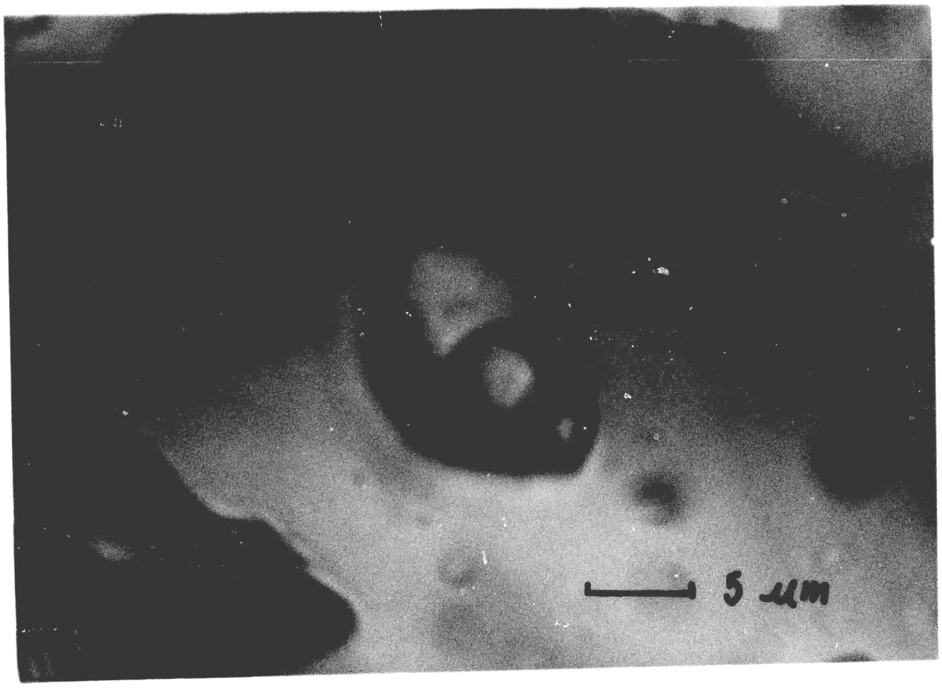

PLATE 3-2 : A typical high temperature homogenizing inclusion. Note the larger vapor to liquid ratio and the negative crystal shape.

fault material. During homogenization runs many of the inclusions developed fractures and leaked. The fractures became invisible upon cooling. The vapor to liquid phase ratios varied over the entire possible range. Inclusions with no vapor bubble occurred adjacent to inclusions which were all vapor (see plate 3-3). This evidence suggests that extensive leakage has occurred in the samples. This was probably due to later movement along the fault. The Portland fault samples were also taken from the actual zone of movement and yielded the same results suggestive of Freezing data was obtained on several inclusions from the Blue Mountain fault. The depression temperatures range from -6.00 to -9.00°C (9 - 13 % NaCl). This is greater salinity than the low temperature group and similiar to the data from the Friedensville zinc mine.

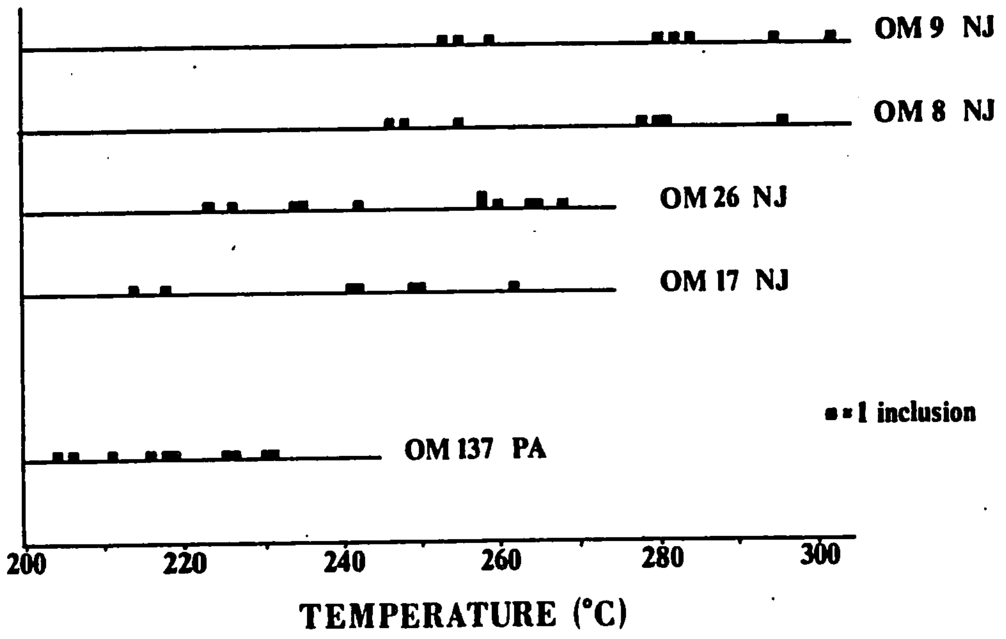

Figure 3-6: High-Temperature Bedding-Slip Faults

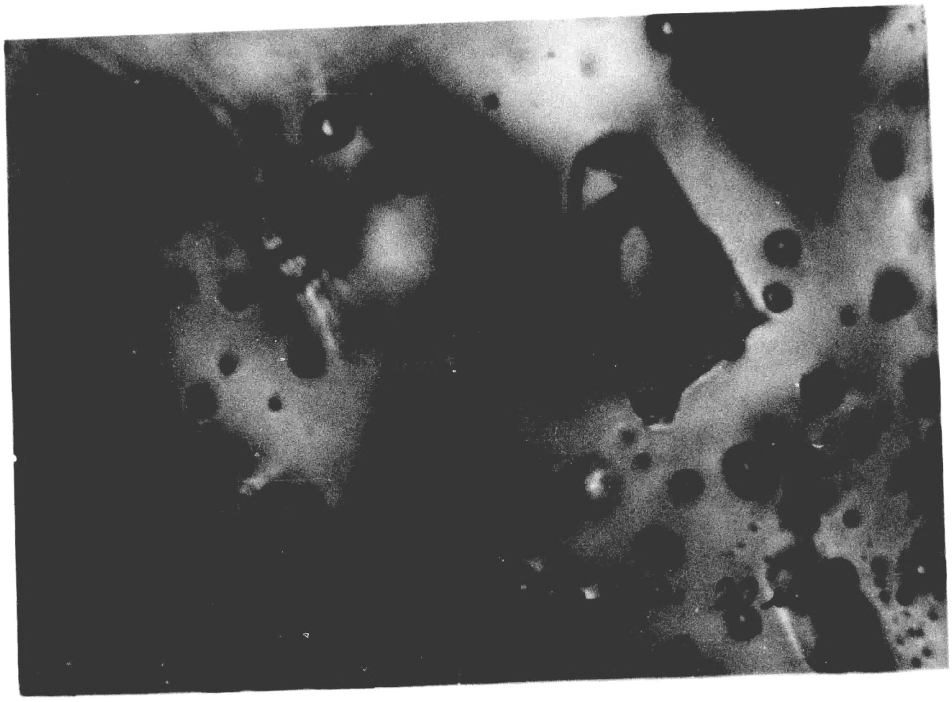

PLATE 3-3 : Most of the inclusions within the field of view have leaked. Notice the very variable vapor to liquid ratio.

Chapter 4
Discussion

Previous work in the Lehigh Valley (Drake,1969; Cameron, 1977) has shown that the low temperature group veins of this study were intraformationally derived by pressure solution. It has also been suggested that mineralization at the Friedensville zinc deposit resulted from pressure solution (Keating,1983). This study established that there is no thermal gradient across a vein indicating that the mineralizing vein and host rock were isothermal. Minute veinlets also were found to give similiar temperatures to regions of massive mineralization. Previous studies and the present data support the conclusion that the vein temperatures closely approximate the host rock temperature during mineralization; and further, mineralization occurred during periods of deformation of the host rock.

Two previous studies revealed the existence of a temperature dichotomy. Cameron(1977) examined the fluid inclusions of the Jacksonburg formation in the Lehigh Valley. He found three sets of inclusions; the hottest homogenizing group rangeing from 135 to 150°C. In the present study several veins from the Jacksonburg limestone were examined and the results were the same as those of Cameron. This group forms the low temperature side in the dichotomous relationship. Later the same year an extensive study of conodonts and the application of their color alteration to geothermometry was published (Epstein,Epstein, and Harris; 1977). The Ordovician limestones of the Lehigh and Kittatiny Valleys yielded conodonts of CAI 4.5 - 5.0. The CAI is basically dependent upon two variables; time and temperature. If we assume the latest possible time for the commencement of erosional unloading was the Middle

Triassic and the earliest in the Late Pennsylvanian (essentially the span of the Alleghanian Orogeny) then the Ordovician rocks were buried for 210 to 270 million years (see Appendix A). These times taken in conjunction with a CAI of 4.5 - 5.0 indicate temperatures of 220 - 300°C (Epstein,Epstein,and Harris; 1977). This is the same range that the high temperature group of this study occupies. This problematic temperature dichotomy is therefore real as revealed by fluid inclusion thermometry.

The high temperature group is the oldest set of inclusions. Bedding-slip veins contain both the low and high temperature groups. Neither shows any sign of inclusion leakage. The low temperature groups in the high temperature veins fit into the overall low temperature trend perpendicular to strike. They cannot be raised to the temperature level of the higher group by a pressure correction. During heating runs the low temperature inclusions leaked and decrepitated before the high temperature group inclusions homogenized. Therefore the low temperature inclusions were never reheated to high temperatures and are the younger group. This suggests that the veins studied have recorded two major orogenic events or major pulses in a continuous Paleozoic event. The youngest and coolest event is common and pervasive. The oldest and hottest event is quite rare and may be the remnants of a strong orogeny or the only evidence left by a strong but atectonitic orogeny.

The low temperature group is directly correlative with folds and faults produced by the Alleghanian Orogeny. Proof of this comes from the cross-section taken along the Lehigh River. Epstein and Epstein (1969) showed that the folds in the Silurian and Devonian rocks are the same as those that fold the Ordovician Martinsburg and fold the Blue Mountain fault. Veins taken from bedding- plane thrusts and from fold hinge fractures yield only the low temperature group. These folds are also related to a regional cleavage in all the rocks, including the regional cleavage in the Martinsburg formation of the Lehigh Valley (Epstein and Epstein,1969). Therefore at least in the northern Lehigh Valley, the regional cleavage and most if not all the existing folds are Alleghanian structures. In New Jersey the Jenny Jump thrust fault is argued to be Alleghanian by classical structural evidence (Drake and Lyttle,1980). Mineralization from this fault also yields only low temperature homogenizing inclusions. This low temperature Alleghanian event was extremely uniform along the strike of the Martinsburg formation. There is no temperature change from the Lehigh River to the New Jersey - New York border parallel to strike. There is however a definite mineralogic metamorphic trend recorded. At Harrisburg , Pennsylvania the rocks are practically unmetamorphosed. Moving ENE along the strike of the Martinsburg it reaches lower greenschist facies by the Delaware River and the biotite zone assemblages at the Hudson River (Epstein,1969). The complete absence of a temperature trend in the quartz veins parallel to strike strongly suggests that the low temperature Alleghanian event was not responsible for determining the metamorphic grade of the host rock. This is not surprising since the temperature dichotomy results of this study clearly suggest the existence of a hotter and older event.

The low temperature group ranges from 100 to 150°C. This is raw inclusion homogenization data uncorrected for pressure. Epstein and Epstein (1969) mapped four lithotectonic units in the Delaware River - Lehigh River area which were all cofolded during the Alleghanian Orogeny. The Martinsburg formation is lithotectonic unit number one (Epstein and Epstein,1969). The approximate thickness of the overlying Silurian and Devonian units 2,3, and 4 is 14,000 feet. A geothermal gradient of 30°C/km and a surface temperature of 15°C gives a temperature of 155°C for unit 1. This thickness would exert a lithostatic pressure on the Martinsburg of about 1200 bars. The calculated pressure correction would average about +20°C for the range of temperatures and salinities of the low temperature group (see Appendix II). Therefore the temperatures during the Alleghanian deformations can be easily accounted for by the overlying section.

The high temperature group defines another major orogenic pulse. It is pre - Alleghanian and most likely due to late Taconic events. The homogenization temperatures range from 200 - 350°C and are similiar to temperatures from the conodont data. This high temperature group was only found within mineralized bedding-slip fault zones of the Ordovician Martinsburg formation. The direction of slip was opposite that of the local thrust faults and was probably related to flexural slip folding. Epstein and Epstein (1969) have shown several examples of bedding plane slickensides offset by slaty cleavage in the Pen Argyl member of the Martinsburg formation. They suggest that this proves that flexural slip folding preceded passive folding and therefore the Martinsburg was competent by the time regional cleavage formed. If the high temperature group is a Taconic feature then the depth of the unrepeated overlying sequence could not account for such high temperatures. There are several possible explanations which would alleviate this problem. First, the Taconic orogeny was an intense event and it is believed that the major nappe units were formed during this time (Drake and Lyttle,1980;Epstein,1980). In a recent evolutionary model of the Martinsburg basin (Shanmugam and Lash,1982) it was suggested that nappes which put Martinsburg over Martinsburg were forming before and during the deposition of the Pen Argyl member. A multiplying of the overlying sequence such as this could account in part for the high temperatures. Second, the geothermal gradient in this area during the Ordovician was most likely higher than it is today. For example, Tillman and Barnes (1983) conclude that when the clays of the Martinsburg sediment underwent dewatering during burial the geothermal gradient would have risen to at least 40°C/km. There also was igneous activity in the study area during the Ordovician; specifically, the Beemerville nepheline syenite complex in New Jersey. All evidence indicates that the highest temperatures to which the rocks of the Martinsburg formation were subjected occurred in the late Ordovician near the end of the Taconic orogeny.

The data collected in this study cannot resolve the regional cleavage problem, but some interesting ideas can be formed from it. The problem arises from contradictory evidence on the timing of regional cleavage formation. Drake and Lyttle (1980) have shown this cleavage to be pre-Alleghanian thrusting in New Jersey and conclude it must be Taconic in age. Epstein and Epstein(1969) however have proven the regional cleavage in the northern Lehigh Valley of Pennsylvania to be Alleghanian in age. In this study most of the low temperature group veins were found parallel to the regional cleavage with a few cutting the cleavage. However, none of the veins have been effected by the cleavage and therefore they are younger features. Both veins and cleavage in the northern Lehigh Valley are unquestionably Alleghanian features. Drake and Lyttle (1980) have warned that it would be dangerous to simply extrapolate these observations east and south to the rest of the formation.

In New Jersey the veins have the same relationship to the regional cleavage and also appear to be Alleghanian. Drake and Lyttle(1980) with detailed structural work in the Martinsburg of New Jersey conclude that there are four main events recorded in the rocks. The earliest was an east- northeast folding event which produced the regional cleavage. Alleghanian thrusting, which includes the Jenny Jump and Portland faults, postdates the cleavage. The third event was a northeast folding episode which produced the local strain-slip cleavage. An episode of near easterly folding was the last event. Drake assumes that the thrusting was the first Alleghanian event and that the cleavage must belong to an earlier orogeny. The results of this study show that the low temperature Alleghanian inclusion group consists of definite peaks spread over 20 to 30°C. These peaks represent real pulses in the Alleghanian Orogeny. In extensively studied samples the maximum number of pulses is four. The Jenny Jump thrust fault samples however only show three pulses over a 15°C spread. This suggests that the four pulses in the inclusion data are the four pulses of Drake and Lyttle(1980).

Four events have also been recognized for the Lehigh Valley, but the regional cleavage was not assigned to any particular episode(Epstein,1980). The thrust faults postdate the first folding event and would lack that peak. This would mean that the regional cleavage and low temperature group veins formed during the east northeast folding episode. The cleavage predates the veining but would still be considered Alleghanian since the veins can be proved to be so. Epstein and Epstein(1969) have observed bedding-slip slickensides which are deformed by the regional cleavage. This could represent the early stages of the east northeast folding episode or it could be the remnant of a Taconic flexural slip fold. The high temperature Taconic group inclusions were unfortunately found in rocks in which the cleavage fault relationship could not be ascertained.

Traverses taken perpendicular to the strike of the Jacksonburg - Martinsburg formations show a distinct temperature trend. This trend has been described above and can be clearly seen in figures 3-1,3-2, and 3-3. The trend is independent from the position of the three members of the Martinsburg. The minimum temperature zone is located structurally about midway between the Blue Mountain structural front fault and the southern fault boundary of the Jacksonburg. Thermal peaks are correlative, but shifted, from sample to sample (see figure 4-1). Consequently the higher temperature edges were not formed before the lower temperature centers, or time of mineralization is not a reasonable explanation. There is also a salinity trend. The maximum salinity is nearly the same as the minimum temperature. However when the salinity-temperature dependent pressure correction is added the trend is accentuated (see Appendix B). To attenuate the trend the cross-sectional center of the Martinsburg formation would have had to been exposed to higher pressure than the flanks. To eliminate the trend a pressure difference of 800 bars is required (see Appendix B). Such a pressure difference may result from a gradual shift from lithostatic pressure and a closed system in the center to a more hydrostatic pressure, and less restricted system near edges. Because this trend was recorded during the Alleghanian Orogeny some type of tectonic pressure difference could have also been in affect, but the mechanism is unknown.

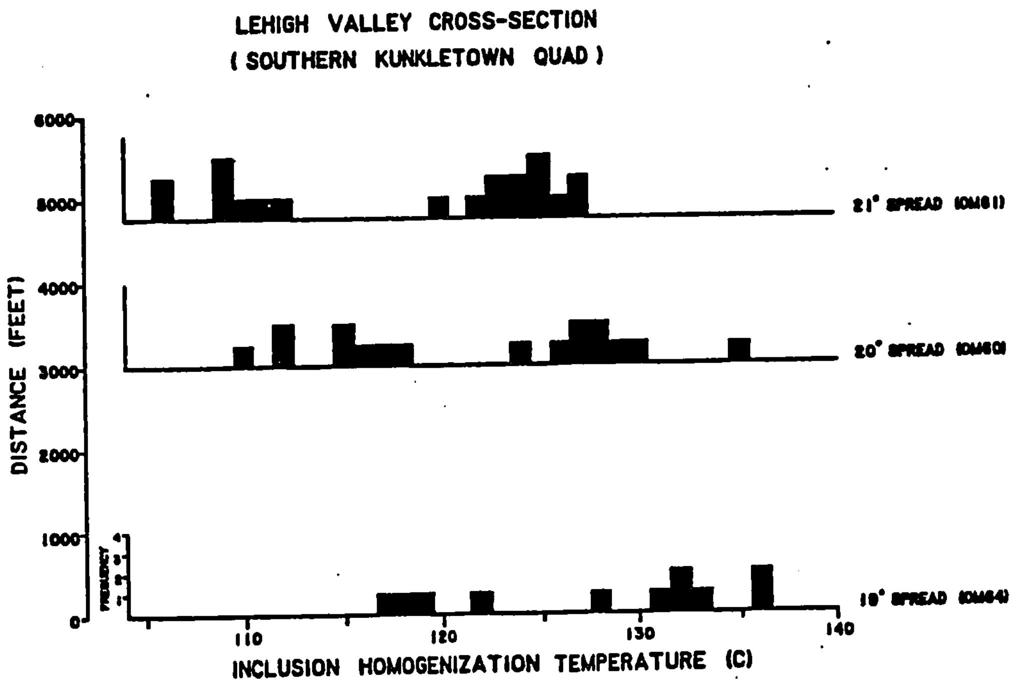

Figure 4-1: Portion of Lehigh Valley Cross-Section

Chapter 5

Conclusions

It is concluded from this study that the Lehigh - Kittatiny Valley area experienced two main orogenic pulses during the Paleozoic. These are recorded by the temperature of mineralization of the quartz veins of the Martinsburg formation. The low temperature quartz mineralization (100 - 150°C) is regionally pervasive and found in all samples except those sheared by fault movement. Veins and faults containing exclusively the low temperature group are Alleghanian features by classical structural analysis. Quartz containing the high temperature inclusion group (200 - 350°C) is older than Alleghanian and therefore records an earlier Paleozoic event, probably the waning stage of the Taconic Orogeny. Burial by nappe formation or a higher geothermal gradient are proposed as the cause of the high temperatures near the close of the Taconic Orogeny. The metamorphic grade was imprinted on the rocks during this late Ordovician event. The range of the high temperature group matches the range given by conodont data. The low temperature group lacks a trend parallel to strike over a region of changing metamorphic grade; therefore the low temperature mineralization was post metamorphism. The regional cleavage is older than Alleghanian thrusting as shown by its concordance with the low temperature veins but younger than Taconic deformation, the structures of which contain high temperature veining. The existence of four distinct populations in many Alleghanian mineralizations but only three in Alleghanian thrust faults suggests that the regional cleavage is related to the commencement of the Alleghanian Orogeny.

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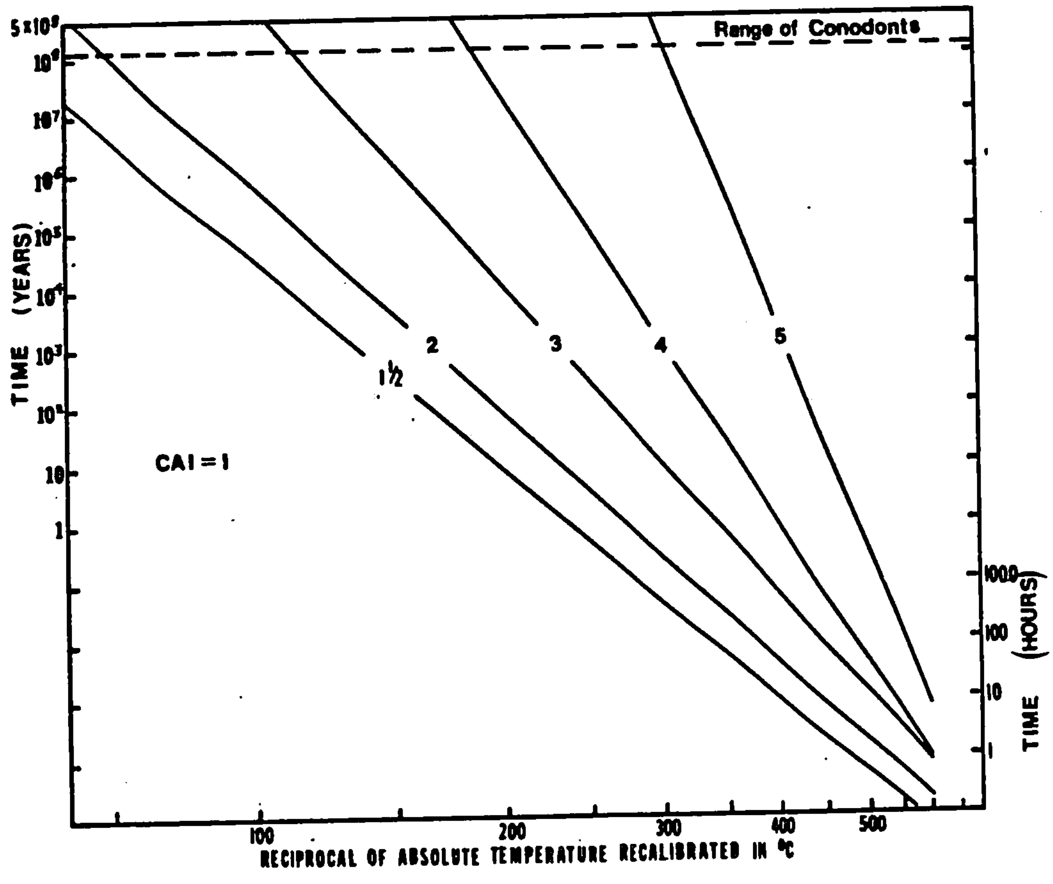
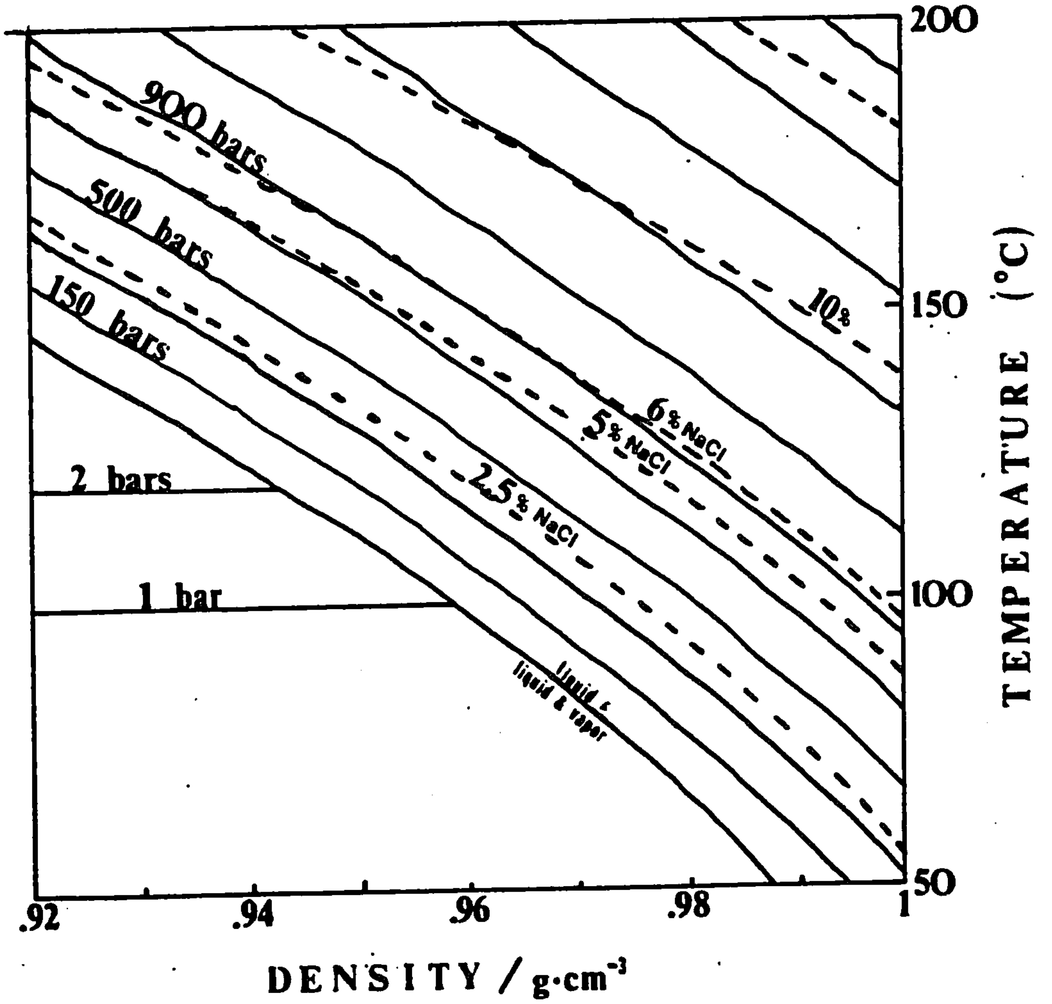
Appendix A
Conodont Color Alteration Index



(after Epstein Epstein and Harris 1977)

Appendix B
Pressure Correction



(after Fisher 1976)

VITA

Robert Martin Bond, the son of Elwood M. Bond, Jr. and Charlotte W. Bond, was born on November 10,1958 in Flushing, New York. He received his primary education in the Bergen County area of New Jersey. He graduated from Pascack Hills High School in 1977. In June of 1981 he received his B.S. in Geological Sciences from Allegheny College. He received his M.S. in Geological Sciences from Lehigh University in June of 1985.