Genesis of Gold Mineralization in the Lone Jack Mine Area, Mt. Baker Mining District, Washington

Lief G. Christenson
Western Washington University

Follow this and additional works at: https://cedar.wwu.edu/wwuet

Part of the Geology Commons

Recommended Citation
https://cedar.wwu.edu/wwuet/774

This Masters Thesis is brought to you for free and open access by the WWU Graduate and Undergraduate Scholarship at Western CEDAR. It has been accepted for inclusion in WWU Graduate School Collection by an authorized administrator of Western CEDAR. For more information, please contact westerncedar@wwu.edu.
GENESIS OF GOLD MINERALIZATION IN THE LONE JACK MINE AREA, MT. BAKER MINING DISTRICT, WASHINGTON

A Thesis Presented
to the Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

Lief G. Christenson

November, 1986
GENESIS OF GOLD MINERALIZATION IN THE LONE JACK MINE AREA, MT. BAKER MINING DISTRICT, WASHINGTON

by

Lief G. Christenson

Accepted in Partial Completion of the Requirements for the Degree Master of Science

Dean of Graduate School

ADVISORY COMMITTEE

Chairman
MASTER'S THESIS

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Western Washington University, I grant to Western Washington University the non-exclusive royalty-free right to archive, reproduce, distribute, and display the thesis in any and all forms, including electronic format, via any digital library mechanisms maintained by WWU.

I represent and warrant this is my original work and does not infringe or violate any rights of others. I warrant that I have obtained written permissions from the owner of any third party copyrighted material included in these files.

I acknowledge that I retain ownership rights to the copyright of this work, including but not limited to the right to use all or part of this work in future works, such as articles or books.

Library users are granted permission for individual, research and non-commercial reproduction of this work for educational purposes only. Any further digital posting of this document requires specific permission from the author.

Any copying or publication of this thesis for commercial purposes, or for financial gain, is not allowed without my written permission.

Name: LIEF CHRISTENSON

Signature: [Signature]

Date: 5/21/2018
Master's Thesis

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at Western Washington University, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of this thesis is allowable only for scholarly purposes. It is understood, however, that any copying or publication of this thesis for commercial purposes, or for financial gain, shall not be allowed without my written permission.

Signed: ____________________________

Date: November 10, 1986
ABSTRACT

The Lone Jack group of claims is in the Mt. Baker Mining District, northern Whatcom County, Washington. Three prominent gold-quartz veins are present, two of which were mined and produced 945 kg of gold between 1901 and 1924. Since then mining operations have not been renewed.

The quartz veins are within 3 km of surface exposures of the Miocene Chilliwack Batholith, above and within a zone of deformation related to the mid-Late Cretaceous Shuksan fault. This major Northern Cascades structure has juxtaposed the Upper Mesozoic Darrington Phyllite over the Paleoozoic volcanic and sedimentary rocks of the Chilliwack Group. The quartz veins are genetically related to local Tertiary block faulting which postdated the metamorphism and deformation related to the Shuksan fault. The style of deformation and timing of these Tertiary faults suggests that they are related to the emplacement of the nearby batholith. The quartz veins were emplaced during, perhaps in the waning stages of, this intrusive activity.

Two generations of mineralization are present; each has a similar paragenesis. Vein minerals other than quartz include pyrrhotite, pyrite, chalcopyrite, tellurbismuth, and free gold. Gold was deposited in equilibrium with pyrrhotite, sericite, and graphite.

Fluid inclusion analyses were used to determine that the ore-forming solutions were boiling, dilute, and contained an average of 0.25 mol% CO₂. Crystallization occurred at about 285°C and 625 bars of lithostatic pressure. Thermodynamic calculations indicate that the gold may have been transported as the Au(HS)₂⁻ complex, and that precipitation of the gold resulted from the physiochemical changes caused by boiling.
Prospecting for similar deposits in the area should be directed toward locating post-metamorphic quartz veins near the Shuksan fault and the Chilliwack Batholith, which show evidence of boiling.
I am indebted to a number of people who provided physical, mental, and patient support during the course of my studies on the Lone Jack property. In particular, Dr. Antoni Wodzicki's enthusiastic support and guidance is here gratefully acknowledged. Dr. R. Scott Babcock introduced me to the project and provided an excellent critical review of the manuscript. I am also indebted to Dr. Edwin Brown for his critical review and for discussions on the geology of the study area. Dr. Steven Aronoff provided helpful editorial comments.

Jim Sevigny, Bill Harrison, and Dave Blackwell from W.W.U. found time to accompany me in the field and helped lug out rock samples. George Mustoe helped familiarize me with lab equipment and also showed me the Lone Jack property for the first time. Patty Combs, the most competent and friendly secretary in the world, helped me get through the maze of office machinery and did some fancy last-minute typing on the manuscript. I am indebted to Peter Jewett, Chuck Ziegler, Jeff Jones, and David Silverberg for helpful discussions on the geology of the North Cascades.

My family all chipped in—brother John lent his jeep and helped carry samples; sister Karen housed me in my early days at Western, and my father, Dr. Earl Christenson, provided financial and motivational support.

The hardest acknowledgment to write is the debt I owe to my wife, Kathryn. She deserves co-authorship for the support she has provided, and I don't think anyone else is quite as happy to see this project terminated. We did it, Kate!
TABLE OF CONTENTS

Abstract i
Acknowledgements iii
List of Figures v

INTRODUCTION
  Location and Topography 1
  Previous Work 1
  Mining History 4
  Scope of Present Study 5

REGIONAL GEOLOGY 6

GEOLOGY OF THE LONE JACK CLAIMS 9
  Lithologic Units 9
  Structure 16
  Faulting 16
  Folding 18

GEOLOGY OF THE ORE BODIES 22
  Lulu 22
  Lone Jack 24
  Whist 25
  Lode Vein Mineralogy and Paragenesis 25
  Economic Geology 30

FLUID INCLUSION STUDIES 35
  Selection and Sample Preparation 35
  Description of Fluid Inclusions 36
  Heating and Freezing Measurements 39
  Results of Fluid Inclusion Studies 55

CONDITIONS OF MINERALIZATION 61
  Thermodynamic Equilibria 61
  Gold Transport and Deposition 64
  Summation of Mineralizing Conditions 68

DISCUSSION 69
  Model for Gold Deposition 70
  Prospecting 72

CONCLUSIONS 75

REFERENCES CITED 76

APPENDIX 1. Fluid Inclusion Data 82
APPENDIX 2. Selected Equilibrium Constants 87
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Location map of the Lone Jack mine</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Claim boundaries of the Lone Jack mine</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Stratigraphy of the North Cascades</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Geologic map of the Goat Mountina-Tomyhoi Peak area</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Geologic map of the Lone Jack claims</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>Cross-sections A-A' and B-B'</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>Photomicrograph of Darrington Phyllite</td>
<td>14</td>
</tr>
<tr>
<td>8</td>
<td>Photomicrograph of hornfelsed Darrington Phyllite</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>Geologic cross-section through Swamp Creek</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>Lower hemisphere stereonet plot of fold axes in the Darrington Phyllite</td>
<td>21</td>
</tr>
<tr>
<td>11</td>
<td>Photograph of Lone Jack stope</td>
<td>23</td>
</tr>
<tr>
<td>12</td>
<td>Photomicrograph of Whist vein wall rock</td>
<td>26</td>
</tr>
<tr>
<td>13</td>
<td>Photomicrograph of pyrrhotite replacing pyrite</td>
<td>28</td>
</tr>
<tr>
<td>14</td>
<td>Photomicrograph of chalcopyrite replacing pyrrhotite</td>
<td>28</td>
</tr>
<tr>
<td>15</td>
<td>Photomicrograph of tellurbismuth and gold</td>
<td>29</td>
</tr>
<tr>
<td>16</td>
<td>Photomicrograph of Lone Jack wall rock</td>
<td>31</td>
</tr>
<tr>
<td>17</td>
<td>Paragenetic sequence of vein mineralization</td>
<td>32</td>
</tr>
<tr>
<td>18</td>
<td>Photomicrograph of three-phase fluid inclusion</td>
<td>37</td>
</tr>
<tr>
<td>19</td>
<td>CO$_2$ melting temperature diagram</td>
<td>39</td>
</tr>
<tr>
<td>20</td>
<td>T-P phase equilibria diagram for CO$_2$-CH$_4$</td>
<td>41</td>
</tr>
<tr>
<td>21</td>
<td>CO$_2$-CH$_4$ determination diagram</td>
<td>42</td>
</tr>
<tr>
<td>22</td>
<td>H$_2$O melting temperature diagram</td>
<td>43</td>
</tr>
<tr>
<td>23</td>
<td>Depression of melting temperature of clathrate and H$_2$O by NaCl</td>
<td>45</td>
</tr>
</tbody>
</table>
24 Clathrate melting temperature diagram
25 CO$_2$ homogenization temperature diagram
26 P-T phase equilibria for CO$_2$
27 $\rho$-$p$ diagram for CO$_2$ and H$_2$O
28 $V_B$-$XH_2O$ diagram
29 Calculated mole fraction H$_2$O diagram
30 Fluid inclusion homogenization diagram
31 Isocompositional curves for H$_2$O-CO$_2$
32 Isocompositional curves for H$_2$O-CO$_2$-NaCl
33 Photomicrograph of fluid inclusions from secondary quartz
34 Geothermal gradient inferred from mineralizing conditions
35 fO$_2$-pH conditions of mineralization
36 pH determination diagram
37 Sketch map of gold-quartz veins within 3 km of the Lone Jack mine
INTRODUCTION

The Lone Jack Mine is located in northern Whatcom County, Washington, within the Mt. Baker mining district. Between 1900 and 1924, 945 kg of gold were recovered from these claims from gold, silver, and tellurium bearing quartz veins. This study contributes to the understanding of the origin of such gold-quartz veins, through analysis of the physical and chemical controls governing these deposits.

Location and Topography

The Lone Jack mine consists of five patented and eleven unpatented claims located in sections 22 and 23, T40N, R9E, northern Whatcom County, Washington (figures 1 and 2). Access to the area is gained by a Forest Service road which runs north from the old Shuksan townsite on Highway 542 to Twin Lakes. This road is not maintained by the Forest Service past the Gold Run Pass trailhead, and its degree of repair varies from year to year. From Twin Lakes a privately owned and maintained cat road goes east and then south 2 km to the claims.

The claims are on the eastern slope of a 1964 m (6508 ft) arete known as Bear Mtn. The terrain is characteristic of the northern Cascade Range, and is steep and glacially carved. Vegetation in the area of the claims consists of a sparse ground cover of alpine fir, blueberries, and wildflowers.

Previous Work

Geologic mapping along the area of the 49th parallel was first undertaken by Daly (1912). Misch (1966) and Brown and others (1981) presented regional Northern Cascades geologic summaries. Detailed geologic mapping of the area of the claims was accomplished by Brown (in Sevigny,
Figure 1. Location map of the Lone Jack property.
Figure 2. Lone Jack mineral claims.
Detailed geologic investigations of areas near the claims include Sevigny (1983) on the Tomyhoi Peak - Winchester Mountain area; Jewett (1984) on the area between the Red Mountain mine and Pierce Mountain, B.C.; Jones (1983) on the area around Church Mt.; and Franklin (1985) near the Excelsior Mine.

The geology of the quartz veins and mining history of the Lone Jack claim group were described by Lindstrom (1941) and Moen (1969). Lindstrom provided results of amalgamation and floatation tests on ore from the mines. Moen described the mines, prospects, and geology of the Mt. Baker mining district.

Several reports have been written on the economic potential of the property by private firms commissioned by various interests. Made available to this writer were unpublished reports by Crossland (1923), Weymark (1983), Grant (1985), and Stone (1986).

Mining History

A brief history of the Lone Jack workings was given by Moen (1969). The ore was discovered by R. S. Lambert, Jack Post, and L. G. Valkenberg in August, 1897. Their claims were sold in 1898 to Henry Hahn and Leo Friede, who organized the Mount Baker Mining Co. A ten stamp mill (expanded to 15 stamps in 1901), and a 1,220 m, 50 ton aerial tramway were constructed, and initial production began in 1901. In July, 1907, fire destroyed the mill and operations ceased until 1915. The claims were sold to Clark and Sperry, who organized the Boundary Gold Co., and constructed an amalgamation mill. Production was limited to "several hundred tons of ore" (Moen, 1969), and ceased in 1917. Phillip Brooks purchased the claims in 1919, and under the supervision of Carl Willis a 100-ton mill and hydroelectric plant were constructed. The mill was destroyed by a snow-
slide, and in 1924 a 75-ton mill was erected. Active mining operations ceased after 1924. At this date no remains are evident of any of the mills, bunkhouses, cook-shacks, assayers office, lumber mill or other features constructed during mining.

Moen (1969) estimated the total production of gold from the Lone Jack and Lulu mining operations to be $550,000, of which $332,583.65 is proven by mint receipts.

The claims are presently owned by John Bullene of Bellingham, WA. Since 1925 investigations of the area have been conducted by several interests, but mining operations have not been renewed. In 1980, the Lone Jack Co., Inc. completed the cat road to the mines from Twin Lakes, and staked 11 unpatented claims adjacent to the patented claims. In 1984, Bud Collimder of Langely, Wa., acquired the lease and is presently conducting investigations.

Scope of Present Study

The objectives of this study are:

1) to examine the nature of the structural control for deposition of the ore;

2) to determine the hydrothermal mineralogy and paragenesis of the ore minerals;

3) to determine the pressure, temperature, and composition of the ore forming fluids, through fluid inclusion analysis;

4) to determine the mechanisms for gold transport and deposition in the study area, by applying thermodynamic analysis to the observed mineral and hydrothermal fluid data;

5) to propose, based on the above findings, a model for the origin of the mineralization at the Lone Jack Mine.
REGIONAL GEOLOGY

Misch (1966) presented the first compilation of the regional geology of the North Cascades and defined many of the lithologic units and structures (fig. 3). Misch divided the rocks of the North Cascades west of the Straight Creek Fault into three units. The structurally lowest unit consists of the mostly andesitic Wells Creek Volcanics and the volcaniclastic sediments of the Nooksack Group. These rocks are inferred to be structurally overridden by the Church Mountain thrust plate, which consists of the volcanic and sedimentary rocks of the Devonian-Permian Chilliwack Group of Daly (1912). Following Misch's interpretation, the Church Mountain thrust plate is in turn overridden by the Shuksan thrust plate, which consists of the Upper Mesozoic Darrington Phyllite and Shuksan Greenschist. The Lone Jack Mine is near the sole of the Shuksan thrust fault within an area of intense deformation, termed the imbricate zone by Misch.

The oldest rocks of the North Cascades are those of the Precambrian to Ordovician meta-plutonic Yellow Aster Complex (Misch, 1966), which are present as tectonic slivers within fault zones. Tertiary North Cascade rocks include the Oligocene Chilliwack Batholith of Daly (1912), the Pliocene Hannegan Volcanics of Misch (1966), and the Eocene Chuckanut Formation of McLellan (1927).

The framework provided by the reconnaissance work of Misch has been modified by more recent, detailed mapping by E. H. Brown and students at Western Washington University (Jewett, 1984; Jones, 1984; Ziegler, 1985). In some areas, subhorizontal juxtaposition of the Chilliwack with other tectonically emplaced units forms a 2km thick zone of imbrication. Near Mt. Baker, allochthonous fragments of the Nooksack Group occupy the upper-
Figure 3. Diagrammatic stratigraphy of the North Cascades west of the Straight Creek Fault (after Misch, 1966).
most structural horizon in this zone of imbrication. This does not agree with the concept of three separate, coherent thrust packets. In other areas, high-angle faults rather than thrusts are found along the trace of the Church Mountain fault zone. High-angle faulting along the Shuksan fault was thought by Misch (1966) to represent a root zone, from which westward-directed thrusting originated. However, strike-slip faulting has been shown to have occurred along these segments. The sense of motion and style of deformation along these two major fault systems has not yet been adequately explained, and the Shuksan thrust fault is referred to by this writer as simply the Shuksan fault.

Uplift of the North Cascades began in the Late Pliocene to Early Pleistocene and continues today (Misch, 1966). Pleistocene glaciation has been a major process in the development of the geomorphology of the study area, as evidenced by the cirques on the north and south sides of Bear Mountain, lateral moraines that lie below the Lone Jack mine, and the U-shaped valley of Silesia Creek. The three quartz lodes were exposed, and partly removed, by the action of these alpine glaciers.
GEOLOGY OF THE LONE JACK CLAIMS

The claims of the Lone Jack group are found within a region of considerable structural complexity. The lithologic units found in the area and their structure are diagrammed in figures 4-6, and are described below.

Lithologic Units

The lithologic units in the study area are the Yellow Aster Complex, the Chilliwack Group, the Darrington Phyllite, and Tertiary intrusives.

The Yellow Aster Complex was mapped by Brown (in Sevigny, 1983) within the imbricate zone below the Shuksan fault at Skagway Pass. There it is represented by trondjhemites and gabbros imbricated with tectonized blocks of the Chilliwack Group. The Yellow Aster Complex was considered by Misch (1966) to represent fragments of a crystalline basement, metamorphosed to the amphibolite facies.

The Chilliwack Group is found below the Shuksan fault on the north face of Bear Mountain, north of the Shuksan fault at Skagway Pass, and along high-angle faults between Skagway Pass and the Lone Jack mine. In the study area, the Chilliwack Group is represented by fine-grained clastics (argillites and shales), sandstones, green aphanitic volcanics, and tectonized limestones. According to Danner (1957) and Brown (1983), the Chilliwack Group is a Devonian to Permian oceanic arc assemblage, metamorphosed to the lawsonite-aragonite subfacies.

The Darrington Phyllite composes most of Bear Mountain, and is found imbricated with rocks of the Chilliwack Group below the Shuksan fault. The Darrington Phyllite consists of a black to silver-gray, graphitic phyllite with a prominent foliation defined by quartz-albite segregations. The
Figure 4. Geologic map of the Goat Mountain-Tomyhoi Peak area. Meadows = Yellow Aster Meadows; WP = Welcome Pass; U = unmapped area (after Sevigny, 1983).

LEGEN

- QUATERNARY ALLUVIUM
- TERTIARY INTRUSIVE
- NOOKSACK GROUP
- WELLS CREEK VOLCANICS
- SHUKSAN SUITE
  - Darrington Phyllite
  - Shuksan Greenschist
- CHILLIWACK GROUP
  - Volcanic rocks
  - Sedimentary rocks
- YELLOW ASTER COMPLEX
- SERPENTINE
Figure 5. Mine area geology
Figure 6. Cross-sections B - B' and A - A' (from figure 5).
phylite contains the mineral assemblage quartz-sericite-albite-graphite (fig. 7), which is locally thermally recrystallized to a biotite-bearing hornfels near igneous intrusives (fig. 8). According to Brown (1983) the quartzo-feldspathic sediments were deposited in a marginal basin during the Jurassic and Early Cretaceous. The Darrington Phyllite lies within the Shuksan Thrust Plate, which has been metamorphosed to the blueschist facies. According to Armstrong (1980) the metamorphism took place during the Late Jurassic to Early Cretaceous.

Tertiary intrusives in the study area include a small plug near the portal of the Lulu mine, small granodioritic and aplitic apophyses in the Lone Jack cirque, and numerous dikes found through the claims. The plug near the Lulu portal is a quartz-diorite which consists of plagioclase, biotite, actinolitic hornblende, quartz, and accessory apatite and zircon. It intruded and contact metamorphosed the Darrington Phyllite.

The granodioritic and aplitic apophyses are found around 1400 m in the Lone Jack cirque. The aplites are composed of quartz and plagioclase; the granodiorites are composed of quartz, plagioclase, and biotite. Both occur as stringers that cross-cut thermally metamorphosed Darrington Phyllite.

Bear Mountain hosts numerous dikes with varying lithologies. They may be categorized into two general types on structural and mineralogical grounds. Those that contain quartz and feldspar phenocrysts + hornblende + biotite are classified as rhyodacites, and were found only along high-angle Tertiary faults. The second type of dike is less silicic, and is found variously orientated within and offset by the Tertiary faults. These less silicic dikes range in composition from basalts(?) with a trachyitic texture, to hornblende micro-diorites with hornblende, plagioclase, calcite, and lesser quartz, epidote, sphene, and apatite.
Figure 7. Photomicrograph of Darrington Phyllite, crossed nicols. Sample collected from the summit of Bear Mountain.

Figure 8. Photomicrograph of hornfelsed Darrington Phyllite, plane polarized light. Sample collected at the portal to the Lulu mine.
Other lithologic units near the claims, but not visited by the writer, are the Chilliwack Batholith, Hannegan Volcanics and the Chuckanut Formation. The Tertiary Chilliwack Batholith of Daly (1912) crops out 2.5 km east of the claims along the base of the Skagit Range. The Chilliwack batholith is a composite of numerous plutons and stocks of different ages and compositions, ranging from quartz-diorites to granodiorites, with smaller amounts of diorites, gabbros, and alaskites (Staatz, 1972). The Hannegan Volcanics unconformably overlie the Chilliwack Batholith along the summit of the Skagit Range (Staatz, 1972). They consist mainly of andesites and dacites, with a mixture of flows and pyroclastics, that were locally extruded after the emplacement of the Chilliwack Batholith. The arkosic Chuckanut Formation, found in the valley of Silesia Creek, is thought to represent deposits of an Eocene stream system (Johnson, 1982; Staatz, 1972).

The close proximity of the Chilliwack Batholith and the small plug at the Lulu portal have created a zone of thermal recrystallization in the overlying Chilliwack Group and Darrington Phyllite. This is observable in the area of the claims west of the Whist vein along the north side of Bear Mountain, at the portal to the Lulu mine, and in the Lone Jack cirque. On the north side of Bear Mountain, argillites and sandstones of the Chilliwack Group and the Darrington Phyllite are thermally recrystallized to biotite hornfels. Recrystallized zones occur as pods and stringers in the Darrington Phyllite above the pre-Tertiary Shuksan fault. It was difficult to determine whether the contact metamorphism was offset by, and therefore older than, the Tertiary faulting.
Structure

The dominant structural feature in the study area is the Shuksan fault, which has been offset by high-angle, N-S Tertiary faults. Both events deformed the Darrington Phyllite, and structural data from the Darrington Phyllite are discussed as they apply to these local deformatinal features.

Faulting

Two generations of faulting were recognized in the study area: the mid-Late Cretaceous Shuksan fault, and high-angle, N-S-trending Tertiary faults.

The trace of the Shuksan fault near the study area has been mapped by Brown (fig. 4). The fault zone is best observed across the ridge to the east of Twin Lakes, where its trace is marked by a zone of mylonite 2-4 meters wide. Through Skagway Pass the fault zone is over 100 meters wide, as indicated by the various imbricated lithologies. In the valley of Swamp Creek, to the southwest of the claims, the fault is nearly horizontal (fig. 9). From the head of Swamp Creek, through Twin Lakes and across the Pleiades the fault is essentially vertical and strikes to the northeast. The change from low-angle to high-angle takes place within a few tens of meters. Two interpretations of this abrupt change in attitude have been suggested.

Misch (1966) interpreted the high-angle segment as representing a root zone, from which westward-directed thrusting originated. Brown and others (1981) questioned this when they reported possible strike-slip motion along the high-angle segments. Jewett (1984) studied a section along Misch's proposed root zone from the Red Mountain mine to Pierce Mountain, British Columbia. Stretching lineations noted by Jewett
Figure 9. Geologic cross-section, oriented perpendicular to Swamp Creek from Gold Run pass to Goat Mountain. uPCV = Chilnualna Group volcanics; uPCs = Chilnualna Group sediments; Kph = Darrington Phyllite; pDY = Yellow Aster Complex; Q = Quaternary (from Sevigny, 1983).
indicate strike-slip motion along the high-angle segments, and Jewett used the wrench-faulting model of Lowell (1972) and Sylvester and Smith (1976) to explain the proximity of high and low-angle segments of the fault.

High-angle, north-south striking faults slightly offset the trace of the Shuksan fault. These faults are marked by brecciated zones 1-3 meters wide. They are best observed along the north face of Bear Mountain, where they have been eroded to form gullies that dissect the face of the mountain. To the north and south of Bear Mountain the faults are traced by topographic depressions and juxtaposed lithologies along ridge tops. Colluvium prohibits the tracing of individual faults over long distances.

One of these faults, located near Twin Lakes, displaces a hornblende diorite dike. A sample collected by E. H. Brown has been dated by R. L. Armstrong at 58 ± 2 Ma, indicating that the fault movement is younger (E. H. Brown, pers. comm., 1986). In the study area, the faults have created horsts and grabens. The ridge to the north of the mines provides the best control for determining the sense of movement along these faults. Displacement along these faults is probably tens of meters, as indicated by the offset of the Shuksan fault on the north side of Bear Mountain, and the 15 meter displacement of the Lulu vein (fig. 6). The block faulting may be related to the injection of the underlying batholith, as suggested by the predominately felsic dikes that lie within the fault zones.

Folding

From structural data collected between Goat Mountain and Winchester Peak, Brown (in Sevigny, 1983) inferred two, and possibly three, deformational events. The first, D_1, developed a pronounced mineral lamination and foliation (S_1). This event completely transposed the original bedding.
F\textsubscript{1} associated with D\textsubscript{1} has not been recognized in the area. S\textsubscript{1} has been refolded (D\textsubscript{2}, F\textsubscript{2}) about a gently plunging, NW-SE axis; in some areas S\textsubscript{1} has been transposed to a vertical, planar S\textsubscript{2} foliation parallel to the F\textsubscript{2} axial planes. A third deformational event, D\textsubscript{3}, may have refolded F\textsubscript{2} folds about a gently-plunging, NW-SE axis; D\textsubscript{3} may possibly be related to the same deformational event as D\textsubscript{2} (Sevigny, 1983).

Fold data were collected from the Darrington Phyllite, in the immediate vicinity of the Lone Jack claims (fig. 10). There, S\textsubscript{1} is best observed along the ridge above the Lone Jack vein, where it has been deformed into broad, open folds (F\textsubscript{2}) with NW-trending, nearly-horizontal fold axes. S\textsubscript{2} is best observed along the road leading from Twin Lakes to the mines and in the head of Lulu cirque, where it trends N-S and dips from 85° to 90°.

N-S-trending faults and shear zones are common in the area of the claims. These zones contain folds with both steeply-plunging and sub-horizontal axes. These folds are difficult to interpret within Sevigny's (1983) framework. The vertically plunging folds show a predominately right-lateral sense of vergence; they may be related to strike-slip movement along the Shuksan Fault. The folds with sub-horizontal axes may be drag folds related to dip-slip movement along the Tertiary fault planes.

The Lone Jack quartz vein lies within a relatively 'coherent' block of Darrington Phyllite between shear zones. That the vein is parallel to the S\textsubscript{1} foliation suggests that the quartz was emplaced along the foliation planes, in what may be a parallel strand of the Shuksan fault. The relationship of the Lulu vein to the regional foliation is difficult to determine, as it lies in an area of intense deformation which has retained few of the "primary" foliation structures. The shallow dip of the Lulu suggests that it was also emplaced parallel to S\textsubscript{1}. 
Figure 10. Lower hemisphere stereonet plot of fold axes in the Darrington Phyllite.
GEOLOGY OF THE ORE BODIES

Three prominent gold-quartz veins, the Lone Jack, the Lulu, and the Whist, are present within the Lone Jack group of claims. The locations of the lodes are shown in figures 1 and 2, and maps of the underground workings of the Lulu and Lone Jack are shown in Plates I and II.

Lulu

The Lulu vein crops out along the northern face of Bear Mountain, at an elevation of approximately 1463 m (4,800 ft). The main body of the vein can be traced for over 75 m within Bear Mt and along the northern cliff face. The vein strikes generally E-W, and the attitude ranges from nearly horizontal to 55°S, with a mean of 30°S. The vein is up to 2.5 meters thick, but thickness is irregular, and it pinches out to the west.

The vein was stoped for approximately 70 meters along strike, and up to 40 m down dip. The shallow dips of the Lone Jack and Lulu veins necessitated mining by the room-and-pillar method, in which parts of the vein were left as support columns (fig. 11). Judging from the remaining pillars within the stoped out portion, the vein within the production zone averaged around 1.5 m in thickness.

The portal to the Lulu mine is at an elevation of 1,463 m (4,800 ft). A haulageway extends westerly from the portal for around 145 m, where it splits; one drift leads westerly for over 100m through contorted phyllite, and one short drift leads northerly to an oreshoot-ladderway leading up to the stope. Vein quartz is first intersected 38 meters west of the portal, where a 5-18 cm quartz vein strikes E-W and dips 50°S. This vein extends to 100 m west of the portal, where a fault apparently displaces it around 10 m upward. A raise driven along this fault intersects a 1 m thick quartz vein 10 m above the haulageway level. This may be the western extension of
Figure 11. Photograph of Terry O'Hara and part of the Lone Jack stope.
the main production vein.

Moen (1969) reported that during the last year of operation (1924), 1,415 metric tons of ore mined yielded 25.8 kg gold and 1.08 kg silver. The average grade of the ore from the Lulu vein was, according to Moen (1969), 24–64 g gold per ton.

**Lone Jack**

The Lone Jack vein, exposed on the southern and eastern sides of Bear Mountain at an elevation of 1646 m (5,400 ft), can be traced for over 100 m along the surface. It strikes N10W–N20W and dips 20–55° SW. The average dip within the stope is about 30°. The vein is up to 1.8 m thick, with a mean thickness of 1.5 m. It terminates in a fault on its eastern and northern margins, and appears to pinch out to the SW.

Judging from the pillars left in the stope, the average thickness in the production zone was approximately one meter. The Lone Jack vein decreases in thickness down-dip, and either pinches out or is truncated by a N–S trending, high angle shear zone that parallels the entire western margin of the stope. Grant (1984) noted what appears to be a down-dip extension of the shear zone near the haulage level face. If the shear does truncate the vein, displacement does not appear to have been great, for a 2 inch-thick segment of vein found in the transfer level may be a down-dropped portion of the stope production vein. This would indicate a displacement of less than five meters.

The portal to the Lone Jack is at an elevation of 1625 m (5,300 ft). Eighty-four meters down this tunnel a ladderway connects to a transfer level, from where five ore-chutes lead to the stope. The stope can also be entered through a small opening in the cliff-face 75 m west of the portal. The stope of the Lone Jack is partially collapsed, and access
through the mine is more easily gained by climbing and descending the ore chutes. The 120 m at the north end of the workings lie within a body of talc schist. No quartz veining is present within this talc body.

The Lone Jack was the richest of the three veins, having accounted for over 70% of the total production. The ore grade was estimated by Moen (1969) to have been approximately 94.5 g gold per ton.

Whist

The Whist vein is 230 m northeast of the Lone Jack vein. It strikes N10E and dips 85SE. The Whist is exposed for about 25 m and is buried by talus at both ends. The vein averages 65 cm in thickness. This prospect is undeveloped. Moen (1969) reported assays from the Whist with 31 gm gold and 3.8 gm silver per ton.

The Whist vein is emplaced within the high-angle fault which truncates the eastern margin of the Lone Jack vein. The Whist appears to pinch out upwards into this fault; its behavior at depth is unpredictable due to the limited exposure.

The wall rocks of the Whist are biotite-bearing hornfels of Chilliwack Group sediments. Biotite in this hornfels has been altered to chlorite by the passage of the fluids which formed the Whist deposit (fig. 12). Thus, emplacement of the Whist post-dates the contact metamorphism.

Lode Mineralogy and Paragenesis

Because the Lone Jack, Lulu, and Whist veins contain similar mineralogy, they will be discussed together. The minerals include dominant quartz, and minor pyrrhotite, pyrite, chalcopyrite, tellurbismuth, and gold. Two generations of mineralization were first observed by Lindstrom (1941). The first, and most voluminous, generation consists mainly of
Figure 12. Photomicrographs of Whist vein wall rock, showing biotite being altered to chlorite. Top view, crossed nicols; bottom view taken in plane polarized light.
quartz, with very sparse, disseminated sulfides, tellurbismuth, and gold. The second generation of minerals was precipitated in cracks and fissures in the earlier generation, and contains the bulk of the sulfide, gold, and tellurium mineralization.

Quartz comprises over 98% of the veins. First generation quartz is milky-white and allotriomorphic, with grain sizes up to 0.5 mm. This quartz is fractured and strained, and exhibits an undulose extinction. The second generation of quartz is generally clear and very fine grained, with an average grain size of less than 0.01 mm.

The sulfide minerals comprise less than 1% of the veins; pyrrhotite comprises over 95% of the sulfide minerals. The sequence of mineral precipitation is the same for both generations of mineralization. Pyrite, the first to crystallize, is the least common sulfide, and was seen in hand samples from only a few localities. It is being replaced by pyrrhotite (fig. 13). Pyrrhotite is partially replaced by very minor chalcopyrite (fig. 14). Chalcopyrite, although more common than pyrite, is also very rare, and was more commonly found in the wall rocks than in the veins themselves.

Tellurbismuth, Te₂Bi₃, and free gold commonly occur together. They occur as disseminated grains in first generation quartz, or more commonly, along veins cross-cutting the earlier quartz gangue (fig. 15). Tellurbismuth occurs as platy, pseudo-hexagonal grains up to 3.5 mm long, with a silvery metallic luster and brittle basal cleavage. Free gold ranges in size up to two millimeters. It was found in discontinuous pockets in all three veins. Gold was found most commonly in fractures paralleling the wall rocks, in areas with some slight iron-staining. The association of gold with the tellurbismuth, fracturing, and iron-staining is
Figure 13. Photomicrograph of pyrrhotite (po) replacing pyrite (py). Reflected light on polished surface. Sample taken from the Lulu vein.

Figure 14. Photomicrograph of chalcopyrite (ccp) replacing pyrrhotite (po). Reflected light on polished surface. Sample taken from the Lulu vein.
Figure 15. Photomicrograph of tellurbismuth (TeB) and gold (Au) in second generation quartz. Sample collected from the Lone Jack vein. Reflected light on polished surface.
characteristic of areas with high-grade gold.

Wall rock alteration is very minor in all three veins. The vein-wall rock contacts are very sharp and defined. In thin section, fine-grained quartz, pyrrhotite, and calcite are seen to have been added to the wall rocks, indicating a loss of sulfur, CO$_2$, and SiO$_2$ from the ore-forming solutions (fig. 16).

The paragenesis of the vein minerals, summarized in figure 17, is as follows:

1. Initial fracturing created open space fissures for the mineralizing solutions to enter;
2. Quartz began to precipitate, followed by pyrite, pyrrhotite, and chalcopyrite. Tellurbismuth and gold sparsely precipitate; they largely post-date the earlier minerals;
3. Fracturing reoccurred;
4. A second generation of minerals similar to the first was deposited, but containing the bulk of the gold-tellurbismuth mineralization.

The position of gold and tellurbismuth in the paragenetic sequence was difficult to determine, as they were seldom found with any of the sulfides.

Economic Geology

Since mining ceased in 1924, various interests have commissioned economic investigations of the Lone Jack properties. Assays contained in these reports indicate the presence of economic-grade ore in all three veins. However, further exploration is needed to prove sufficient tonnages exist to warrant future mining.

Grant (1984) provides the most complete evaluation of the economic
Figure 16. Photomicrograph of Lone Jack wall rock, showing the formation of fine-grained quartz (Qz), pyrrhotite (po), and calcite (Ca). Crossed nicols.
Figure 17. Paragenetic sequence of vein mineralization.
potential of the Lone Jack property. His assays of the Lone Jack and Lulu veins are shown in Plates I and II. Much of the following discussion is summarized from his report to the S. A. Collender Co. of Langley, Wa.

Of the three prominent gold-quartz veins present, the Lone Jack vein appears to be the least promising target for future development. Most of this vein was removed during mining, and what remains is seen to be either pinching out or terminating in cliff faces and fault zones in all directions save the SW; in this area the vein is less than 1/3 m thick and disappears into talus and snow. The highest gold assays are from the southern parts of the stope, however the narrowness of the vein, difficulty of access, and lack of exposure make further exploration in this area difficult to justify.

Grant suggested that the Lulu vein has potential for limited development. His assays indicate that economic-grade ore remains in the eastern part of the stope (Plate I). Grant projected >7,750 tons of ore grading >15ppm gold may exist if the vein extends from the eastern stope face to the Lulu fault and 100' to the south. Based on Grant's projections two sites were diamond drilled in October, 1985, under the supervision of Charles Stone of Bellingham, Washington. These sites were chosen to test the possible eastward extension of the stope production vein. The first was located in the north wall of the main haulageway, 1.5m west of the Lulu fault. This was drilled at N31W at +45° and extended 24.5m. The second, located across the haulageway, was drilled to the west at +75° for 18m. Neither intersected vein quartz. It is possible that these sites should have been drilled at a shallower angle. Grant's projections were proposed on the assumption that the vein continues horizontally eastward from the stope; evidence exists that this is not the case.

Approximately 10 m up the raise driven in the Lulu fault a short
drift was driven on a 1 m thick quartz vein that bears E-W and dips 50°S. During the drilling, a sample was collected from this vein segment that assayed 15.6 ppm gold. This value correlates with the values in the eastern part of the stope. If this vein segment in the Lulu fault represents the eastern extension of the Lulu vein, both drill holes were above the target.

Possible reserve tonnage calculations are also complicated by the lack of a controlled survey through the Lulu mine. A transit survey may reduce the area of the projected ore block.

Based on Grant's assay data and the possible eastward extension of the Lulu vein, Stone (1986) presented a plan for further diamond drilling and mining of the Lulu. His plan is presently under consideration.

The Whist vein assays between 3.75 and 91.25 ppm gold (Grant, 1984). This vein hasn't been developed, probably because of its limited exposure and relative inaccessibility. A limited magnetic survey, followed by diamond drilling to test any anomalies present, would seem to be justified.
FLUID INCLUSION STUDIES

Vein quartz samples for fluid inclusion study were collected from underground ore of the Lone Jack and Lulu lodes, and from the surface exposure of the Whist lode. Each suitable inclusion has been both frozen and heated, and the nature and temperature of the observable phase changes were recorded. The comparison of these results with experimental data enabled estimates to be made of the chemical and physical conditions prevailing during ore deposition.

Selection and Sample Preparation

The three lodes at the Lone Jack group of claims have quartz gangue similar in appearance. All veins are fine-grained, milky white, fractured and strained, and vuggy in places. The vein quartz is commonly Fe-stained and invariably milky and unclear as a result of the incorporation of numerous small fluid inclusions, pieces of wall rock, and minor amounts of sulfides. In thin section several generations of fluid inclusions could be recognized, and Roedder's (1976) criteria for differentiating between primary, pseudosecondary, and secondary inclusions had to be carefully applied. Quartz from epithermal gold veins is usually fine-grained, and it is notoriously difficult to find suitable material for fluid inclusion study from these types of deposits (Sawkins and others, 1979). The search for relatively undeformed quartz with large primary inclusions was the major factor in sample selection.

Eighteen locations within the three quartz lodes were sampled. After petrographic examination, nine of these samples were selected as being the most suitable for study: four from the Lone Jack, three from the Lulu, and two from the Whist. Plates I and II show the localities of the
samples taken from the Lone Jack and Lulu. Sample 193 was taken from the bottom of the Whist; sample 73 is from the upper part of the Whist exposure. Ten doubly-polished quartz slabs were prepared from each sample, and those slabs with suitable primary inclusions were chosen for study.

Description of Fluid Inclusions

Fluid inclusions analyzed in this study ranged in size from 10\(\mu\)m to 25\(\mu\)m, in their longest dimension, with an average size of 15\(\mu\)m. The phase transitions in inclusions less than 10\(\mu\)m in size could not be optically determined, and for this reason inclusions in the fine grained, secondary quartz were unsuitable for analyses.

Upon viewing the samples at room temperature, three features are readily apparent: (1) there is considerable \(\text{CO}_2\) present, as evidenced by the abundance of liquid \(\text{CO}_2\); (2) no solid phases are present within the inclusions; and (3) the inclusions tend to be vapor-rich, with variation in the degree of fill indicating that boiling was occurring during deposition. A photomicrograph of a typical three-phase inclusion is shown in figure 18.

Three types of inclusions were recognized based on the volume and composition of the phases present at room temperature:

Type I. Three phase, \(\text{CO}_2\) rich inclusions with aqueous phases >50 volume \%. These comprised 31\% of the population studied.

Type II. Three phase, \(\text{CO}_2\) rich inclusions with aqueous phases <50 volume \%. These comprised 60\% of the population studied.

Type III. Two phase, water rich inclusions, with the vapor phase <30 volume \%. These comprised 9\% of the population studied.

All three types of inclusions display varied morphologies, with
Figure 18. Photomicrograph of a three-phase inclusion. Sample #212, Lulu vein. Plane polarized light. Inclusion diameter ~15μm.
irregular, prismatic, or equant outlines. Larger inclusions are invariably highly irregular, making estimation of liquid and vapor volume percentage difficult. Necking down and shearing of the inclusions is common; primary inclusions are found alone or in small groups without obvious planar orientation.

Heating and Freezing Measurements

Eighty-nine fluid inclusions were analyzed using an SGE Model II heating and freezing stage. Liquid nitrogen was blown over the sample for freezing, and air blown over a heating element was used for heating. A 16x eyepiece and 30x objective provided an effective magnification of 480x for observation of the phase changes.

Each inclusion was first heated to 40°C and carefully sketched to estimate the vapor and liquid volume percentages, using the procedure outlined by Roedder (1976) and Ashworth (1983). The inclusion was then cooled until the CO\textsubscript{2} froze, usually between -95°C to -105°C. At this point the inclusion was slowly warmed and the temperature and nature of the phase transitions was recorded.

Upon warming, the following phase changes were observed in sequence: CO\textsubscript{2}-rich solid melting; water ice melting; clathrate melting; CO\textsubscript{2} homogenization; and aqueous liquid and vapor homogenization. The melting temperatures and temperature of CO\textsubscript{2} homogenization were reproducible to within ± 0.2°C; temperatures of final homogenization were in most cases reproducible to within ±3°C. The observed results are tabulated in Appendix 2, and their relation to experimentally determined equilibria are as follows:

(1) The first observed phase change was the melting of a CO\textsubscript{2}-rich solid between -56.4°C and -59.3°C (figure 19). CO\textsubscript{2} melting was noted in
Figure 19. CO$_2$ melting temperature diagram.
86% of all inclusions studied. This temperature is dependent on the amount of CH₄ in the system, and experimentally determined phase boundaries for the system CO₂-CH₄ are shown in figure 20 (Burruss, 1981). Swanenburg (1979) provides a convenient technique for determining bulk CH₄ from the melting temperature of CO₂ and the estimated liquid/vapor ratio at that temperature (fig. 21). The average CO₂ melting temperatures and the CO₂-CH₄ compositions derived from figure 21 are given in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Lone Jack</th>
<th>Lulu</th>
<th>Whist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average CO₂ melt Temp.</td>
<td>-56.6°C</td>
<td>-57.2°C</td>
<td>-58.1°C</td>
</tr>
<tr>
<td>X CH₄</td>
<td>0.0</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>X CO₂</td>
<td>1.00</td>
<td>0.96</td>
<td>0.94</td>
</tr>
</tbody>
</table>

The Whist vein contains the most CH₄, and the Lone Jack contains the least, which is to be expected if the fluids became more oxidizing as they approached the surface. This suggests that the three veins were formed at the same relative elevation as seen today, and were not formed together and subsequently faulted apart.

(2) The melting of water ice occurred between -3.4°C and -2.0°C (fig. 22). This phenomenon was noted in 8 inclusions, or 9% of the total studied. This phase change is dependent on, and provides a means to measure, the salinity of the fluid (Collins, 1979).

H₂O melt was only noted in type III inclusions; i.e. those with a high liquid/vapor ratio and no observable CO₂ at room temperature.
Figure 20. Experimentally observed P–T phase equilibria for the system CO$_2$–CH$_4$ (after Burruss, 1981).
Figure 21. Bulk $X_{CH_4}$ defined by final melting temperature of CO$_2$ ($T_{fm}' \, ^oC$) and degree of filling with liquid at that temperature (after Swanenburg, 1979).
Figure 22. H$_2$O Melting temperature diagram.
The average water ice melting temperature was -2.6°C, and this indicates salinities of about 4 weight % NaCl equivalent (fig. 23).

(3) Clathrate melting occurred between 9.0°C and 11.5°C (fig. 24), and was noted in 65 inclusions; 73% of all inclusions studied, and 84% of those inclusions displaying CO₂ melting.

Clathrate compounds are non-stoichiometric gas hydrates in which gas molecules are trapped in the host crystal lattice of water molecules. It is common for inclusions with both a water-rich phase and a CO₂-rich phase at room temperatures to crystallize the compound carbon dioxide hydrate (CO₂ · 5.75 H₂O) upon freezing, and clathrates have been detected from a variety of ore deposits, metamorphic terranes, and vein minerals (Collins, 1979). Clathrate hydrates also form from a number of other molecules, including CH₄, H₂S, SO₄, N₂, O₂, and various other carbon compounds (Ashworth, 1983).

Clathrates form very pure compounds, and prohibit dissolved salts from entering the hydrate structure. Thus, after clathration occurs, any residual aqueous solution is more saline than the original solution. This prohibits the use of water-ice melt for determining salinities from inclusions containing clathrates.

A procedure for determining salinities in the CO₂-NaCl-H₂O system, using clathrate melting temperatures, is given by Collins (1979). Figure 23 shows the depression of clathrate melting temperature by NaCl. The presence of additional gases complicates the use of this technique; CH₄ in particular raises the temperature of clathrate melting.

Average clathrate melting temperatures are: Lone Jack 9.7°C; Lulu 10.3°C; and Whist 10.3°C. It can be seen from figure 23 that these temperatures are indicative of extremely dilute solutions. The melting
Figure 23. Depression of the melting temperature of H$_2$O by NaCl and depression of the melting temperature of CO$_2$ by NaCl (after Collins, 1979).
Figure 24. Clathrate melting temperature diagram.
temperatures above 10°C confirm the presence of CH₄ in the Whist and Lulu. The presence of CH₄ was also indicated by the variation in the CO₂-rich liquid melt, as discussed earlier.

(4) The next observed phase change was the homogenization of the CO₂-rich liquid and vapor, between 8.00°C and 29.5°C (fig. 25). Sixty-nine inclusions, or 78% of the total, contained sufficient CO₂ to display an aqueous-rich CO₂ phase at room temperature, or upon slight cooling. This CO₂ homogenization temperature was used along with the estimated volume % H₂O to estimate the bulk composition and molar volume of the solution. The procedure is described by Burruss (1981) and Ashworth (1983). A short outline is as follows:

(a) The volume % H₂O is estimated at 40°C (in the discussion which follows, let us consider an inclusion containing 50 volume % H₂O).

(b) The pressure within the inclusion at 40°C is determined from the isochore defined by the nature and temperature of the CO₂ homogenization (figure 26). Thus, an inclusion with CO₂ homogenizing at 25°C into the liquid phase has an internal pressure of 133 bars at 40°C.

(c) Using figure 27, the bulk density can be determined from the estimated volume % H₂O and pressure at 40°C. In the example, an inclusion with 50 volume % H₂O and pressure of 133 bars at 40°C has a bulk density ρ = 36 moles/liter.

(d) Bulk molar volume, V_B, is calculated from the bulk density from the equation: V_B = 10³/ρ. Thus, 36 moles/liter = 27.8 cc/mole.

(e) The mole % H₂O in the system can now be determined from figure 28, using the bulk molar volume and CO₂ homogenization temperature. The example, with V_B = 27.8 cc/mole and CO₂ homogenization at 25°C into the liquid phase, contains 77-79 mol % H₂O.

Figure 29 gives the calculated mole fraction of H₂O for all
Figure 25. CO\textsubscript{2} homogenization temperature diagram.
Figure 26. Phase diagram for CO$_2$, showing densities (g/cc) of several isochors. The dashed lines relate to example in text (after Hollister, 1981).
Figure 27. A quantitative, isothermal $\rho$-$P$ diagram for coexisting $\text{CO}_2$ and $\text{H}_2\text{O}$ fluids at $40^\circ\text{C}$. The volume percent $\text{H}_2\text{O}$ contours allow estimation of the bulk density of an inclusion for any observed $\text{CO}_2$ phase density and estimated pressure. $\rho$ moles/liter = $1\overline{V}_B \times 10^3$, where $\overline{V}_B$ is expressed in cc/mole.
Figure 28. A polythermal $\bar{V}$-$X_{H_2O}$ diagram with tie lines for coexisting $CO_2$ fluids and $H_2O$-rich liquid for the designated $CO_2$ liquid-vapor homogenization temperatures ($T_H$, where the subscript L or V indicates homogenization to liquid or vapor). Tie lines refer to example in text (after Burruss, 1981).
inclusions from which suitable data were obtained. Calculated mol % H₂O ranges between 57% and 88%, with an average value of 75%. This large spread is a result of the nature of the boiling, vapor-dominated system, which tends to irregularly partition volatiles into the vapor phase.

(5) The last phase change observed upon heating is the homogenization of the liquid and vapor to one fluid phase. Because of the high CO₂ content of the system, internal pressures of some inclusions exceeded the tensile strength of the enclosing quartz upon heating and decrepitation commonly occurred.

Twenty-five percent of the inclusions homogenized to liquid, 34% homogenized to vapor, 9% displayed critical behaviour, and 33% decrepitated (fig. 30). Type I inclusions generally homogenized to vapor, and types II and III to liquid. All three quartz lodes produced similar homogenization phenomena, with temperatures ranging from 130°C to 325°C.

Type III inclusions homogenized between 130°C and 222°C, and are most likely secondary inclusions that indicate a drop in the temperature subsequent to the mineralization. Inclusion types I and II homogenized between 260°C and 310°C, with a pronounced peak of values at 285°C, and are thought to represent the mineralizing conditions.

As the P-T conditions were such that boiling took place during deposition of all three quartz lodes, the true trapping temperature is represented by the final homogenization temperature. The trapping temperature of a boiling solution can be used to determine the trapping pressure, assuming the fluid composition is known. Experimentally determined vapor-pressure curves for the system CO₂-H₂O are shown in figure 31. It can be seen from these curves that a solution with .75 mol % H₂O and .25 mol % CO₂ boils at approximately 625 bars. This diagram also illus-
Figure 29. Mole fraction $\text{H}_2\text{O}$ calculated from the $\text{CO}_2$ homogenization temperature and the estimated volume $\%\ \text{H}_2\text{O}$.
Figure 30. Fluid inclusion homogenization temperature diagram.
trates that such a P-T-X condition lies along the critical curve, and explains the observed homogenization critical phenomena. Figure 32 illustrates the effect of NaCl on the CO₂-CH₄ system, and shows that even a small component of NaCl raises the solvus dramatically. Thus, if the solutions had been more saline, boiling would not have occurred.

Results of Fluid Inclusion Studies

The fluid inclusion studies indicate that the bulk of the quartz deposition occurred in the temperature range of 260°C to 310°C, with a peak of values around 285°C. The fluids were low in salinity (<0.5 equivalent wt.% NaCl), boiling, and contained an average of 75 mol % H₂O and 25 mol % CO₂. Variations in CO₂ and clathrate melting temperatures demonstrate that some additional gaseous component was present (probably methane) in an amount less than 6 mol % relative to CO₂. The amount of CH₄ decreased with the elevation of the quartz vein; the Whist vein has the most CH₄ and the Lone Jack the least.

The second generation of quartz did not produce inclusions suitable for heating and freezing, however visual estimates of their composition were possible using a higher power magnification than that of the heating-freezing apparatus. At 800x magnification, these inclusions from the fine-grained, secondary quartz are resolved to show a liquid-vapor filling ratio indicative of boiling (fig. 33), and the larger inclusions contain CO₂ liquid. Three inclusions in the second-generation quartz from the Lone Jack vein were seen to homogenize to the vapor phase at approximately 300°C, indicating the fluids were essentially similar in composition to the fluids responsible for the bulk of the quartz deposition.

To determine the depth of burial at the time of formation, it must first be determined if the pressure of 625 bars is hydrostatic or litho-
Figure 31. Iso-compositional curves of the liquid phase in equilibrium with the gas phase in the system H$_2$O-CO$_2$ (after Takenouchi and Kennedy, 1964). Tie lines refer to mineralizing conditions.
Figure 32. Isochores (solid curves, designated in g cm\(^{-3}\)) for fluids with the bulk compositions labeled in the lower right corner of each diagram. The dashed curves represent the limits of the miscibility gap in the system H\(_2\)O-CO\(_2\)-NaCl (after Bowers and Helgeson, 1983).
Figure 33. Two inclusions from second generation quartz. The variable degree of fill indicates boiling at time of deposition (800X, plane light).
static. The relationship between hydrostatic pressure and depth is:

\[ h = \frac{P}{gd} \]

where \( h \) is height in cm; \( P \) is pressure in dynes/cm\(^2\); \( d \) is density in gm/cm\(^3\); and \( g \) is the acceleration due to gravity in cm/sec\(^2\). The density of the fluid at the Lone Jack vein group is 0.8 gm/cm\(^3\) \((X_{H_2O} = .74; X_{CO_2} = .25)\). At 625 bars hydrostatic pressure, depth of emplacement is calculated to be approximately 8 km.

Assuming a density of 2.9 gm/cm\(^3\) for the phyllite, 625 bars of lithostatic pressure occurs at a depth of approximately 3.4km. The geothermal gradients resulting from these two depth of burial determinations are diagrammed in figure 34, an isobaric temperature-depth graph. Assuming a hydrostatic pressure, the geothermal gradient at the time of mineralization was 35°C/km, which is 5°C above that given for average continental crust (Best, 1982). Assuming lithostatic pressure, the geothermal gradient would be 84°C/km. This higher gradient would be expected in an area of igneous activity such as the study area. The nature of the open-space vein fillings which characterize the lodes also suggests they were formed at the shallower depth inferred from lithostatic conditions.
Figure 34. An isobaric temperature-depth diagram, showing the geothermal gradients inferred from the mineralizing conditions.
CONDITIONS OF MINERALIZATION

The mode of transport and deposition of gold is derived from a knowledge of the chemistry and pressure-temperature conditions prevailing at the time of mineralization. A log $f_02$-$pH$ diagram is an instructive graphic representation of these chemical and physical conditions, and enables an estimation to be made of possible gold complexing mechanisms. Thermodynamic values necessary for construction of such a diagram were derived from the fluid inclusion studies and vein mineralogy equilibria. Using these calculated fluid-mineral equilibria, the mechanism for gold transport and precipitation can be inferred.

Thermodynamic Equilibria

In order to construct a log $f_02$ - $pH$ diagram the following parameters are here derived: pH, the fugacities of oxygen and sulfur, and the activities of chloride, sodium, and potassium ions. Solution equilibria are plotted on figure 35. Equilibrium constants used to determine these relationships are given in Appendix 2.

The fugacity of oxygen in the system is constrained by the presence of CO$_2$ within the fluid inclusions existing in equilibrium with graphite in the wall rocks. The equilibrium constant for the reaction:

$$C + O_2 = CO_2$$

is given by Ohmoto and Kerrick (1977). At 285°C, determined from the fluid inclusion studies, the $f_02$ was calculated to be $10^{-35}$ bars.

Sulfur fugacity is limited by the presence of pyrrhotite without pyrite. The equilibrium constant for the reaction:

$$2FeS_2 = 2FeS + S_2$$

is given by Helgeson (1969). Total sulfur has to be an amount which places the py-po boundary above the CO$_2$-graphite boundary, and $\Sigma S$ was estimated
to be $10^{-3}$ m. Using $\varepsilon S = 10^{-3}$ m and 285°C, the sulfide species equilibria were calculated from data provided by Helgeson (1969).

Salinities determined from the clathrate melting were less than 0.5 and close to 0 wt.% NaCl equivalent; which is the range of accuracy of the method described by Collins (1979). A value of 0.2wt% NaCl was used for the thermodynamic calculations, chosen to correspond to the study of the Broadlands geothermal system where deep well waters contain 1130ppm NaCl (Browne and Ellis, 1970).

The chloride and sodium activities were calculated from the salinity data as follows:

1. A 0.2 wt% NaCl solution was calculated to be equal to a 0.034 m solution.

2. The activity of sodium was related to the concentration of NaCl by the equation:

$$a^{\text{Na}^+} = m_{\text{NaCl}} + \gamma_{\text{NaCl}}$$

$\gamma_{\text{NaCl}}$, the stoichiometric mean activity coefficient, is equal to 0.332 at 285°C (Helgeson, 1969). Using $m_{\text{NaCl}} = 0.034$, the activity of sodium was calculated to be 0.011m, which is also equal to the activity of Cl$^-$. The potassium ion activity was obtained by assuming that at depth, albite is in equilibrium with K-feldspar (Orville, 1963) according to the reaction:

$$\text{NaAlSi}_3\text{O}_8 + K^+ = \text{KAlSi}_3\text{O}_8 + \text{Na}^+$$

The equilibrium constant for this reaction was extrapolated from Helgeson (1969) to be $10^{+0.87}$. From the equilibrium relationship:

$$10^{+0.87} = \frac{a_{\text{Na}^+}}{a_{K^+}}$$

the activity of potassium was calculated to be 0.002 m.
Figure 35. Log $f_{O_2}$–pH diagram at 285°C and 625 bars. Shaded area represents conditions of ore deposition.

$ES = .001 \text{ m}; \quad ^{a}\text{Na}^+ = 0.01 \text{ m}; \quad ^{a}\text{Cl}^- = 0.01 \text{ m}; \quad ^{a}\text{K}^+ = .002 \text{ m}; \quad \text{Py} = \text{pyrite}; \quad \text{Po} = \text{pyrrhotite}; \quad \text{Kao} = \text{kaolinite}; \quad \text{Ser} = \text{sericite}; \quad \text{Kfd} = \text{potassium feldspar}.
The pH is constrained by the presence of sericite in the wall rocks, and the absence of kaolinite and potassium feldspar. The equations governing the formation of these secondary minerals are:

\[
3\text{KAlSi}_3\text{O}_8 + 2\text{H}^+ \rightarrow \text{KAl}_3\text{Si}_3\text{O}_{10} (\text{OH})_2 + 6\text{SiO}_2 + 2\text{K}^+ \tag{7}
\]

\[
2\text{KAl}_3\text{Si}_3\text{O}_{10} (\text{OH})_2 + 2\text{H}^+ + 3\text{H}_2\text{O} \rightarrow 3\text{Al}_2\text{Si}_2\text{O}_5 (\text{OH})_4 + 2\text{K}^+ \tag{8}
\]

from the equilibrium data provided by Helgeson (1969) the pH is estimated to be between 5.9 and 7.0. Henley and others (1984) provide another means of estimating pH based on salinity and temperature. Using figure 36 and \(m(\text{Na}^+ + \text{K}^+) = 0.01\) (from the previous derivations), pH at 285°C is equal to approximately 6.8. As neutral pH is about 5.6 at 285°C, the system is slightly alkaline.

Gold Transport and Deposition

Gold may be chemically transported in solution by the formation of gold-chloride complexes (Helgeson, 1969; Henley, 1973; Seward, 1972) and thio complexes (Hattori, 1975; Seward, 1972; Weissburg, 1969). The study of present-day hydrothermal systems has shown them to be nearly neutral in pH (White, 1967; Weissburg, 1969), and in this range thio complexes have been shown to be the most stable (Seward, 1972). Thio complexes are considered to be the dominant metal transporting agent in precious metal vein deposits (Smith and others, 1982). Both gold-chloride and thio solution equilibria are here calculated and compared with conditions which prevailed at the time of mineralization.

The equation governing gold-chloride transport and precipitation is given by Henley (1973) as:

\[
\text{Au} + 0.25\text{O}_2 + 2\text{Cl}^- + \text{H}^+ = \text{AuCl}_2^- + 0.5\text{H}_2\text{O}.
\]

It can be seen from this equation that high pO2, high aCl-, and low pH favor the formation of chloride complexes. The equilibrium constant for
Figure 36. Comparison of pH-temperature relations constrained by the Kspar-Kmica-quartz equilibrium at 3 salinities with observed pH in fluids discharged from a number of geothermal fields (Henley and others, 1984).
this reaction at 285°C was extrapolated from Helgeson (1969). Gold solubility curves for various concentrations of AuCl\textsuperscript{2-} were plotted on figure 35, assuming a chloride concentration of .034 m. As these curves plot well outside of the stability field which depicts the mineralization conditions, gold-chloride complexing was probably insignificant.

The equation governing gold-sulfide complexing is given by Seward (1972) as:

\[
\text{Au}^0 + \text{H}_2\text{S} + \text{HS}^- + 0.25\text{O}_2 = \text{Au(HS)}_2^- + 0.5\text{H}_2\text{O}.
\]

This equation indicates that thio complexing is enhanced by oxidizing, near-neutral conditions. The equilibrium constant for this equation was extrapolated from data provided by Seward (1972) and Casadevall and Ohmoto (1977) to be $10^{-1.16}$. Three gold solubility curves were plotted on fig. 36, using various Au(HS)\textsubscript{2-} concentrations. The .01ppm and .001ppm Au(HS)\textsubscript{2-} curves intersect the stability field of the mineralizing fluids, which indicates gold-sulfide complexes are a viable mechanism for gold transport. For comparison, Broadlands, New Zealand is an active geothermal system presently precipitating gold from highly undersaturated solutions containing .04ppb Au (Weissburg, 1969).

Au(HS)\textsubscript{2-} complexes will precipitate gold in response to changes in temperature, pH, and oxygen and/or sulfur fugacities (Seward, 1972). A change in temperature cannot be ruled out as a precipitating mechanism, because fluid inclusions in the fine-grained, gold-bearing, secondary quartz were difficult to analyze. However, the following lines of indirect evidence point against such a cause: (1) using a higher power magnification (800x) than that available with the heating-freezing apparatus (480x), the second-generation quartz appears to contain inclusions similar to the first-generation quartz (i.e. boiling and dilute); (2) three inclusions in the secondary quartz from the Lone Jack lode homogenized to the
Boiling takes place when the vapor pressure of a rising fluid exceeds the confining hydrostatic pressure. Boiling has the effect of partitioning volatiles into the vapor phase, thereby changing the bulk chemistry of the residual fluid. When boiling results from a sudden change in physical conditions, such as drop in pressure, volatiles with differing partial pressures may be induced to boil simultaneously. The loss of H₂S into the vapor phase has two effects: it increases pH by consuming hydrogen ions, and the decrease in total sulfur decreases the solubility of metal-bearing sulfide complexes (Kamilli and Ohmoto, 1977). The loss of CO₂ to the vapor phase also tends to increase pH and precipitate carbonate complexes.

It can be seen from figure 36 that lowering the pH or decreasing the total sulfur concentration will shift the solution equilibria to a position where thio complexes will precipitate. Boiling of the hydrothermal solutions is believed to be the cause of such a shift.

Mineralogic assemblages found in some areas indicate the possibility of gold forming complexes such as gold-antimony, gold-tellurium, gold-arsenic (Seward, 1972), or various carbonate complexes (Kerrick and Pyfe, 1981). Gold-tellurium complexing may have occurred in the study area, as evidenced by the tellurbismuth-gold association. The abundance of CO₂ in the system may also indicate gold-carbonate complexing occurred. Experimental studies have not been made of these possible complexing mechanisms, and their effect on gold transport and deposition cannot yet be evaluated.
Summation of Mineralizing Conditions

The derived fluid-mineral equilibria show the chemical conditions at the time of mineralization to be reducing \((\log f_O^2 = -35)\) and slightly alkaline \((pH \text{ at } 285^\circ C = 5.9 \text{ to } 7.0)\). Gold-chloride complexing was probably insignificant; gold-bisulfide complexing is a more likely agent for gold transport. Precipitation of gold probably resulted from the change in pH and the decrease in total available sulfur caused by boiling of the ore-forming fluids.

The solutions which formed the Lone Jack vein system belong to a class of hypogene gold-quartz deposits whose characteristics are: low salinities, temperatures between \(250^\circ C \text{ and } 300^\circ C\), reducing and neutral to slightly alkaline in pH, and variable concentrations of \(CO_2\) (Ashworth, 1983; Casadevall and Ohmoto, 1977; Kamilli and Ohmoto, 1977; Weissburg, 1969). Sulfide complexing is considered to be the mechanism for transport, and boiling is commonly considered to be a precipitation mechanism (Ashworth, 1983; Kamilli and Ohmoto, 1977).
DISCUSSION

Hypogene gold-quartz veins such as in the Lone Jack Mine are thought to have formed in hydrothermal convection cells, driven by a deep heat source, and precipitated within fracture systems created by tectonic activity. Any model of such a system should propose a possible heat source, a source for the circulating waters, a source for metals and sulfur, and should discuss the nature and timing of the fracturing that provided the sites for deposition. A genetic model which seeks to explain the source and mechanism of mineralization also would help to define favorable areas for exploration. Such a model should combine the regional and local geology with calculations of the chemical and physical parameters of the ore-forming fluid.

A geologic model that explains the formation of the gold-quartz ore of the Lone Jack claims must account for the following observations:

1) The quartz veins are indistinguishable mineralogically, but veins lower in elevation have higher X CH₄. This indicates that they were formed from the same fluids, and that the fluids became more oxidizing as they travelled upward. Thus, the Lone Jack and Lulu veins formed with the same elevation relationship as seen today, and were not formed and subsequentially faulted apart.

2) The quartz veins are genetically related to high-angle, Tertiary faults. The Whist vein lies within such a fault; the Lone Jack and Lulu veins are bordered by them. Subsequent movement on these faults brecciated the early-formed quartz gangue, and offset the Lulu vein 15 m. The low-angle dips exhibited by the Lone Jack and Lulu veins are a puzzling feature and require a mechanism to create and maintain open-space fracturing.
3) The mineralization occurred during, or in the waning stages of, a period of intense igneous activity. The surface exposure of the Miocene Chilliwack batholith lies within 2.5 km to the east of the claims, and a small satellite stock of quartz-diorite and aplitic apophyses are found at the entrance to the Lulu. The underlying igneous rock created a zone of thermal alteration, containing the metamorphic mineral assemblage biotite-quartz-plagioclase, through which the veins were emplaced. Dikes, compositionally similar to the grano-dioritic batholith, are found lying within the same faults that controlled the quartz veins. This constrains the timing of these faults to the same time-frame as the period of batholith emplacement (and may represent an effect of the intrusion).

4) Ore-forming fluids were dilute and boiling at a temperature of 285°C and a pressure of 625 bars. The fluids were probably emplaced under lithostatic conditions, at a depth of approximately 3.4 km.

Model for Mineralization

The intense igneous activity in the area of the mineralization provided the necessary heat to drive the hydrothermal system. The source for the ore-forming fluids is best determined by oxygen isotope studies, and isotope studies of similar dilute, gold-quartz veins genetically associated with igneous activity have shown their ore-forming solutions to be largely composed of meteoric water, with varying, lesser amounts of formation and magmatic waters (Kamilli and Ohmoto, 1977; Casedevall and Ohmoto, 1977). Sulfur, gold and associated metals are thought to be derived primarily from the leaching of the country rock; a component of magmatic water may also add metals and sulfur to such a system. Such a system grows with time, as the area heated increases and the downward percolation of rainfall adds water. The heated water rises convectively,
seeking a channelway for transport.

The high-angle Tertiary faults, which are probably related to the emplacement of the Chillawack Batholith and the uplift of the area, provided the channelways for the mineralizing solutions. The gently-dipping fractures into which the Lone Jack and Lulu lodes were precipitated, are considered to have been created as ladder-veins formed parallel to the Darrington Phyllite S₁ foliation planes, with the aid of hydraulic fracturing from the rising fluids.

Metal-rich fluids entered the dilatant zones produced by the faulting, boiling commenced, and the metals were immediately precipitated. As the fluids were injected under lithostatic pressure, they were able to maintain the open fracture systems and prevent their collapse. The spent solutions were subsequently convected outward.

An outline of the events leading to the creation of these deposits constitutes a model for their formation:

(1) Well after the time of regional metamorphism and and Shuksan faulting, igneous activity at depth began to heat the overlying rock. This igneous activity, related to the emplacement of the Miocene Chilli-wack batholith, caused the formation of a contact-metamorphic aureole in the area of the mines.

(2) Meteoric and formation waters begin to heat and circulate, becoming enriched in CO₂, sulfur and metals by leaching from the surrounding rocks.

3) High-angle, block faulting occurred, caused by the injection of the underlying intrusives. Fissures were created along foliation planes in the Darrington Phyllite, aided by hydraulic fracturing from the ascending, hot waters. Orebearing solutions were injected into the fractures, where the sudden drop in pressure caused boiling to occur. This
resulted in the rapid precipitation of quartz and minor sulfides and gold.

4) Later, minor movement along the Tertiary faults brecciated the quartz-gangue and deposited the majority of the sulfides, gold, and tellurbismuth in fine-grained veinlets cementing the fractured gangue.

5) Continued uplift and erosion exposed the veins at the surface.

Prospecting

The search for similar deposits should center on locating post-metamorphic quartz veins near the Chilliwack Batholith which show evidence of boiling. Locally, high gold values appear to be centered in the Darrington Phyllite, as an examination of the prospects around the Lone Jack Mine indicates (fig. 37).

The principal quartz veins and claims in the area of the Lone Jack Mine were examined by Moen (1969). Assay and vein mineralogy data provided by Moen were used to classify the deposits found within 2 km of the Lone Jack Mine. The two reported lodes that lie within the Darrington Phyllite, the Lone Jack group and the Blonden mine, are the only ones reported with free-milling gold and little or no reported base metal sulfides. Each vein found within the Chilliwack Group, stratigraphically below the Shuksan fault, is reported to contain base metal sulfides and very low Au/Ag ratios (<<1). The zone of imbrication below the Shuksan fault appears to provide a useful stratigraphic horizon for prospecting.

White (1980) discusses a possible mechanism for such metal zonation. He noted that many hypothermal gold-quartz veins are similar in chemistry and mineralization to the active geothermal systems at Broadlands, New Zealand (Weissburg and others, 1969) and Steamboat Springs, Nevada (Nash, 1972). White noted a relationship between the Au/Ag content, associated
Figure 37. The principal gold-silver-quartz veins found within 3 km of the Lone Jack mine.
vein mineralogy, and depth of emplacement in these geothermal systems and in hypothermal gold-quartz veins in general, and classified two types of these deposits:

(1) Au-dominated. These quartz veins contain free gold, few if any base metal sulfides, and exhibit little if any wall rock alteration.

(2) Ag-dominated. These contain abundant base metal sulfides (chalcopyrite, sphalerite, galena, etc.), exhibit more marked alteration of the wall rocks, and commonly contain calcite or adularia.

The Au-dominated deposits, to which the Lone Jack veins can be compared, are shown by White (1980) to be similar to the upper parts of the Broadlands and Steamboat Springs hydrothermal systems. Ag-dominated deposits are similar to the deeper, base metal sulfide zone at Broadlands. White (1980) noted that Ag-dominated epithermal veins commonly grade upward into Au-dominated deposits, hence Ag-rich deposits may lie at depth below the Lone Jack. An examination of the ore deposits surrounding the Lone Jack claims shows many small Ag-rich deposits; perhaps such a deposit lies below the Shuksan fault in the area of the Lone Jack property.

The Lone Jack and Lulu veins do not seem capable of significant future development. The Whist vein should be explored by geophysical methods for possible extension. Geophysical surveys should be run perpendicular to the Tertiary fault traces on both sides of Bear Mt. and down toward the valley of Silesia Creek to locate ore bodies emplaced along these faults.

Because these veins were formed under lithostatic pressure, without a continuous vent to the surface, exploration in the area is of a blind nature. Similar deposits will most likely occur only as discontinuous pods and stringers.
CONCLUSIONS

The Lone Jack group of gold-quartz veins formed from boiling, dilute, CO₂-rich aqueous solutions. They were emplaced during high-angle Tertiary faulting at approximately 285°C and 625 bars of lithostatic pressure, during (or in the waning stages of), a period of igneous activity. Au(HS)₂⁻ complexes probably transported the gold; precipitation was almost certainly caused by boiling of the ore-forming solutions. In the area of the Lone Jack claims, additional ore shoots may lie at depth; the search for such deposits should center on locating zones of boiling within and above the trace of the Shuksan fault.
REFERENCES CITED


Casadevall, T., and Ohimoto, H., 1977, Sunnyside Mine, Eureka Mining District, San Juan County, Colorado: Geochemistry of gold and base metal ore deposition in a volcanic environment: Econ. Geol., v. 72, p. 1285-1320.

Crerar, D. A., and Barnes, H. L., 1976, Ore solution chemistry vs. solubilities of chalcopyrite and chalcocite assemblages in hydrothermal solution at 200° to 350°C: Econ. Geol., v. 71, p. 772-794.


Hattori, K., 1975, Geochemistry of ore deposition at the Yatani lead-zink and gold-silver deposits, Japan: Econ. Geol., v. 70, p. 677-699.


Kamilli, R. J., and Ohmoto, H., 1977, Paragenesis, zoning, fluid inclusion, and isotopic studies of the Finlandia vein, Colqui District, central Peru: Econ. Geol., v. 72, no. 6, p. 950-982.


Sawkins, F. J., O'Neil, J. R., and Thompson, J. M., 1979, Fluid inclusions and geochemical studies of vein gold deposits, Baguio District,
Phillipines: Econ. Geol., v. 74, p. 1420-1434.


Weissburg, B. G., 1969, Gold-silver ore-grade precipitates from New Zealand thermal waters: Econ. Geol., v. 64, p. 95-108.


## Appendix 1

**LULU FLUID INCLUSION DATA**

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>EST.VOL. % H₂O</th>
<th>INCLUSION TYPE</th>
<th>CO₂ SOL.</th>
<th>H₂O SOL.</th>
<th>CLATHRATE MELT</th>
<th>CO₂ LIQ.</th>
<th>INCLUSION HOMOG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>212</td>
<td>35</td>
<td>II</td>
<td>-56.6</td>
<td></td>
<td></td>
<td>27.0L</td>
<td>301V</td>
</tr>
<tr>
<td>17</td>
<td>II</td>
<td>-56.6</td>
<td></td>
<td></td>
<td></td>
<td>27.8L</td>
<td>278D</td>
</tr>
<tr>
<td>21</td>
<td>II</td>
<td>-56.6</td>
<td></td>
<td></td>
<td></td>
<td>28.1L</td>
<td>299V</td>
</tr>
<tr>
<td>29</td>
<td>II</td>
<td>-56.4</td>
<td></td>
<td></td>
<td></td>
<td>10.0</td>
<td>25.3L</td>
</tr>
<tr>
<td>43</td>
<td>II</td>
<td>-56.6</td>
<td></td>
<td></td>
<td></td>
<td>9.8</td>
<td>25.6L</td>
</tr>
<tr>
<td>32</td>
<td>II</td>
<td>-56.3</td>
<td></td>
<td></td>
<td></td>
<td>11.1</td>
<td>20.6L</td>
</tr>
<tr>
<td>52</td>
<td>I</td>
<td>-56.7</td>
<td></td>
<td></td>
<td></td>
<td>10.3</td>
<td>24.9L</td>
</tr>
<tr>
<td>29</td>
<td>II</td>
<td>-57.3</td>
<td></td>
<td></td>
<td></td>
<td>9.6</td>
<td>25.6L</td>
</tr>
<tr>
<td>34</td>
<td>II</td>
<td>-56.9</td>
<td></td>
<td></td>
<td></td>
<td>10.4</td>
<td>22.9L</td>
</tr>
<tr>
<td>41</td>
<td>II</td>
<td>-57.3</td>
<td></td>
<td></td>
<td></td>
<td>10.4</td>
<td>23.0L</td>
</tr>
<tr>
<td>204</td>
<td>66</td>
<td>I</td>
<td>-56.6</td>
<td></td>
<td></td>
<td>10.1</td>
<td>26.8C</td>
</tr>
<tr>
<td>46</td>
<td>II</td>
<td>-56.8</td>
<td></td>
<td></td>
<td></td>
<td>10.3</td>
<td>21.7L</td>
</tr>
<tr>
<td>54</td>
<td>I</td>
<td>-57.8</td>
<td></td>
<td></td>
<td></td>
<td>10.3</td>
<td>23.9V</td>
</tr>
<tr>
<td>42</td>
<td>II</td>
<td>-57.6</td>
<td></td>
<td></td>
<td></td>
<td>10.3</td>
<td>299L</td>
</tr>
<tr>
<td>51</td>
<td>I</td>
<td>-58.2</td>
<td></td>
<td></td>
<td></td>
<td>10.5</td>
<td>24.6V</td>
</tr>
<tr>
<td>51</td>
<td>I</td>
<td>-56.7</td>
<td></td>
<td></td>
<td></td>
<td>9.9</td>
<td>28.4C</td>
</tr>
<tr>
<td>70</td>
<td>I</td>
<td>-56.6</td>
<td></td>
<td></td>
<td></td>
<td>9.5</td>
<td>28.2L</td>
</tr>
<tr>
<td>45</td>
<td>II</td>
<td>-56.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>278L</td>
</tr>
<tr>
<td>55</td>
<td>I</td>
<td>-56.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>274D</td>
</tr>
<tr>
<td>201</td>
<td>32</td>
<td>II</td>
<td>-57.7</td>
<td></td>
<td></td>
<td>11.0</td>
<td>21.5C</td>
</tr>
<tr>
<td>46</td>
<td>II</td>
<td>-58.3</td>
<td></td>
<td></td>
<td></td>
<td>11.5</td>
<td>308C</td>
</tr>
<tr>
<td>32</td>
<td>II</td>
<td>-57.9</td>
<td></td>
<td></td>
<td></td>
<td>11.3</td>
<td>21.5L</td>
</tr>
</tbody>
</table>

82
<table>
<thead>
<tr>
<th>Sample</th>
<th>EST. VOL.</th>
<th>INCLUSION</th>
<th>CO2 SOL.</th>
<th>H2O SOL.</th>
<th>CLATHRATE</th>
<th>CO2</th>
<th>H2O</th>
<th>MELT</th>
<th>CO2 VAP.</th>
<th>HOMOG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>50</td>
<td>I</td>
<td>-57.0</td>
<td></td>
<td></td>
<td>26.6V</td>
<td></td>
<td></td>
<td>295L</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>I</td>
<td>-57.1</td>
<td>9.0</td>
<td></td>
<td>27.0L</td>
<td></td>
<td></td>
<td>281L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>II</td>
<td>-57.4</td>
<td>9.1</td>
<td></td>
<td>23.2L</td>
<td></td>
<td></td>
<td>303V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>II</td>
<td>-57.4</td>
<td>9.3</td>
<td></td>
<td>23.0L</td>
<td></td>
<td></td>
<td>325V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>II</td>
<td>-58.6</td>
<td>10.8</td>
<td></td>
<td>16.4V</td>
<td></td>
<td></td>
<td>314V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>I</td>
<td>-58.4</td>
<td>10.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>323V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>III</td>
<td></td>
<td>-2.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>164L</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## LONE JACK FLUID INCLUSION DATA

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>EST. VOL. %H₂O</th>
<th>INCLUSION TYPE</th>
<th>CO₂ SOL</th>
<th>H₂O SOL H₂O LIQ</th>
<th>CLATHRATE MELT</th>
<th>CO₂ LIQ</th>
<th>CO₂ VAP</th>
<th>INCLUSION HOMOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>121</td>
<td>44</td>
<td>II</td>
<td>-56.6</td>
<td>10.5</td>
<td>25.6L</td>
<td>284D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>I</td>
<td>-56.6</td>
<td></td>
<td>10.5</td>
<td>24.4C</td>
<td>292L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>II</td>
<td>-56.4</td>
<td></td>
<td>10.3</td>
<td>26.4L</td>
<td>269D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>II</td>
<td>-57.0</td>
<td></td>
<td>10.5</td>
<td>22.0L</td>
<td>264D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>II</td>
<td>-57.8</td>
<td></td>
<td>11.9</td>
<td></td>
<td>302V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>II</td>
<td>-57.4</td>
<td></td>
<td>10.2</td>
<td>23.3L</td>
<td>283V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>II</td>
<td>-56.7</td>
<td></td>
<td>23.5L</td>
<td>301V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>II</td>
<td>-56.7</td>
<td></td>
<td>23.9L</td>
<td>276D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>II</td>
<td>-56.7</td>
<td></td>
<td>23.9L</td>
<td>275V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>128</td>
<td>22</td>
<td>II</td>
<td>-56.3</td>
<td>10.2</td>
<td>24.6L</td>
<td>295V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>II</td>
<td>-55.9</td>
<td></td>
<td>10.1</td>
<td>26.4L</td>
<td>287L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>II</td>
<td>-56.5</td>
<td></td>
<td>10.0</td>
<td>25.6L</td>
<td>283L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>II</td>
<td>-55.4</td>
<td></td>
<td>10.0</td>
<td>22.2L</td>
<td>279L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>I</td>
<td>-56.6</td>
<td></td>
<td>9.8</td>
<td>26.4L</td>
<td>282L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>II</td>
<td>-56.6</td>
<td></td>
<td>9.8</td>
<td>25.1L</td>
<td>289V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>II</td>
<td>-56.5</td>
<td></td>
<td>9.8</td>
<td>25.3L</td>
<td>256D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>II</td>
<td>-56.5</td>
<td></td>
<td>24.7L</td>
<td>285V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>II</td>
<td>-56.5</td>
<td></td>
<td>24.7L</td>
<td>277D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>222L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>139</td>
<td>70</td>
<td>I</td>
<td>-56.1</td>
<td>9.8</td>
<td>26.5L</td>
<td>284V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>II</td>
<td>-56.4</td>
<td></td>
<td>9.0</td>
<td>23.3C</td>
<td>292C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>I</td>
<td>-57.1</td>
<td></td>
<td></td>
<td>302D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td>Group</td>
<td>Temperature</td>
<td>Refractive Index</td>
<td>Value</td>
<td>Code</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>-------------</td>
<td>-----------------</td>
<td>-------</td>
<td>------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>III</td>
<td>-2.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>II</td>
<td>-58.0</td>
<td></td>
<td></td>
<td>305V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>II</td>
<td>-57.6</td>
<td>10.8</td>
<td>22.7C</td>
<td>300V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>II</td>
<td>-56.7</td>
<td>9.5</td>
<td>27.0V</td>
<td>300V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>II</td>
<td>-56.5</td>
<td>9.4</td>
<td>29.3V</td>
<td>266D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>II</td>
<td>-56.5</td>
<td>9.5</td>
<td>28.8C</td>
<td>267D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>II</td>
<td>-56.4</td>
<td>9.6</td>
<td>29.3V</td>
<td>285D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>II</td>
<td>-56.4</td>
<td>9.5</td>
<td>28.8V</td>
<td>269D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>I</td>
<td>-56.5</td>
<td></td>
<td>27.3V</td>
<td>214D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>136</td>
<td>I</td>
<td>-56.6</td>
<td>9.1</td>
<td>28.1L</td>
<td>283L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>II</td>
<td>-56.7</td>
<td>9.2</td>
<td>27.8L</td>
<td>285V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>II</td>
<td>-56.6</td>
<td>9.1</td>
<td>28.0L</td>
<td>284V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>II</td>
<td>-56.4</td>
<td>9.2</td>
<td>28.5L</td>
<td>294D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>I</td>
<td>-56.4</td>
<td>9.2</td>
<td>28.7L</td>
<td>295D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>I</td>
<td>-56.2</td>
<td></td>
<td>28.2L</td>
<td>292V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>III</td>
<td>-3.4</td>
<td></td>
<td></td>
<td>165L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>I</td>
<td>-56.5</td>
<td>9.5</td>
<td>27.0L</td>
<td>295L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>I</td>
<td>-56.6</td>
<td>9.1</td>
<td>28.0L</td>
<td>281D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>I</td>
<td>-56.6</td>
<td>9.1</td>
<td>28.0L</td>
<td>300L</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### WHIST FLUID INCLUSION DATA

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>EST. VOL. %H₂O</th>
<th>INCLUSION TYPE</th>
<th>CO₂ SOL H₂O</th>
<th>H₂O SOL H₂O LIQ</th>
<th>CLATHRATE MELT</th>
<th>CO₂ LIQ</th>
<th>CO₂ VAP</th>
<th>INCLUSION HOMOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>192</td>
<td>23</td>
<td>II</td>
<td>-59.2</td>
<td></td>
<td>10.5</td>
<td>14.5L</td>
<td></td>
<td>298V</td>
</tr>
<tr>
<td>96</td>
<td>III</td>
<td></td>
<td>-2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>160L</td>
</tr>
<tr>
<td>97</td>
<td></td>
<td></td>
<td>-2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>130L</td>
</tr>
<tr>
<td>38</td>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>293C</td>
</tr>
<tr>
<td>52</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>310C</td>
</tr>
<tr>
<td>37</td>
<td>II</td>
<td>-57.1</td>
<td>9.9</td>
<td>24.5L</td>
<td>273D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>II</td>
<td>-59.3</td>
<td>10.0</td>
<td>14.4L</td>
<td>300V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>I</td>
<td>-69.3</td>
<td>10.2</td>
<td></td>
<td>290D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>II</td>
<td>-57.0</td>
<td>9.6</td>
<td>25.5L</td>
<td>260D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>II</td>
<td>-57.3</td>
<td>9.7</td>
<td>24.6L</td>
<td>264D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>45</td>
<td>II</td>
<td>-57.4</td>
<td>10.6</td>
<td>16.0L</td>
<td>303C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>III</td>
<td></td>
<td>-2.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>156L</td>
</tr>
<tr>
<td>43</td>
<td>II</td>
<td>-58.2</td>
<td>11.3</td>
<td>15.4L</td>
<td>305L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>III</td>
<td></td>
<td>-2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>167L</td>
</tr>
<tr>
<td>95</td>
<td>III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>185L</td>
</tr>
<tr>
<td>50</td>
<td>I</td>
<td>-58.2</td>
<td>9.7</td>
<td>24.5L</td>
<td>312C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>I</td>
<td>-57.4</td>
<td></td>
<td>24.5L</td>
<td>298V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>II</td>
<td>-59.2</td>
<td>10.2</td>
<td>27.0L</td>
<td>296V</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 2. Selected Equilibrium Constants

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Log K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250°C</td>
</tr>
<tr>
<td>$3\text{KAlSi}_3\text{O}_8 + 2\text{H}^+ \leftrightarrow \text{KAl}_3\text{Si}<em>3\text{O}</em>{10}(\text{OH})_2 + 6\text{SiO}_2 + 2\text{K}^+$</td>
<td>8.12</td>
</tr>
<tr>
<td>$2\text{KAl}_3\text{Si}<em>3\text{O}</em>{10}(\text{OH})_2 + 2\text{H}^+ + 3\text{H}_2\text{O} \leftrightarrow 3\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 2\text{K}^+$</td>
<td>6.20</td>
</tr>
<tr>
<td>$\text{H}_2\text{S} + 2\text{O}_2 \leftrightarrow 2\text{H}^+ + \text{SO}_4^{2-}$</td>
<td>57.1</td>
</tr>
<tr>
<td>$\text{H}_2\text{SO}_4 + \text{H}^+ \leftrightarrow 2\text{O}_2 + \text{H}_2\text{S}$</td>
<td>-62.5</td>
</tr>
<tr>
<td>$\text{SO}_4^{2-} + \text{H}^+ + \text{HS}^- + 2\text{O}_2$</td>
<td>-64.4</td>
</tr>
<tr>
<td>$\text{SO}_4^{2-} \leftrightarrow 2\text{O}_2 + \text{S}^{2-}$</td>
<td>-72.7</td>
</tr>
<tr>
<td>$2\text{FeS}_2 \leftrightarrow 2\text{FeS} + \text{S}_2$</td>
<td>-14.06</td>
</tr>
<tr>
<td>$3\text{FeS}_2 + 2\text{O}_2 \leftrightarrow \text{Fe}_3\text{O}_4 + 3\text{S}_2$</td>
<td>35.81</td>
</tr>
<tr>
<td>$\text{FeS}_2 + 1.5\text{O}_2 \leftrightarrow \text{Fe}_2\text{O}_3 + 2\text{S}^{2-}$</td>
<td>29.35</td>
</tr>
<tr>
<td>$3\text{Fe}_2\text{O}_3 \leftrightarrow 2\text{Fe}_3\text{O}_4 + 0.5\text{O}_2$</td>
<td>-16.44</td>
</tr>
<tr>
<td>$\text{Au}^0 + \text{H}_2\text{S} + \text{HS}^- + 0.25\text{O}_2 \leftrightarrow \text{Au(HS)}^- + 0.5\text{H}_2\text{O}$</td>
<td>-3.52</td>
</tr>
<tr>
<td>$\text{Au}^0 + 0.25\text{H}_2\text{O} + \text{H}^+ \leftrightarrow \text{Au}^+ + 0.5\text{H}_2\text{O}$</td>
<td>-6.21</td>
</tr>
<tr>
<td>$\text{AuCl}_2^- \leftrightarrow \text{Au}^+ + 2\text{Cl}^-$</td>
<td>21.9</td>
</tr>
<tr>
<td>$0.5\text{O}_2 + \text{H}_2 \leftrightarrow \text{H}_2\text{O}$</td>
<td>-7.59</td>
</tr>
<tr>
<td>$\text{H}_2\text{S} \leftrightarrow \text{HS}^- + \text{H}^+$</td>
<td>8.61</td>
</tr>
<tr>
<td>$\text{CO}_2 \leftrightarrow \text{C}^+ + \text{O}_2$</td>
<td>-36.97</td>
</tr>
<tr>
<td>$\text{H}_2\text{CO}_3 = \text{HCO}_3^- + \text{H}^+$</td>
<td>-7.73</td>
</tr>
<tr>
<td>$\text{HCO}_3^- = \text{CO}_3^{2-} + \text{H}^+$</td>
<td>-11.24</td>
</tr>
</tbody>
</table>

(a) Helgeson, 1969; (b) Casadevall and Ohmoto, 1977; (c) Crerar and Barnes, 1976; (d) Ohmoto and Kerrick, 1977.