Geology and Mineralization of the Great Excelsior Mine, Whatcom County, Washington

Russell J. Franklin

Western Washington University

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GEOLOGY AND MINERALIZATION OF THE GREAT EXCELSIOR MINE,
WHATCOM COUNTY, WASHINGTON

A Thesis
Presented to
The Faculty of
Western Washington University

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

By
Russell J. Franklin
March, 1985
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Dean of Graduate School

ADVISORY COMMITTEE

Chairman
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Name: Russell J. Franklin
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Date: May 29, 2018
ABSTRACT

The Great Excelsior Mine is located in the North Cascades of northwest Washington, approximately 6 miles (10 km) east of the town of Glacier. The deposit consists of Ag with subordinate Au and is hosted within felsic volcanic breccias, tuffaceous siltstones and graywackes, and felsic tuffs belonging to the Middle Jurassic Wells Creek Volcanics. The deposit is located approximately 1000 feet (305 m) below the contact between the Wells Creek Volcanics and the overlying Nooksack Group metasediments. Both units comprise the lowermost structural-metamorphic unit of the western North Cascades System.

The Wells Creek Volcanics have been informally subdivided into four mappable units. From oldest to youngest they are: 1) the Lower Volcanic Unit, 2) the Sedimentary Unit, 3) the Siliceous Tuff Unit, and 4) the Upper Volcanic Unit. Combined, these units represent a minimum of 4000 feet (1220 m) of intermediate volcanics along with intercalations of marine shales, siltstones, volcanic graywackes, and shaley tuffs. The contact between the Wells Creek Volcanics and the overlying Nooksack Group appears to be gradational. The base of the Wells Creek Volcanics is not exposed in the study area.

The Wells Creek Volcanics and Nooksack Group have been subjected to regional low-grade metamorphism which produced mineral assemblages common to the prehnite-pumpellyite metamorphic facies. The Wells Creek Volcanics are structurally dominated by a large, open, upright, north trending anticline.
At least three vertically separated mineralized zones (based on a 1.5 oz/ton Ag cutoff) have been identified on the property. These occur in gently to steeply dipping tabular zones which are commonly subparallel to the stratigraphy. The mineralization is characterized by microscopic argentite, tetrahedrite, polybasite?, and electrum replacing pyrite and locally calcite. The three zones combined represent 2.5 million tons of mineralization which average 4.67 oz/ton Ag and 0.047 oz/ton Au.

The Great Excelsior deposit shares several features common to typical Kuroko-type deposits. These features include: 1) the mineralization is associated with felsic volcanics, 2) it was deposited in a submarine environment, 3) fluid temperature and composition are similar to those of Kuroko fluids, and 4) it was deposited in an island arc tectonic setting. The major differences between them are the Excelsior deposit lacks massive stratiform mineralization and commercial base metal concentrations.

The absence of massive stratiform mineralization can be explained by either: 1) extensive boiling of the hydrothermal solution resulting in subsurface deposition of metals, or 2) by dispersal of a low density hydrothermal plume by current action above the sea floor.

The absence of commercial base metal concentrations can be explained by one or more of the following: 1) the base metals have been removed by erosion, 2) the hydrothermal solution was devoid of base metals, or 3) the base metals were flushed through the system and were
Thermochemical calculations suggest that the metals were transported primarily as chloride complexes and petrographic and field observations indicate precipitation took place in response to boiling and/or reaction with host rocks.
ACKNOWLEDGMENTS

Completion of this thesis would not have been possible if not for the guidance and assistance of many people. I would especially like to thank U.S. Borax and Chemical Corporation for providing me with employment while I completed my field work, funds for a U/Pb radiometric age date, and materials which were used to complete my thesis. A special thanks is in order for my friends in the Spokane office for simply putting up with my presence for several months.

I am indebted to Dr. Thomas A. Henricksen of U.S. Borax who was instrumental in providing me with employment, contributed many hours of stimulating discussions (not necessarily geologic), and critically reviewed my thesis. The assistance of Jim Ebisch, who accompanied me on my worst traverses, and together fell prey to several "driller traps" in the local bar, is deeply appreciated. Thanks also to Dave Flint and Carl Henderson for providing their perspective on the mine area geology.

For spending many long hours and sacrificing much of her free time typing my thesis, I would like to thank Kathy Wilson. I would also like to acknowledge Karen Bogle who drafted and sometimes redrafted my maps and cross sections.

My committee chairman, Dr. Antoni Wodzicki, deserves a special thanks for sacrificing much of his time with trips to my study area, contributing many hours of informative discussions, and for critically and constructively reviewing my thesis. Likewise, I am grateful to Dr. R. S. Babcock and Dr. E. H. Brown for critical and constructive
reviews of my manuscript, maps, and cross sections.

Dave Blackwell deserves a great deal of thanks as well as a Purple Heart for wounds received while helping me collect 70 pounds of rock (for age dating), and packing it for what seemed like miles, through 4 feet of snow.

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INTRODUCTION

The Great Excelsior Mine is located approximately 36 miles (58 km) east of Bellingham and 8 miles (13 km) north of Mt. Baker in the North Cascade Mountains of northwest Washington (Fig. 1). Access to the mine from Bellingham is east along Washington State Highway 542 to Glacier then, by 6 miles (10 km) of gravel logging road (Dead Horse Creek Road) to the west side of the mine area.

The mine is at an elevation of about 1800 feet (549 m) and is located approximately 200 vertical feet (61 m) above the west side of Wells Creek, one half mile above its confluence with the Nooksack River (Fig. 2). The topography of the area is steep with local relief approximately 900 feet (274 m).

Previous Investigations

Discovery of the Great Excelsior Ag-Au deposit was made by W. H. Norton and others in August 1900. Mining and the shipment of concentrates began in 1902 when the Great Excelsior Mining Company was incorporated and a 20-stamp mill (Fig. 3) was constructed on the property (Moen, 1969). Prior to 1917 approximately 30,000 to 50,000 tons of ore grading about 7 oz/ton Ag and 0.1 oz/ton Au were mined and milled (Henricksen, 1980). The mill was shut down in 1916 due to low grades and poor recovery (Moen, 1969).

In 1934 the property was examined by the State and this included some 200 channel and crosscut samples taken from the underground workings. Preliminary milling tests on these samples showed that 85
Figure 1. Index map of Washington State with enlargement of study area.
Figure 2. View of the mine area facing south toward Mt. Baker. The prominent gorge on the left is Wells Creek.
Figure 3. The Great Excelsior Mine. Circa 1914. Photograph courtesy of U.S. Borax and Chemical Corp., Spokane Exploration.
percent of the Ag and Au can be recovered (Moen, 1969).

Control of the property changed hands several times in subsequent years until 1977 when U.S. Borax and Chemical Corporation acquired the property. At that time Henricksen and other U.S. Borax geologists began detailed mapping and diamond core drilling of the property.

Regional mapping of the area was completed by Misch in 1959 (Misch, 1966) and has been the only comprehensive regional work done on the Wells Creek Volcanics to date (Fig. 4). Other important regional work which has not focused directly on the Wells Creek Volcanics includes a metamorphic facies and tectonics study on the Cascade Range and Puget Lowland by Brown and others (1981), and Masters theses completed at Western Washington University by Jones (1984) and Sevigny (1983) on the Chilliwack and Nooksack Groups around the Church Mountain and Mt. Tomyhoi areas, respectively.

In 1979 Sondergaard (Sondergaard, 1979) completed a mapping and petrology thesis at Western Washington University on the Nooksack Group metasediments around and to the west of the mine area.

Statement of the Problem

The purpose of this study has been to gain a better understanding of the physical and chemical processes responsible for the deposition of silver and gold at the Great Excelsior Mine, and to compile a regional geologic map of the Wells Creek Volcanics.
Figure 4. Regional geological map with outline of the study area (from Misch, 1977).
Initially, the emphasis was placed on developing a 1"=1000' scale geologic map of the Wells Creek Volcanics and the lower portion of the Nooksack Group. The objective of this work was to determine the structural setting and to trace out the time-stratigraphic equivalent of the Excelsior Mine rocks. Also of primary importance was the location of other hydrothermally altered and/or mineralized units within the Wells Creek Volcanics.

During the course of this study the author has collected numerous hand specimens of the Wells Creek Volcanics for petrographic study, examined and sampled hundreds of feet of selected drill cores, and field checked detailed (1"=50') mine area maps.

The vast majority of geologic field work in the mine area (surface and underground) was carried out by U.S. Borax geologists Thomas A. Henricksen, James F. Ebisch, Jim Ashleman, Dave Flint, and Carl Henderson.

The U.S. Borax Research Corporation in Anaheim, California performed all of the base metal analytical geochemical tests while Bondar-Clegg Ltd. of Vancouver, B.C., Canada performed all of the precious metal analyses. All analytical tests were performed with an atomic absorption spectrophotometer (AA). The results obtained by this method averaged between 7 and 10% error (Bob Deal: Chemist, U.S. Borax Research Corp., oral communication, 1985).
REGIONAL GEOLOGY

The Great Excelsior Mine lies approximately 1000 feet (305 m) below the contact between the Middle Jurassic Wells Creek Volcanics and the overlying Nooksack Group metasediments. Both units comprise the lowermost structural-metamorphic unit of the Western North Cascades System which is commonly referred to as the Mt. Baker Window (Misch, 1966, 1977). The rocks which host the Ag-Au mineralization are felsic volcanic breccias, tuffaceous siltstones and graywackes, and felsic tuffs. The geology of the Mt. Baker Window is shown in Plate 1 and the detailed geology of the mine area is shown in Figure 14.

The Wells Creek Volcanics are exposed in a 4 mile (6.5 km) by 7 mile (11 km) area centered on the North Fork of the Nooksack River (Plate 1). These rocks make up the interior of the Mt. Baker Window and are composed of about 4000 feet (1220 m) of intermediate volcanics (andesite-dacite) along with intercalations of marine shales, siltstones, volcanic graywackes, and shaley tuffs. Subsequent regional low-grade metamorphism of these rocks during the Late Cretaceous has albitized the plagioclase and altered all primary mafic minerals to chlorite and pumpellyite. Minor lawsonite is present locally in most of the dacitic tuffs.

The Wells Creek Volcanics are overlain by the Upper Jurassic-Lower Cretaceous Nooksack Group metasediments. This is a thick (6-7 km) sequence of sediment thought to have been deposited mainly in a submarine fan environment (Sondergaard, 1979). The sediments of the Nooksack Group are composed of a local basal conglomerate (Misch, 1966),
tuffaceous sandstone, black argillite, and volcaniclastic sandstone (Sondergaard, 1979).

On the eastern margin of the Mt. Baker Window the basal portion of the Nooksack Group consists of a poorly-sorted conglomerate containing well-rounded clasts of chert, volcanics, and hypabyssal granite (Fig. 5). Misch (1966) interpreted this conglomerate to represent a disconformable contact between the Wells Creek Volcanics and the Nooksack Group. However, Misch (1966) and Sondergaard (1979) point out that this conglomerate does not extend to the west side of the Mt. Baker Window. Sondergaard (1979) described the basal portion of the Nooksack in this area as a 45-60 m thick breccia unit which overlies tuff. He concluded that this unit is not continuous with Misch's basal conglomerate, but its presence and sharp contact with the underlying tuff suggest the presence of an unconformity. Work by the present author has reclassified Sondergaard's basal Nooksack to Upper Wells Creek Volcanics because the breccia has the appearance of a pyroclastic flow which is interbedded with crystal and vitric tuffs. These tuffs are gradational with the overlying volcaniclastic sediments of the Nooksack Group and the contact between the two units is therefore interpreted as conformable. The conglomerate present on the eastern flank of the Mt. Baker Window is interpreted to represent local shallow submarine channels.

The Wells Creek Volcanics and the Nooksack Group, collectively have been termed by Misch (1966, 1977) as "the 'autochthon' of the North Cascades." This term has been used by Misch (1966, 1977) to
Figure 5. Nooksack basal conglomerate with well-rounded clasts of hypabyssal? rock set in a graywacke matrix. From the east flank of the Mt. Baker Window, south of the North Fork of the Nooksack River.
designate pre-Late Cretaceous rocks which underlie the Church Mountain Thrust and have an unexposed base. Misch (1977) pointed out that another level of major thrusting could be present at depth and based on regional structure it is probable that telescoping has occurred.
REGIONAL STRATIGRAPHY OF THE WELLS CREEK VOLCANICS

The bulk of the Wells Creek Volcanics consists of andesitic to dacitic submarine flows which have undergone various degrees of Na-metasomatism. Local intercalations of marine sediments and tuffs include black shales, shaley tuffs, crystal, lithic and vitric tuffs, volcanic graywackes, and minor sedimentary breccias. Although these are not volumetrically important, they often serve as excellent marker units which aid in both stratigraphic and structural interpretations.

The total thickness of the Wells Creek Volcanics is estimated to be a minimum of 4000 feet (1220 m). This figure was obtained from measurements taken from cross sections constructed across both the northern and southern portions of the Mt. Baker Window (Plate 2).

A total of four mappable units are recognized within the Wells Creek Volcanics. These have been mapped on an informal basis to aid in structural and stratigraphic control. From oldest to youngest they are: 1) the Lower Volcanic Unit which is composed dominantly of porphyritic keratophyre and minor tuffaceous sediments and pyroclastics, 2) the Sedimentary Unit which is composed dominantly of black slate and minor shaley tuffs, crystal tuffs, and sedimentary breccias, 3) the Siliceous Tuff Unit which is composed primarily of siliceous felsic tuffs and breccias, and 4) the Upper Volcanic Unit which is composed dominantly of porphyritic keratophyre and locally voluminous crystal and vitric tuffs.
Lower Volcanic Unit

The Lower Volcanic Unit is exposed in several locations throughout the Mt. Baker Window. North of the Nooksack River several excellent exposures of massive cliff-forming keratophyre are present. South of the Nooksack River scattered outcrops occur along the Wells Creek Road and along the northern portion of Cougar Divide (Plate 1).

The Lower Volcanic Unit is composed of voluminous andesitic to dacitic submarine flows. The thickness of this unit is unknown because its base is not exposed. The bulk of this unit is of andesitic (keratophyric) composition with plagioclase compositions ranging between $\text{An}_3$ to $\text{An}_8$ as determined by the a-normal method. Oligoclase ($\text{An}_{21}$) is present locally where the albitization process was incomplete. Plagioclase commonly makes up approximately 40% of the total volume occurring as large phenocrysts and glomeroporphyritic clots. Small randomly oriented plagioclase laths are also common in the groundmass. Partial to total replacement of plagioclase by calcite, sericite, pumpellyite, and lawsonite is common. Relict amphibole and pyroxene phenocrysts have been completely replaced by chlorite, pumpellyite, and locally epidote. Pumpellyite displays brilliant indigo blue anomalous interference colors and in plane polarized light exhibits a strong apple-green to yellow-green pleochroic scheme. Chlorite also has blue interference colors and light green pleochroism. Together, pumpellyite and chlorite make up approximately 30% of the rock and are responsible for its apple-green color in outcrop.

Minor quartz keratophyre flows are present locally. These contain
large embayed quartz phenocrysts and abundant albite phenocrysts set in an aphanitic matrix rich in randomly oriented albite laths. In outcrop these flows have autobrecciated tops and are commonly overlain by coarse crystal tuffs of similar composition.

The upper portion of the unit contains intercalated lapilli tuffs, tuff-breccias, and minor tuffaceous sediments. Some of the lapilli tuffs and tuff-breccias bear some resemblance to the subaqueous pyroclastic flows described by Fiske and Matsuda (1964). The tuff-breccias contain dense volcanic fragments of andesitic to dacitic composition and minor relict attenuated pumice fragments which are set in a fine grained tuff matrix. This sequence grades upward into a poorly-sorted lapilli tuff containing large angular volcanic lithics in a crystal-rich matrix. This is overlain by a well-bedded, moderately sorted, ash tuff.

**Sedimentary Unit**

The Sedimentary Unit is a fairly continuous band of sediments which average approximately 400 feet (122 m) in thickness and locally may be as thick as 800 feet (244 m). These sediments can be traced throughout the entire northern portion of the Mt. Baker Window and serve as an excellent marker unit. Excellent exposures of this unit occur along the Mt. Baker Highway approximately 1000 feet (305 m) east of the Excelsior Lookout trailhead (Plate 1). On the east flank of the Mt. Baker Window this unit pinches out less than 3000 feet (914 m) south of the Deadhorse Fault whereas on the western flank it appears to be continuous with exposures along the upper portion of Deadhorse
Creek.

The unit consists of dark gray to black marine shale, tuffaceous siltstone, bedded to massive ash and crystal tuffs, and local sedimentary breccias and conglomerates. The vast majority of the unit is composed of marine shale. This shale exhibits a well-developed penetrative foliation (Fig. 6) and has been referred to as slate in Plate 1 and Figure 14. It is fairly well-sorted and consists primarily of illite and chlorite with minor rounded quartz and albite silt-sized grains. At one locality along the Wells Creek road, east of the Great Excelsior Mine, the slate is in contact with an apparently underlying keratophyre sill. The intrusion of keratophyre thermally metamorphosed the bottom one meter of argillite, leaving it competent enough to escape strong internal deformation. Here, abundant undeformed radiolarians and skeletal particles were observed. Other fossils have recently been located in the well-deformed black slates along the Mt. Baker Highway by students from Western Washington University. Among these are deformed but generally well-preserved belemnites which measure approximately 8 cm in length.

Siltstones and tuffs are also common within this unit. The siltstones are commonly tuffaceous and contain abundant small relict attenuated pumice fragments and minor dacitic and andesitic volcanic clasts. The clasts are set in a chlorite-sericite-rich matrix with a moderate amount of small subrounded quartz grains and rare albite grains. Calcite occurs in small veinlets and as pseudomorphs after plagioclase.
Figure 6. Well-developed penetrative foliation is shown here in dark gray to black slates located in Wells Creek. The hammer is approximately one foot (30.5 cm) long.
The tuffs are andesitic to dacitic in composition and are generally very fine grained. They are composed dominantly of small angular albite crystals and variable amounts of subrounded to rounded quartz grains and rare albite grains. Calcite occurs in small veinlets and as pseudomorphs after plagioclase.

The tuffs are andesitic to dacitic in composition and are generally fine grained. They are composed dominantly of small angular albite crystals and variable amounts of subrounded to rounded quartz grains. The crystals are commonly broken and are set in a clay-rich matrix with minor relict glass shards. Small-scale graded bedding is present locally.

The upper portion of the unit is generally coarser grained and contains abundant volcanic material. There are local interbedded tuffs ranging in grain size from lapilli to ash, fragmental tuffaceous graywacke, dacitic tuff-breccia, medium bedded volcaniclastic sandstone, and massive siltstone. In the vicinity of the Great Excelsior Mine portions of these lithologies are mineralized and constitute a significant part of the mineral deposit.

The contact between the Sedimentary Unit and the underlying Lower Volcanic Unit is sharp and appears conformable.

**Siliceous Tuff Unit**

The Siliceous Tuff unit is made up of several lithologies which range in composition from andesitic to rhyolitic. The unit is fairly
continuous throughout the Mt. Baker Window and has an average thickness of approximately 300 feet (91 m). Excellent exposures exist along the Mt. Baker Highway near the Excelsior Lookout trailhead and along Wells Creek south of the Deadhorse Fault (Plate 1). It is distinguished from the overlying volcanics by ubiquitous hydrothermal alteration and disseminated pyrite. In outcrop it has a strong dark brown to yellow iron stain and is easily distinguishable from the other units. In the vicinity of the Great Excelsior Mine the unit consists of dacitic to rhyolitic tuffs, breccias, and minor flows, portions of which contain significant Ag-Au mineralization. These lithologies will be described later in detail.

Dacitic crystal-ash tuffs make up the bulk of the unit. These commonly contain abundant broken albite crystals which have been partially replaced by calcite and sericite, and minor devitrified pumice fragments and glass shards. The matrix is composed of very fine grained quartz, sericite, and finely disseminated pyrite. Sphene, apatite, and locally zircon occur in trace amounts in the groundmass.

Minor flows of porphyritic dacite and andesite are present locally. These contain abundant albite and sometimes quartz phenocrysts set in a sericite-chlorite-rich matrix. Primary plagioclase phenocrysts have been partially replaced by calcite and sericite. Pyrite is also abundant within these flows occurring as fine disseminations and veins.

Hydrothermal alteration has been intense and is pervasive through-
out the unit. Locally it has been so intense as to almost completely obliterate primary textures. Primary feldspars have been replaced by calcite and sericite, relict glass shards and pumice have been completely sericitized, and relict ferromagnesian minerals, where present, have been pseudomorphed by chlorite. Primary quartz grains typically have optically continuous quartz overgrowths. The groundmass is generally dominated by microcrystalline quartz and finely disseminated pyrite (3-10%). Small veinlets are common throughout the unit which consist of quartz-calcite±albite±adularia±pyrite.

This unit contains significant precious metal mineralization only in the mine area. Elsewhere pyrite is the only sulfide mineral that has been observed. The siliceous-pyritic nature of this unit away from the mine area makes it a likely candidate to represent a distal facies of a typical Kuroko-type sequence, whereas the sole occurrence of rhyolitic rocks and Ag-Au mineralization within the mine area are suggestive of a proximal Kuroko-type facies (siliceous stringer ore) related to a felsic volcanic center.

The contact between the Siliceous Tuff Unit and the underlying Sedimentary Unit is very gradational.

Upper Volcanic Unit

The Upper Volcanic Unit is dominated by two lithologies, porphyritic keratophyre and coarse crystal tuff. It has an average thickness of approximately 2000 feet (610 m) and is well exposed throughout the Mt. Baker Window (Plate 1).
The bulk of the unit consists of massive cliff-forming flows of porphyritic keratophyre (Fig. 7). In outcrop it is light-green to apple-green with small dark-green phenocrysts of relict amphibole. In thin section, abundant albite phenocrysts accompanied by a moderate amount of subhedral to euhedral relict amphibole phenocrysts are set in a matrix rich in equigranular randomly oriented albite laths. Albite commonly makes up greater than 40% of the rock with calcite, chlorite, pumpellyite and often epidote making up the balance. Plagioclase compositions were generally difficult to obtain due to partial to total replacement by minerals such as calcite, sericite, pumpellyite, and chlorite. The average range of plagioclase compositions are between An$_3$ to An$_8$ as determined by the a-normal method. Relict amphibole phenocrysts without exception have been replaced completely by chlorite, pumpellyite±epidote±calcite. Common accessory minerals which occur in trace amounts are apatite, sphene, and rarely zircon.

On the western flank of the Mt. Baker Window, north of the Deadhorse Fault, these flows give way to voluminous pyroclastic deposits. Dacitic crystal tuff is the dominant lithology in this area with subordinant vitric and lithic tuff intercalations. The crystal tuffs are generally coarse grained, poorly-sorted dacites which consist of abundant broken angular crystals of albite and subordinant broken quartz crystals. Albite commonly makes up greater than 50% of the rock while quartz averages 10-15%. Lithics, although minor, are generally intermediate volcanics and often siltstones. Vitric tuff intercalations are common and contain abundant relict pumice clasts with relict glass shards dominating the matrix. Although these have been com-
Figure 7. Large outcrop of massive porphyritic keratophyre belonging to the Upper Volcanic Unit. This is located in the upper Deadhorse Creek drainage just below Skyline Divide. The strata are dipping approximately 20° to the west (to the left).
pletely replaced by pumpellyite, their delicate cuspate morphology has been perfectly preserved (Fig. 8).

Subordinate rhyodacitic flows are also present within this unit. These generally contain less than 20% albite phenocrysts and have a highly siliceous-feldspathic aphanitic matrix. The matrix appears to have an axiolitic fabric in which grain boundaries are extremely diffuse. Under low power magnification a subtle flow-banded texture is observable where the matrix bends around phenocrysts.

The albite in this lithology has been almost completely replaced by calcite, colorless epidote, and minor slender radiating crystalline masses of colorless chlorite. Accessory minerals include zircon and apatite which occur as small discrete idioblastic to hypidioblastic crystals. The presence of zircon has been useful in determining a U/Pb radiometric age date for the crystallization of this particular volcanic flow. The zircons were separated into two size fractions which yielded ages very close to concordance. These have been interpreted to represent an age of emplacement for the Wells Creek Volcanics of 175-180 Ma (Mattinson, personal communication, 1984; See Appendix II).

The contact between the Upper Volcanic Unit and the underlying Siliceous Tuff Unit is sharp and appears conformable.
Figure 8. Photomicrograph of a vitric tuff with relict glass shards and pumice which have been completely replaced by pumpellyite. Note how well preserved the delicate cuspate morphology of the pumice is (center of photo). Magnified 40 times, plane polarized light. Sample taken near Bridge Campground.
The Wells Creek Volcanics and overlying Nooksack Group have undergone low-grade regional metamorphism during Middle to Late Cretaceous (Misch, 1966, 1977). Mineral assemblages present within these two units are indicative of the low temperature and pressure conditions of the prehnite-pumpellyite metamorphic facies (Turner, 1981; Winkler, 1976).

The mineral assemblages present in the Wells Creek Volcanics which are important as temperature and pressure indicators are listed in Table 1. These minerals were identified by petrographic examination of thin sections.

Description of Metamorphic Minerals

The albitization of calcic plagioclase has occurred in nearly all lithologies of the Wells Creek Volcanics. Plagioclase compositions determined primarily by the a-normal method generally ranged between An₃ to An₈ although two samples contained plagioclase with An₂₁ compositions. The latter composition reflects incomplete albitization of a more calcic plagioclase which could have been due to a restricted reaction time.

Chlorite occurs primarily as an alteration product of ferromagnesian minerals (primarily amphiboles), occurring both as large directionless mats and as spherulitic patches. It is generally abundant in the groundmass of intermediate to mafic rocks occurring as interstitial fillings between albite laths. In the more felsic lithologies it commonly occurs as elongate splintery patches which occupy...
TABLE 1. Important Metamorphic Mineral Assemblages (+Quartz)

1. albite-chlorite-pumpellyite-calcite-epidote
2. albite-chlorite-pumpellyite-calcite±white mica
3. albite-chlorite-pumpellyite-lawsonite
4. albite-chlorite-pumpellyite-lawsonite-calcite±white mica
5. albite-chlorite-prehnite-calcite
6. albite-pumpellyite-lawsonite
7. albite-chlorite-pumpellyite-prehnite-calcite
pressure fringes around sulfides. In the more mafic lithologies it exhibits strong anomalous blue interference colors while in the more felsic lithologies it commonly displays brown anomalous interference colors.

**Epidote** is restricted to the more mafic lithologies such as calcic keratophyres and has not been observed in any of the tuffs. It occurs as discrete xenoblastic grains which replace both plagioclase and amphiboles (Fig. 9). It is commonly colorless but sometimes exhibits a faint lime-green pleochroism.

**Pumpellyite** occurs primarily in flow rocks and less commonly in tuffs and graywackes. It forms fine, acicular radiating needles and optically continuous microcrystalline aggregates partially replacing plagioclase. Where good plagioclase zoning exists, pumpellyite commonly grows along zonal margins. In some of the vitric tuffs it has completely replaced all of the relict glass shards and fiamme (Fig. 8). It commonly displays a deep apple-green to light apple-green pleochroic scheme and blue-brown anomalous interference colors.

**Prehnite** occurs mainly in coarse grained crystal tuffs as small, stubby, prismatic radiating sheaves (Fig. 10). It replaces plagioclase extensively, and is readily recognizable in thin section by its bow-tie extinction and length-fast character.

**Calcite** is ubiquitous with respect to lithology. It has several modes of occurrence which include: 1) microcrystalline xenoblastic
Figure 9. The metamorphic mineral assemblage of epidote-calcite-albite-chlorite is present in this sample of basaltic-andesite taken near the East Fork of Deadhorse Creek. Magnified 100 times, crossed polars. Sample BP-18.
Figure 10. Photomicrograph of a crystal tuff with prehnite, calcite, and white mica. Note the bow-tie appearance of the prehnite (center of photo). Magnified 100 times, crossed polarized light. Sample JET-22A.
aggregates which partially to totally replace plagioclase, 2) idio-
blastic linings of amygdules, 3) interstitial xenoblastic grains in
the groundmass, and 4) multistage vein fillings. In most cases it
displays moderate to strong deformation twinning depending upon its
mode of occurrence. All vein calcite has been strongly deformed and
commonly has more than one set of twin planes.

**Lawsonite** occurs dominantly in the coarse-grained tuffs and
breccias and is only rarely seen in flow rocks. It is intimately
related to plagioclase and has not been observed to occur with any other
mineral. It clearly developed from the calcic fraction of plagioclase
during albitization as evidenced by its growth along zonal margins and
in the core of phenocrysts. It commonly occurs as medium to dark brown,
fine stubby prisms and hair-like fibers less than 0.05 mm in length.
Locally, relatively large (>0.1 mm) idioblastic prismatic crystals
displaying upper first-order interference colors, length-fast extinc-
tion, and moderate relief are present (Fig. 11). Observation of
lawsonite was not made by Sondergaard (1979), but is reported by
Sevigny (1983), and Jones (1984) for the Nooksack Group north of the
North Fork of the Nooksack River.

**Pressure-Temperature Conditions**

Important temperature constraints are realized by the presence of
prehnite and pumpellyite in the absence of actinolite. This requires
that the metamorphic conditions were at temperatures above the
laumontite subfacies stability field and below the pumpellyite-
actinolite subfacies field. A stable prehnite-pumpellyite assemblage
Figure 11. Photomicrograph of a crystal tuff with idioblastic lawsonite crystals (center of photo). Magnified 500 times, crossed polarized light. Sample JET-22A.
suggests a temperature range between 200-300° C, assuming $P_{total} = P_{H_2O}$ (Winkler, 1976).

The presence of lawsonite in many of the tuffs and coarse grained volcanics places important pressure constraints on the metamorphic conditions. At confining pressures above 3 kb the liberation of $Ca^{2+}$ and $Al^{3+}$ from the albitization of calcic plagioclase will help form lawsonite as well as epidote, sericite, pumpellyite, and calcite. At pressures below 3 kb lawsonite will be absent and the by-products of this reaction will be only epidote, sericite, pumpellyite, and calcite (Winkler, 1976).

The presence of these temperature and pressure sensitive minerals (pumpellyite, prehnite, lawsonite) suggests that the Wells Creek Volcanics and the lower portion of the Nooksack Group were metamorphosed at temperatures ranging between 200-300° C, and pressures above 3 kb. This compares rather favorably with the observations of Brown and others (1981), and Sondergaard (1979) for the Nooksack Group north of Mt. Baker. Although the presence of lawsonite was not reported in either case, Brown and others (1981) stated that lawsonite could be stable given the proper rock composition.

All of the fine grained sediments and many of the tuffs exhibit a well-developed penetrative foliation which is axial planar to the large-scale open folding of the Wells Creek Volcanics and Nooksack Group, and is generally inclined to bedding. Metamorphic minerals such as chlorite, white mica, albite, and minor pumpellyite microscopically define these
planes of foliation ($S_1$). This may be an indication that this episode of deformation accompanied the regional metamorphic event. Alternatively, these metamorphic minerals could have been recrystallized along planes of foliation during a post-metamorphic episode of folding as suggested by Sevigny (1983). The more competent aphanitic and porphyritic flow rocks show no sign of internal deformation and give the appearance of static recrystallization (Fig. 12).
Figure 12. Photomicrograph of a porphyritic keratophyre with albitized plagioclase phenocrysts and pumpellyite and chlorite replacing relict amphiboles. This rock lacks internal deformation and gives the appearance of having been recrystallized under static conditions. Magnified 40 times, crossed polars. Sample A80EX10R.
REGIONAL STRUCTURE

The Wells Creek Volcanics and Nooksack Group comprise the lowermost structural-metamorphic unit in the North Cascades (Misch, 1966, 1977; Brown et al, 1981). These two units have been folded into a large, open, upright, doubly plunging anticline which trends approximately north-south (Plate 1). The axis of the anticline is located in the vicinity of Excelsior Lookout to the north and continues south across Wells Creek, Cougar Divide, and Deadhorse Creek.

Several small-scale folds exist within the Wells Creek Volcanics with axes that trend approximately north-south. These folds are generally confined to the more ductile lithologies such as the fine grained sediments and many of the tuffs. These lithologies exhibit a well-developed penetrative foliation (Fig. 6) which is axial planar and on the average trends N10°E and dips steeply to the east. Minerals which have crystallized along the planes of foliation include, chlorite, white mica, albite, and minor pumpellyite and quartz. These minerals are common to regional metamorphic mineral assemblages and may indicate that the metamorphism was possibly accompanied by east-west compressive deformation.

A later episode of deformation is recognized by folded and disrupted S1 foliation which can best be observed in Wells Creek and immediately south of the Excelsior Mine (Fig. 13). Mapping and core drilling in this area have identified several east-northeast trending faults and shears which dip steeply to the southeast. The largest of these structures is the Deadhorse Fault which trends approximately
Figure 13. Drag folding of $S_1$ foliation is shown here in the black slates along Wells Creek. The fault is to the left just out of the field of view.
N70°E, closely parallelling a tributary of Wells Creek known informally as the East Fork of Deadhorse Creek (Fig. 14; Plate 1). Although this fault is not exposed, its existence is made certain by the presence of overturned beds, shattered keratophyre outcrops, severely disrupted S1 foliation, offset of the Sedimentary Unit, and strong topographic expression. These features collectively serve to delineate the trace of the fault. The rocks on the southeast side of the Deadhorse Fault have moved up relative to rocks on the northwest side. The amount of displacement appears to be less than 400 feet (122 m) based on the thickness of the Sedimentary Unit which has been offset in the Wells Creek area. This type of movement is consistent with the east-northeast trending drag folds observed on both sides of the fault. These folds consist of a syncline on the northwest and an anticline on the southeast. Both folds are locally overturned and have southeast dipping axial planes (Plate 2).

The presence of north-south trending folds and local small-scale east-northeast trending folds and faults suggests that the Wells Creek Volcanics have undergone at least two episodes of deformation. The first event produced the large north-south trending anticline and axial planar foliation in the fine grained sediments and tuffs. This event could have been associated with the regional metamorphism. The second event cross-cuts the north-south fabric of the first event (foliation, etc.) and has modified the original structure on a local scale. This event could also be responsible for the two directions of plunge along the major anticlinal axis.
MINE AREA GEOLOGY

Stratigraphy

The rocks in the mine area have been subdivided into eight mappable units (Fig. 14). Combined, these units represent in excess of 1000 feet (305 m) of volcanic and sedimentary rock. From oldest to youngest they are 1) Slate, 2) Lower Green Tuff, 3) Fragmental Tuffaceous Graywacke, 4) Dark Sediments, 5) Felsic Volcanic Breccia, 6) Felsic Volcanics, 7) Gray Siliceous Tuff, and 8) Upper Green Tuff. All units share gradational contacts with one another. These rocks are unique to the Mt. Baker Window in that they are directly related to a felsic volcanic center and they contain the only known precious metal occurrence in the Wells Creek Volcanics. These units belong to three of the previously described regional stratigraphic units. The Slate, Lower Green Tuff, Fragmental Tuffaceous Graywacke, and Dark Sediments belong to the Sedimentary Unit; the Felsic Volcanic Breccia, Felsic Volcanics, and Gray Siliceous Tuff belong to the Siliceous Tuff Unit; and finally the Upper Green Tuff belongs to the Upper Volcanic Unit.

Slate (sl)

This unit is primarily composed of dark gray to black marine slate. It is exposed along Wells Creek and the East Fork of Deadhorse Creek (Fig. 14). It is generally very well-sorted and consists of abundant illite and chlorite with minor well-rounded silt-sized quartz and albite grains. Locally, abundant radiolarians and skeletal particals can be observed where internal deformation is less intense. Thin sandstone lenses and pods occur locally. Near the top of the unit volcanic clasts (primarily pumice) are present and the slate grades into a gray
Mt. Baker Andesite
Crystal Tuff
Upper Green Tuff
Gray Siliceous Tuff
Felsic Volcanics
Felsic Volcanic Breccia

Dark Sediments
Lower Green Tuff
Slate
Keratophyre
Strike & Dip of Bedding
Strike & Dip of Foliation
Plunging Syncline

Lithologic Contact
Fault
Shear Zone
Plunging Overturned Anticline

Figure 14. MINE AREA GEOLOGY.
wispy tuffaceous shale.

The entire unit shows no sign of hydrothermal alteration and does not contain commercial base or precious metal mineralization.

Lower Green Tuff (lgt)

The Lower Green Tuff is composed of a variety of lithologies which combined have a maximum thickness of approximately 250 feet (76 m). It is exposed at the portal of the Lower Tunnel and at the south end of the mine area just north of the East Fork of Deadhorse Creek (Fig. 8). The vast majority of the unit is composed of vitric tuff which contains abundant glass shards and local attenuated pumice fragments replaced by sericite (Fig. 15). These tuffs are generally fine to medium grained and poorly-sorted. Minor relict feldspar crystals are present locally and these have been replaced by either calcite or adularia. Sericite generally accounts for greater than 50% of the total mineral content whereas quartz, adularia, calcite, and minor sulfides make up the remainder.

Also present in this unit are dacitic crystal tuffs containing angular feldspar phenocrysts set in a matrix of sericite, feldspar, quartz, chlorite, and pyrite. The primary feldspars have been completely replaced by adularia and to a lesser extent calcite and sericite. In some cases hydrothermal alteration has almost completely destroyed the primary texture. Veining is locally intense with quartz-calcite-adularia±sulfides.
Figure 15a and b. Photomicrograph of a vitric tuff with relict pumice. The lower photo shows the outline of the pumice whereas the upper photo shows that it has been completely replaced by sericite. Magnified 100 times. Sample EX-24, 314.
Tuffaceous siltstone is present locally and is composed of angular volcanic clasts set in a fine clay-rich matrix. Sericite generally accounts for 80% of the total mineral content with adularia, quartz, chlorite, and pyrite making up the balance.

All components of this unit have been subjected to intense hydrothermal alteration. This generally consists of the primary feldspars completely replaced by adularia and/or sericite and/or calcite, the primary mafic minerals completely replaced by chlorite, volcanic glass replaced by sericite, and the matrix altered to clay, quartz, adularia, leucoxene, and minor chlorite. Some zones exhibit vugs and veinlets which are filled with adularia-calcite-quartz±apatite±sulfides. Typically, adularia has been the earliest mineral to crystallize whereas the sulfides are generally late stage.

Portions of this unit contain potentially commercial concentrations of silver and gold mineralization (>1.5 oz/ton Ag). These are generally confined to the upper part of the unit within the poorly-sorted crystal and lithic tuffs. The lower two-thirds of the unit is made up of vitric tuffs which are generally poor hosts for mineralization due to intense seritization of the primary volcanic glass.

**Fragmental Tuffaceous Graywacke (ftg)**

The Fragmental Tuffaceous Graywacke is not exposed in the mine area and has been left out of Figure 14. Description of this unit is based solely on examination of drill cores. This unit is a rhyolitic to dacitic, poorly-sorted, coarse grained lithic-feldspathic sandstone
(graywacke) which has an average thickness of approximately 80 feet (24 m). The angular to subrounded lithic fragments consist primarily of rhyolite, dacite, and minor argillite. The volcanic fragments generally contain relict feldspar phenocrysts that have been completely replaced by adularia which is commonly partially replaced by calcite. Primary quartz phenocrysts have been completely recrystallized. The matrix consists primarily of adularia, quartz, sericite, chlorite, and pyrite.

Hydrothermal alteration has been intense and is ubiquitous throughout this unit. This is probably due to a high primary permeability which this unit must have inherited from the poor-sorting and angularity of the fragments. In some samples at least three episodes of hydrothermal alteration can be identified. The earliest episode involved the complete replacement of primary feldspars by adularia along with quartz-adularia±apatite veining. Minor sulfides were associated with this event and were generally concentrated in the pore spaces of the matrix. The second event involved intense carbonate replacement which in some cases has completely destroyed all primary textures to such an extent that clasts and matrix are barely discernable in thin section. Numerous calcite-quartz-sulfide veinlets are also associated with this event. The third episode of alteration includes strong quartz-calcite-white mica veinlets which may have taken place during regional metamorphism.

Mineralization greater than 1.5 oz/ton silver with associated gold is widespread throughout the unit with the thickest intervals
being concentrated near the top and bottom of the unit. The base metals (Cu, Pb, Zn), although present, do not constitute a commercial deposit.

**Dark Sediments (ds)**

This unit consists of a variety of lithologies, all of which are dominantly sedimentary in origin. Outcrops of this unit are limited to the southern portion of the mine area (Fig. 14). The total thickness is variable and difficult to determine due to faulting, but it appears to have a minimum thickness of approximately 100 feet (30 m).

The most common lithology is a dark gray massive to crudely bedded siltstone containing quartz, feldspar, clays, and pyrite. Also common are tuffaceous siltstones which are poorly-sorted, coarse grained, and have angular to subrounded clasts of rhyolite, chert, siltstone, local massive pyrite, and rare pumice. Quartzo-feldspathic sandstones are present locally and these are poorly-sorted and contain angular quartz, relict feldspar, and minor chert (Fig. 16). Sedimentary breccias and lithic tuffs are scattered throughout the unit but appear to be dominant near the top. These generally have a wide variety of clast compositions, including volcanics (flows and tuffs), argillite, and minor chert. Near the top of the unit however, there seems to be a predominance of rhyolitic clasts which are angular and measure up to 65 mm in length. The clasts contain relict feldspar phenocrysts and minor recrystallized quartz phenocrysts.

Hydrothermal alteration has been intense and pervasive. Primary
Figure 16. Photomicrograph of a poorly-sorted quartzofeldspathic sandstone (graywacke). Magnified 40 times, plane polarized light. Sample BL-4.
feldspars have been completely replaced by adularia, sericite, calcite, and locally by albite. Some volcanic clasts have been sericitized and are surrounded by a siliceous-adularia-rich matrix. Clasts of hydrothermal quartz veins are present locally and are indicative of a hydrothermal event prior to the deposition of this unit (Wodzicki, 1981). Veins rich in quartz-adularia-apatite, adularia-calcite, and adularia-quartz-calcite-pyrite are common throughout the unit. Adularia is commonly an early stage phase occurring as euhedral crystals along vein walls (Fig. 17).

This unit contains thick and fairly extensive zones of mineralization greater than 1.5 oz/ton silver with associated gold. The upper and lower portions of the unit are commonly well mineralized but mineralization is not restricted to these two zones. The highest grade mineralization in the entire section are found within this unit with some values of up to 100 oz/ton Ag and 1 oz/ton Au.

**Felsic Volcanic Breccia (fvb)**

The Felsic Volcanic Breccia crops out at the Big Stope portals and south of the old workings (Fig. 14). This unit consists primarily of rhyolitic to dacitic volcanic breccia and tuff-breccia and ranges between 50 to 110 feet (15-34 m) in thickness. The lithic fragments are angular to subrounded dacite, rhyolite and less commonly, vitric tuff. The volcanic clasts contain relict feldspar phenocrysts and minor quartz phenocrysts whereas the tuff clasts contain relict glass shards (Wodzicki, 1981). Rare pumice clasts are present locally and are completely replaced by sericite.
Figure 17. Photomicrograph of euhedral adularia which has crystallized along a vein wall within the Dark Sediments Unit. Magnified 40 times, crossed polarized light. Sample EX-44-220.
Mesoscopically the matrix appears to be a volcanic graywacke and locally the breccia grades into a dacitic, poorly-sorted, angular, crudely bedded, lithic graywacke sandstone (Fig. 18). Microscopically, the matrix is composed of sericite, feldspar, quartz, calcite, and minor chlorite and sphene (Wodzicki, 1981).

This unit has a variety of textures but is generally of uniform composition. Near the Big Stope and Mill Level Tunnel of the mine, the clasts are very large and blocky, often with diameters of up to hundreds of millimeters (Figs. 19a & b). They commonly exhibit at least two periods of alteration and brecciation with some brecciation in situ. This appears to indicate a phreatic style of brecciation which could have occurred proximal to a volcanic center. To the south and down-dip of the Big Stope and Mill Level Tunnel the clasts become much smaller, averaging approximately 20 mm in length, and in situ brecciation is absent (Fig. 20). This seems to indicate that the source of the clasts and possibly the hydrothermal fluids was in the direction of the Big Stope and has since been eroded away.

Hydrothermal alteration of this unit has been intense and very widespread. Primary feldspars have been completely replaced by adularia, quartz, sericite, minor albite, and often a later stage of calcite. The upper portion of the unit commonly has both adularia and albite present with the latter occurring as "islands" within the former. These "islands" of albite have random optical orientations and are possibly a replacement feature related to the regional metamorphic event.
Figure 18. Photomicrograph of a crudely bedded graywacke. The dark layers are clay-rich. Magnified 40 times, plane polarized light. Sample EX-5.
Figure 19a and b. Samples of the Felsic Volcanic Breccia taken from the Mill Level Tunnel. Note the large, angular rhyolite clasts. The scale in the upper photo is in inches, the person's thumb in the lower photo measures approximately 2 inches (51 mm).
Figure 20. Core samples of the Felsic Volcanic Breccia located down-dip of the Blacksmith Level and slightly up-dip of the Lower Level Tunnel. Note the smaller clast size and crowding. The pen measures 5.5 inches (140 mm).
Silicification is ubiquitous throughout the unit and pervasive carbonate replacement is common (Fig. 21). Intense veining is common locally (especially in the Big Stope and Mill Level Tunnel) with quartz-sericite-calciteapatite. Primary fluid inclusions have been found in one vein where euhedral quartz is surrounded by calcite. The calcite acted as a physical barrier during metamorphism absorbing all of the deformation and allowing the quartz to remain unstrained. These inclusions are both liquid-rich and vapor-rich (Wodzicki, 1981) which indicates that the fluid was boiling at the time of trapping (Roedder, 1979). The implications of this as well as fluid chemistry will be discussed later.

The Felsic Volcanic Breccia is the uppermost mineralized stratigraphic unit in the vicinity of the Great Excelsior Mine. The rock units immediately above this unit, although hydrothermally altered, do not contain significant silver-gold mineralization. Although intense hydrothermal alteration has affected the entire unit, large non-mineralized zones exist within the breccia (Fig. 39; Plate 8). The highest grade mineralization occurs in the Big Stope and down-dip into the Blacksmith Level but pinches out further down-dip before it reaches the face of the Lower Level Tunnel. This may be related to distance from the source of hydrothermal fluids which seems to be in agreement with stratigraphic evidence.

Felsic Volcanics (fv)

The bulk of this unit consists of rhyolitic to dacitic breccia with angular clasts which contain relict feldspar and quartz pheno-
Figure 21. Photomicrograph of carbonate replacement in the Felsic Volcanic Breccia. More than 50% of this thin section is composed of calcite. Magnified 40 times, crossed polarized light. Sample MLDP-2.
crysts. Locally present is a siliceous "cherty" breccia (Fig. 22) which contains fine grained quartz and muscovite which exhibits weak foliation (Wodzicki, 1981). This "cherty" breccia could represent devitrified glass derived from a viscous rhyolitic flow into cold sea water. This likely would have undergone intense auto-brecciation of the type described by Pichler (1965) for acid hyaloclastites. This unit is of variable thickness, ranging from 0 to 40 feet (0-12 m). It crops out to the south and west of the Big Stope (Fig. 14).

The primary feldspars have been completely replaced by adularia. The matrix is composed of adularia, quartz, and minor pyrite (Wodzicki, 1981). Quartz and quartz-adularia veins are common but base and precious metals are almost completely absent in this unit.

The Felsic Volcanics Unit appears to be stratigraphically discontinuous within the mine area. It is present in the underground workings and on the surface above the workings but has not been detected by drilling both to the south of the mine and down-dip below the Blacksmith Level.

Gray Siliceous Tuff (gst)

The Gray Siliceous tuff crops out to the west of the Big Stope and can be traced to the northwest for approximately 1000 feet (305 m). It is not exposed south of the old mine workings (Fig. 14). This unit consists primarily of rhyolitic tuffs and breccias and ranges between 0 to 40 feet (0-12 m) in thickness. The clasts typically contain relict feldspar phenocrysts and minor quartz phenocrysts which are
Figure 22. Photomicrograph of the Felsic Volcanic Unit. Here microcrystalline quartz clasts are set in a sericite-quartz-rich matrix. This "cherty breccia" could represent an auto-brecciated rhyolitic flow which was later devitrified. Magnified 40 times, crossed polarized light. Sample CLAT-22G.
often embayed. The matrix is composed of quartz, adularia, sericite, calcite, pyrite, chlorite, minor albite and trace graphite and leucoxene (Wodzicki, 1981).

The primary feldspars have been completely replaced by adularia and lesser albite, and were later replaced by sericite and calcite. Minor quartz-adularia veining is present, some of which are within the margins of clasts, suggesting an earlier stage hydrothermal event prior to the deposition of the unit (Wodzicki, 1981).

This unit is known to contain local Ag-Au mineralization (>1.5 oz/ton Ag) only in the Blacksmith Level, and here restricted to one drift. Drilling to date has not proven the Gray Siliceous Tuff to be of any economic significance.

Upper Green Tuff (ugt)

Outcrops of the Upper Green Tuff occur high above, and to the west of the old workings. These exposures are very few and are too small to be shown in Figure 14. The description of this unit is based largely upon examination of drill cores.

This unit is composed dominantly of crystal lithic tuffs of andesitic to dacitic composition. It is the uppermost mine unit and is a minimum of 400 feet (122 m) thick as indicated by drilling. There are a variety of different lithologies present within this unit, among which are epiclastic rocks, intercalated argillites and tuffaceous argillites, crystal tuffs, vitric tuffs, and lithic tuff-breccias.
This unit is recognized for its complete lack of hydrothermal alteration and Ag-Au mineralization. Metamorphic minerals such as pumpellyite and albite are common with prehnite present, although rare. Primary feldspars have been completely replaced by albite, sericite-calcite, albite-calcite, calcite-quartz-chlorite, and minor pumpellyite. Relict mafic phenocrysts have been completely replaced by chlorite. Relict volcanic glass has been completely replaced by sericite and rarely by pumpellyite. Pressure fringes containing feathery intergrowths of albite and Fe-rich chlorite are nearly always present around euhedral pyrite crystals (Fig. 23).

The groundmass is generally composed of sericite, chlorite, albite, minor quartz and minor pumpellyite. Trace amounts of apatite, zircon, and sphene are also present. Euhedral pyrite often makes up as much as 2% of the rock but is generally present in trace amounts. The pyrite may be the result of syngenetic or diagenetic precipitation of Fe and bacterially reduced sea water sulfate.

The Upper Green Tuff appears to grade into a massive coarse crystal tuff which caps the ridge west of the mine. This latter unit represents the upper portion of the Wells Creek Volcanics and appears to be the time-stratigraphic equivalent of the massive keratophyre flows to the northeast near Excelsior Lookout. The contact between the tuffs of the Upper Wells Creek Volcanics and the overlying Nooksack Group appears to be gradational with a change from dominantly volcanic tuffs to tuffaceous fine grained sediments.
Figure 23. Photomicrograph of the Upper Green Tuff Unit. Here a pressure fringe of intergrown albite and Fe-chlorite has developed around a euhedral pyrite crystal. Magnified 40 times, crossed polarized light. Sample EX-42, 266.5'.
Structure

As previously mentioned, the Great Excelsior Ag-Au deposit is hosted within felsic volcanic breccias, tuffs, and tuffaceous sediments belonging to the Middle Jurassic Wells Creek Volcanics. These lithologies, which belong to the previously described Sedimentary Unit and Siliceous Tuff Unit, have been folded into a tight, locally overturned west-plunging syncline (Fig. 14) which is superimposed on the west limb of the regionally important north trending anticline (Plate 1). The old mine workings are located along the nose of the syncline where the strata strikes north-northwest and dips steeply to the west. Slight overturning of strata occurs locally at higher structural levels. Drilling has indicated a general flattening of dip to the west approximately along the east-northeast fold axis.

South of the old workings the strata strike approximately N85°E with dips ranging between 45-70° to the north. Northwest strikes with dips averaging 60° to the southwest are present north of the workings.

A well-developed penetrative foliation is present in most of the fine grained sediments and many of the tuffs. This foliation is axial planar to the large-scale regional anticline (Plate 1), and has an average trend of N10°E, dipping steeply to the east. Small-scale folds within the slates in Wells Creek, east of the mine, appear to share the same trend.

Several faults and shears have been recognized in the mine area. In the vicinity of the old workings these structures trend to the north.
whereas south of the workings they are east-northeast trending. All of
the faults and shears in the underground workings trend approximately
north, and dip steeply to the west. These structures, such as Earl's
Fault (Fig. 24; Plates 7 & 8), are almost always confined within the
fine grained sediments and tuffs, and are generally subparallel to
bedding. They are characterized by abundant clay gouge, broken rock,
closely spaced fracture cleavage, and local horizontal striations.
Relative displacement along these faults has not been determined, but
the presence of local horizontal striations suggests that the latest
movement was north-south strike-slip.

A N10°E trending shear zone known informally as the Skid Road
Shear (Fig. 14), is present west of the underground workings. This
shear zone can be traced over 3000 feet (914 m) along strike and is as
much as 50 feet (15 m) wide locally. It is characterized by closely
spaced fracture cleavage, broken rock, and minor gouge. The shear zone
generally dips to the east about 70°. Relative displacement is up on
the east with minor offset in the mine area.

Several closely spaced east-northeast trending and southeast
dipping faults are present south of the underground workings (Fig. 14).
The largest of these is the Deadhorse Fault which trends approximately
N70°E and marks the southern boundary of the mine area rock units and
the Skid Road Shear. The rocks on the south side of the fault have
moved up relative to the rocks on the north side, possibly as much as
400 feet (122 m) based on the thickness of the Sedimentary Unit which
has been offset in the Wells Creek area (Plate 1). The small east-
northeast trending faults immediately north of the Deadhorse Fault have been identified primarily by drill hole intercepts which are characterized by abundant gouge and rubbly core. These faults appear to have the same type of relative movement as the Deadhorse Fault based on the repetition of strata, and drag folding of foliation present in the slates exposed in Wells Creek (Fig. 13). The amount of offset along these faults appears to be very small.

The structures present in the mine area reflect at least two episodes of deformation. The first event resulted in the small-scale north trending folds and penetrative axial planar foliation within the slates in Wells Creek. The Skid Road Shear, which parallels the foliation, is probably related to this event as well. Since displacement along the Skid Road Shear appears to have resulted from compressive deformation, it is possible that both the foliation and the shear resulted from the same directions of principle stress.

The second episode of deformation resulted in movement along the Deadhorse Fault and similar trending faults immediately to the north. These faults have cross-cut the original structural fabric such as the Skid Road Shear and the axial planar foliation. The tight, locally overturned syncline which governs the outcrop pattern of the mine rocks, appears to be a drag feature related to movement along the Deadhorse Fault.
ECONOMIC GEOLOGY OF THE GREAT EXCELSIOR DEPOSIT

At least three vertically separated mineralized zones (based on a 1.5 oz/ton Ag cutoff) have been identified on the property (Fig. 24; Plate 3). The mineralization occurs in gently to steeply dipping tabular zones, which are commonly subparallel to the stratigraphy.

The lowermost zone is contained within gray-green vitric-lithic tuffs and volcaniclastic sediments belonging to the Lower Green Tuff and Fragmental Tuffaceous Graywacke Units. It has an average thickness of 25 feet (7.62 m), and contains 500,000 tons of mineralization. This zone has an average grade (based entirely on drill hole intercepts) of 3.40 oz/ton Ag and 0.031 oz/ton Au.

The Lower Tunnel Zone (middle zone) is confined primarily to poorly-sorted volcaniclastic sediments belonging to the Dark Sediments and Fragmental Tuffaceous Graywacke Units. Rock types present in this zone include variable amounts of siltstone, tuffaceous siltstone, and tuffaceous graywacke. The zone represents approximately 1.5 million tons of mineralization averaging 5.75 oz/ton Ag and 0.055 oz/ton Au, and averages 35 feet (10.57 m) in thickness. Local high-grade "pockets" of mineralization are present proximal to faults in this zone which have significantly enriched the overall grade. By omitting the drill hole intercepts of these "pockets" the average grade for the Lower Tunnel Zone is 4.25 oz/ton Ag and 0.037 oz/ton Au.

The Big Stope Zone (upper zone) includes the bulk of the high-grade ore extracted in the early years from the underground workings.
Figure 24. Cross section B-B' showing the three separate mineralized zones which have been identified on the property. See Plate 4 for reference to location of cross section.
The vast majority of mineralization is contained within the Felsic Volcanic Breccia Unit and subordinantly within volcaniclastic sediments of the Dark Sediments Unit. The zone averages 40 feet (12.19 m) in thickness, has a strike length of at least 400 feet (122 m) and extends down-dip approximately 200 (61 m) to 300 feet (91 m). It represents 500,000 tons of mineralization which averages 3.41 oz/ton Ag and 0.038 oz/ton Au.

The three zones combined contain approximately 2.5 million tons of mineralization which averages 4.67 oz/ton Ag and 0.047 oz/ton Au. A potential of another one million tons of reserve could be present along strike and down dip of the Lower Tunnel Zone.

Mineralogy and Paragenesis

Figure 25 is a paragenetic diagram which illustrates the relative abundance and time of deposition of the ore and gangue minerals found in the Excelsior deposit. The paragenetic sequence of the three separate mineralized zones does not appear to vary significantly and therefore have been considered as one.

The "ore" minerals present in the Excelsior deposit include argentite, tetrahedrite, polybasite?, electrum, and two unidentified silver-rich phases. The non-economic sulfides which are present include sphalerite, galena, chalcopyrite, bornite, and pyrite. Non-metallic gangue minerals are adularia, albite, calcite, apatite, sericite, quartz, and local graphite.
Figure 25. Paragenetic diagram of the Great Excelsior deposit.
Pyrite was the earliest sulfide mineral deposited and from its mode of occurrence as disseminated cubes appears to have been largely syngenetic or early diagenetic. Pyrite has been rimmed and partially replaced by argentite (Fig. 26), tetrahedrite, polybasite? (Fig. 27), chalcopyrite (Fig. 28), sphalerite (Fig. 29), galena, and electrum (Fig. 28). Chalcopyrite, galena, and sphalerite occur primarily in veinlets and also as fine disseminations replacing pyrite. Bornite is a minor constituent and has been observed in only one sample where it appears to have exsolved from chalcopyrite (Fig. 30).

Argentite appears to be the most abundant silver-bearing mineral present. As with most of the other silver minerals present it occurs primarily replacing pyrite which is disseminated throughout the groundmass. It also commonly occurs in veins where it replaces calcite both along cleavage (Fig. 31) and at oblique angles to the cleavage (Fig. 32).

Electrum is the only gold-bearing mineral that has been identified. It is found exclusively replacing pyrite, occurring as rims around, and elongate patches within euhedral pyrite crystals. An electron microprobe analysis by Payne (1980) has indicated that the electrum contains 65% Au and 25% Ag. The electron microprobe analysis also detected two additional phases, both of which contain a large amount of silver. The first contained 84% Ag and significant sulfur (no standard was used), whereas the second contained very high silver (reported as 100% but needs correction), 7% As, 10% Sb (no standard but counts higher than As), and 10% sulfur (Payne, 1980). From the combination of optical properties and chemical composition Payne (1980) could not identify the
Figure 26. Photomicrograph of disseminated pyrite (py) and argentite (arg). The pyrite has been pseudomorphed and partially replaced by argentite. Magnified 200 times, plane polarized reflected light.
Figure 27. Photomicrograph of polybasite? (pb) replacing pyrite (py). Magnified 200 times, plane polarized reflected light. Sample EX-2, 16'.
Figure 28. Photomicrograph of electrum (el) replacing pyrite. Also present are argentite (arg), tetrahedrite (tt), and chalcopyrite (cpy) which also replace pyrite. Magnified 200 times, plane polarized reflected light.
Figure 29. Photomicrograph of sphalerite (sph) replacing pyrite (py). Chalcopyrite (cpy) recurs as exsolution blebs within sphalerite. Magnified 200 times, plane polarized reflected light.
Figure 30. Photomicrograph of bornite (bn), chalcopyrite (cpy), and argentite (arg). The bornite may have exsolved from the chalcopyrite. Magnified 200 times, plane polarized reflected light. Sample EX-2, 16'.
Figure 31. Photomicrograph of chalcopyrite (cpy), tetrahedrite (tt), and argentite (arg) replacing calcite (dark gray) along cleavage. Magnified 200 times, plane polarized reflected light.
Figure 32. Photomicrograph of argentite (arg) replacing calcite (dark gray) at an oblique angle to the cleavage. Magnified 200 times, plane polarized reflected light.
first mineral but suggests that the second mineral is most likely pearceite-polybasite.

Of the non-metallic gangue minerals, adularia appears to have been the first to crystallize. It occurs as euhedral crystals along vein walls and vugs (Fig. 17), and it has replaced primary feldspars and groundmass in much of the deposit (Fig. 33). Albite is also present in portions of the deposit. It commonly occurs in the absence of adularia in the upper portions of the deposit as subhedral to euhedral crystals in veins and vugs and generally replaces primary feldspars. It is not uncommon to see both adularia and albite occurring together. Euhedral to subhedral quartz accompanied adularia in many of the veins and also occurs pervasively throughout many of the coarser grained and poorly-sorted lithologies. Calcite appears to be a late stage mineral occurring in veins where it surrounds and often partially replaces adularia. Calcite also replaces adularia, groundmass, and clasts in many samples. This was possibly the result of fluid boiling and the loss of volatiles (including CO$_2$) which caused pervasive replacement of the host rock by calcite. Calcite appears to have crystallized prior to, during, and after sulfide mineralization (except pyrite). Sulfides have replaced calcite in many of the samples, whereas in others they appear to have crystallized together, and in some calcite obviously crystallized after sulfides.
Figure 33. Photomicrograph of adularia (yellow) replacing groundmass and occurring in veins. Note the sulfide veinlet which offsets the quartz veins. Magnified 40 times, plane polarized light, section stained for K. Sample EX-44, 170'.
Ore Solution Chemistry

The thermochemical modeling of the Great Excelsior deposit has been based primarily upon one sample taken from the Big Stope Zone. This sample is a section of diamond drill core taken 16 feet (4.88 m) vertically below the Big Stope drill site (EX-2, 16'; Plate 6).

Present in this sample are primary fluid inclusions contained within hydrothermal quartz that is surrounded by calcite (Fig. 34). Since these rocks have been subjected to the temperature and pressure effects of prehnite-pumpellyite facies metamorphism and two periods of deformation, primary fluid inclusions are rare within the deposit due to the fact that the hydrothermal gangue minerals such as quartz, which host them, are easily recrystallized. These inclusions have been fortuitously preserved in this particular sample because the calcite, which completely surrounds the euhedral quartz host, has absorbed all of the strain, allowing the quartz to remain in its original state, completely undeformed. Both liquid-rich and vapor-rich primary two-phase inclusions are present (Wodzicki, 1981), implying that the fluid was boiling at the time the quartz was crystallizing (Roedder, 1979).

Heating and freezing runs have been made on these quartz samples in order to obtain a fluid temperature and salinity. Figure 35 is a frequency versus temperature histogram of homogenization temperatures from liquid-rich two phase inclusions. The data in Figure 35 suggest that the mean homogenization temperature is approximately 300° C. Since the inclusions were trapped along the vapor pressure curve of water, the
Figure 34. Photomicrograph of euhedral quartz surrounded by calcite. Note the deformation twinning within the calcite and lack of deformation in the quartz. Magnified 40 times, crossed polarized light. Sample EX-2, 16'.
Figure 35. Frequency versus homogenization temperature histogram. Frequency (%) represents measured homogenization temperatures from liquid-rich primary inclusions.
homogenization temperature is equal to the trapping temperature, therefore eliminating the need to make a pressure correction (Roedder, 1979).

Table 2 is a list of the freezing point depression temperatures along with their respective homogenization temperatures and corresponding values of weight percent NaCl equivalent calculated from equations of Potter and others (1978).

The average weight percent NaCl equivalent calculated from these values is 3.64. However, for simplicity an average of 3.5 wt. % NaCl equivalent (0.6 M) will be used hereafter for thermochemical calculations.

Since the temperature and salinity of this boiling solution is known, the minimum total confining pressure which acted upon the system can be determined since it must be equal to the vapor pressure (Cunningham, 1978). A solution lying on the vapor pressure curve for water and containing 3.5 wt. % NaCl equivalent at $300^\circ$ C will be under a hydrostatic pressure of about 8,500 kPa (85 bars), which is comparable to a water depth of about 1025 m (Cunningham, 1978; Haas, 1971). It should be kept in mind, however, that the activity of CO$_2$ in the solution has not been considered. Its presence will have the effect of raising the vapor pressure curve thereby increasing the depth of the system. With this in mind it can be said that the Excelsior mineralization was likely deposited by a submarine geothermal system at a minimum sea water depth of 1000 m.

With empirical values of solution temperature and salinity an ore-
<table>
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<tr>
<th>Homogenization Temp. (°C)</th>
<th>Freezing Point Depression (°C)</th>
<th>Wt% NaCl</th>
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</thead>
<tbody>
<tr>
<td>294</td>
<td>- 1.9</td>
<td>3.21</td>
</tr>
<tr>
<td>284</td>
<td>- 1.8</td>
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<td>356</td>
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<td>16.91</td>
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<tr>
<td>326</td>
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<tr>
<td>268</td>
<td>- 2.0</td>
<td>3.37</td>
</tr>
<tr>
<td>312</td>
<td>- 0.9</td>
<td>1.56</td>
</tr>
<tr>
<td>317</td>
<td>- 2.3</td>
<td>3.85</td>
</tr>
<tr>
<td>210</td>
<td>- 2.0</td>
<td>3.37</td>
</tr>
<tr>
<td>302</td>
<td>- 2.9</td>
<td>4.79</td>
</tr>
<tr>
<td>311</td>
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<td>- 1.5</td>
<td>2.56</td>
</tr>
</tbody>
</table>
depositing environment can be identified through thermochemical calculations using mineralogic constraints. Figure 36 depicts the area of mineral deposition in \( f_{O_2} - pH \) space at 300\(^{\circ}\) C for the Great Excelsior ore solution.

Since this particular sample contains hydrothermal albite in the absence of adularia the activity of \( K^+ \) cannot be definitively determined. The equilibria between adularia and albite (an assemblage present elsewhere in the deposit) is expressed by the following equation:

\[
\text{NaAlSi}_3\text{O}_8 + K^+ \rightleftharpoons \text{KAlSi}_3\text{O}_8 + \text{Na}^+ \\
(\text{Albite}) \quad (\text{Adularia})
\]

The equilibrium constant, \( K = \frac{[\text{Na}]_{Na^+}}{[\text{Na}]_{K^+}} \), at 300\(^{\circ}\) C is equal to 6.17 (Helgeson, 1969). Had these two minerals been together in equilibrium in this particular sample \( a_{K^+} \) would have been fixed at \( 10^{-1.70} \) M (see Appendix III for calculations). Therefore this value is the maximum possible \( a_{K^+} \) in this particular zone of mineralization. Elsewhere in the deposit, however, adularia occurs in the absence of albite. Where this relationship occurs \( 10^{-1.70} \) M is the minimum possible value for \( a_{K^+} \).

The activity of \( K^+ \) strongly influences the reaction sericite \( \rightleftharpoons \) kaolinite. The higher the \( a_{K^+} \), the lower the pH must become to make the reaction proceed to the right. This has the effect of widening the sericite field at the expense of kaolinite. Conversely, lowering the \( a_{K^+} \) will cause the sericite field to shift to higher pH values, narrowing it until it becomes unstable.
Figure 36. The stability fields for the system Cu-Fe-S-O-C. The minerals include calcite (cal), anhydrite (anhy), sericite (ser), albite (ab), adularia (ad), kaolinite (kao), pyrite (py), pyrrhotite (po), chalcopyrite (cpy), bornite (bn), magnetite (mt), hematite (hm). Activities are $\xi S=10^{-1}$, $\xi C=10^{0}$, $Ba=10^{-6}$, $Ca=10^{-2.49}$. 
Since sericite and albite are both present in this sample, the solution must lie close to the sericite-albite equal activity boundary. Since adularia is present throughout much of the deposit, a pH range is possible above the kaolinite boundary and just to the right of the sericite-adularia equal activity boundary.

The presence of calcite in the absence of anhydrite and/or gypsum puts additional constraints on the ore solution as do the presence of pyrite, chalcopyrite, and bornite. The latter assemblage buffers the oxygen fugacity for various values of total sulfur activity ($\Sigma S$), whereas the assemblage calcite+anhydrite buffers the oxygen fugacity for various values of both total sulfur ($\Sigma S$) and total carbon activity ($\Sigma C$). The presence of calcite alone confines the solution to the calcite-insoluble field shown in Figure 36.

In order to calculate calcite solubility for this solution it is imperative to have a value for the activity of Ca$^{2+}$ ($a_{\text{Ca}^{2+}}$). Since this cannot be measured directly it must be derived by another means. The depositional environment of the Excelsior rocks appears to be very similar to that which has been described by numerous authors for Kuroko-type deposits. It therefore seems reasonable to closely compare the chemical conditions of Kuroko deposits with those of Excelsior. In this way a value for the activity of calcium ($a_{\text{Ca}^{2+}}$) can be obtained through the work of others on the younger and better preserved Japanese deposits. Franklin and others (1981) report a value for $a_{\text{Ca}^{2+}}$ equal to $10^{-2.4}$M for a pH of 5.0.
Another method for obtaining this value which is slightly more direct may also be used. By using the Fournier and Truesdell (1973) equation for the Na-K-Ca geothermometer with known values for temperature, $a_{Na}^+$ and $a_{K}^+$ (keeping in mind that this $a_{K}^+$ is approximate), the activity of calcium can be calculated. In order to accomplish this, one must work in the reverse of how the geothermometry equation was intended. By knowing the temperature of the solution ($300^\circ$ C) and using Figure 6 (p. 1266) of Fournier and Truesdell (1973), a value for $f(T)$ can be obtained. From this point the various values can simply be inserted into the equation in the following manner.

\[
f(T)=0.65
\]
\[
Na^+=0.15 \text{ M (see Appendix III)}
\]
\[
K^+=2.43 \times 10^{-2} \text{ M}
\]
\[
f(T)=\log \left(\frac{Na^+}{K^+}\right) + \frac{1}{3}\log \frac{Ca^{2+}}{Na^+}
\]
\[
0.65=\log \left(\frac{0.15}{0.0243}\right) + \frac{1}{3}\log \frac{Ca^{2+}}{0.15}
\]
\[
-0.14=\frac{1}{3}\log \frac{Ca^{2+}}{0.15}
\]
\[
-0.42=\log \frac{Ca^{2+}}{0.15}
\]
\[
0.38=Ca^{2+}/0.15
\]
\[
Ca^{2+}=3.24 \times 10^{-3} \text{ M } = 10^{-2.49} \text{ M}^*
\]

This value was then used to plot calcite solubility curves in $fO_2$-pH space for various values of total carbon activities ($\Sigma C$). At $\Sigma C=10^{-3}$ M the calcite solubility curve lies just to the right of the sericite/adularia equal activity boundary, in the adularia field. This is close to the maximum pH limit of the solution, therefore it represents the absolute minimum value for $\Sigma C$ since calcite is abundant in this

* This value compares extremely well with the value given by Franklin and others (1981).
sample. A value of $C=10^0$ M is more conservative since this moves the calcite solubility line down to a pH=4.54 which makes calcite insoluble over most of the sericite field (at log $f_O_2>-35$).

Since anhydrite is absent in the mineralized zone it is necessary to represent the equal activity boundary for anhydrite/calcite. This equilibria, presented by the reaction

$$CaSO_4 + H_2CO_3 \rightleftharpoons CaCO_3 + H_2S + 2O_2$$

is dependent both upon $S$ and $C$. If we assume $C=10^0$ M, then the value for $S$ can be chosen such that the equilibria for anhydrite/calcite falls either on or above the bornite+pyrite/chalcopyrite equal activity boundary (if bornite were not present this would not be so critical). It may seem reasonable to again draw a comparison to Kuroko ore solutions and assume a similar value for $S$. Kajiwara (1973a) has reported that most hydrothermal solutions responsible for depositing Kuroko ores have total sulfur ($S$) activities ranging from $10^{-2.5}$ M at a pH of 5.0 to $10^{-1.1}$ M at a pH of 6.0. In the case of the Excelsior deposit, however, $S$ values less than $10^{-2}$ M result in the bornite+pyrite/chalcopyrite equal activity boundary failing to extend into the sericite stability field as it must do in order to be stable in this solution. At $S=10^{-1}$ M the anhydrite/calcite equal activity boundary falls slightly above the bornite+pyrite/chalcopyrite boundary (Fig. 36). This is consistent with the observed mineralogy for this portion of the deposit and therefore places acceptable limits on the values of $C$ and $S$.

The complete absence of pyrrhotite, magnetite, and hematite, and the presence of pyrite, places the ore solution within the pyrite
stability field between pH=4.54 and pH=6.0. The presence of chalco-
pyrite and local bornite indicates that at one point in time the
solution was on or near the pyrite+bornite/chalcopyrite equal activity
boundary. The absence of anhydrite indicates that the solution was less
than a log $f_{O_2}$ value of -31.60 atmospheres. And finally, the absence
of graphite throughout the majority of the deposit requires that the
solution, with local exceptions, lies above the graphite stability
field.

This mineralogic criteria defines an area in $f_{O_2}$-pH space which
represents the idealized thermochemical conditions of the Great
Excelsior mineralizing solution (shaded area in Fig. 36). It should be
kept in mind, however, that a wide variety of assumptions have been made
in the construction of this thermochemical model.

Ore Metal Solubility

By having identified the region of ore deposition in $f_{O_2}$-pH space
the relative solubilities for the various ore metals can be determined.
Because the most important complex-forming ligands are Cl$^-$, HS$^-$, and
H$_2$S, these will be the only ones dealt with when considering the solu-
bility of base and precious metals (Barnes, 1979; Franklin et al, 1981).
Of these, Cl$^-$ is probably dominant given the thermochemical conditions
previously outlined. The reason for this is that, of the sulfur
species, HS$^-$ forms a stronger complex and is the dominant species.
However, at temperatures above about 300° C, very alkaline solutions
are required for HS$^-$ to become a dominant species (relative to Cl$^-$).
For this reason, at temperatures above the 300-350° C range, sulfide
complexes may not be as important in transporting ore metals (Barnes, 1979). This is not to say that base and precious metal sulfide complexes did not exist in the Excelsior mineralizing solution. Since the mineralizing solution temperature was obtained on the basis of one sample containing fluid inclusions it may not be considered definitive of the entire deposit throughout the lifespan of mineralization. Therefore both chloride and sulfide species may have played an important role in metal transport.

Copper Solubility

Copper has not been found in commercial quantities in the Great Excelsior deposit. Nevertheless it is present in small amounts, although it is greatly depleted with respect to silver (2.62:1, Ag:Cu ratio). Copper concentrations rarely exceed 1,000 ppm in the Great Excelsior deposit and average approximately 67 ppm.

The complexes of Cu which have been evaluated here are Cu(HS)$_2^-$, Cu(HS)$_2$(H$_2$S)$^-$, and CuCl (Crerar and Barnes, 1976). As shown in Figure 37a, CuCl is probably the dominant species in the region of interest. And in fact, Crerar and Barnes (1976) and Barnes (1979) have concluded that for weakly acidic solutions in the temperature range of 250-350° C, with $\Sigma S=0.1$ to 1.0 M, such as is the case for this solution, CuCl is the dominant species.

Copper is capable of being transported in amounts ranging between 1-100 ppm as the complex CuCl in the presence of pyrite (Fig. 37a). As a sulfide complex, 0.01 to 10.0 ppm Cu is capable of being transported.
Figure 31a-d. Solubility of the metals Cu, Zn, Pb, and Au at 300°C, \( a_{\text{Cl}^-} = 10^{-8.2} \), and \( S = 10^{-11} \). Solid lines represent complexes and dashed lines are sulfide complexes. See text for stoichiometries. Stippled area represents ore solution.
The amount of Cu which was capable of being deposited over an extended period of time is far below that which has actually been deposited. This could be due to the solution being greatly undersaturated with respect to Cu, or the Cu could have been flushed through the system and either dissipated or was concentrated elsewhere.

Zinc Solubility

Zinc, although more abundant than Cu, is far below commercial concentrations. Zinc values rarely exceed 6,000 ppm (.6%) and these are located within the highest grade Ag zones. In zones where Ag is greater than 1.5 oz/ton, Zn is typically greatly depleted with respect to Ag (1.22:1, Ag:Zn ratio).

The complexes of Zn which have been evaluated here are Zn(HS)\textsuperscript{3-} and ZnCl\textsubscript{2} (Barnes, 1979). Figure 37b shows that again the chloride complex dominates. As the complex ZnCl\textsubscript{2}, the Excelsior ore solution was capable of transporting between 0.01 to 10 ppm Zn as opposed to the Zn(HS)\textsuperscript{3-} complex which was capable of transporting between 10\textsuperscript{-4} to 10\textsuperscript{-2} ppm Zn.

From Figure 37b it can be seen that, if saturated, the average fluid composition would contain about 1 ppm Zn. In the Excelsior mineralized zones, Zn concentrations average 294 ppm. By comparing average discharge rates and lifespans of active geothermal systems (Weissberg, 1969) with the Excelsior system (considering projected reserves to be 4 million tons at 294 ppm Zn), it would require 1.07 \times 10^{12} kg of H\textsubscript{2}O over a lifespan of 76 years to deposit all of the Zn (see Appendix III for calculations). This figure is incredibly small and
possibly indicates that 1) the discharge rate at Excelsior was much slower than that of Wairakei, 2) the solution was greatly under-saturated with respect to Zn, and/or 3) most of the Zn was lost from the system.

**Lead Solubility**

Lead is also present far below commercial concentrations in the Excelsior deposit. It is depleted with respect to both Ag (1.81:1, Ag:Pb ratio) and Zn (2.04:1, Zn:Pb ratio) but is slightly enriched with respect to Cu (1.20:1, Pb:Cu ratio). Lead values for the Excelsior deposit average approximately 151 ppm.

The complexes of Pb which have been evaluated here are PbCl$_2$ and Pb(HS)$_2$(H$_2$S) (Giordano and Barnes, 1979, 1981; Barnes, 1979). Figure 37c shows the relative solubilities of each complex. It is obvious from the diagram that the complex Pb(HS)$_2$(H$_2$S) does not contribute to Pb solubility under the conditions of the Excelsior fluid(s) (10$^{-3}$ ppm contour plots just to the right of the H$_2$S/S$^{2-}$ boundary). This is actually not too surprising in light of the work of Giordano and Barnes (1979 and 1981) on Pb solubility in typical hydrothermal solutions. They found that within the general pH and $z_S$ range of typical hydrothermal solutions, calculated Pb solubilities due to sulfide complexes were found to be one to two orders of magnitude below that which is required to form an ore deposit.

Also from Figure 37c, it is evident that the complex PbCl$_2$, although several orders of magnitude above the sulfide complex, is
still far below the estimated 10 ppm concentration required to form an ore deposit (Giordano and Barnes, 1979, 1981). This may appear enigmatic considering Pb is several orders of magnitude less soluble than Zn yet Zn is present in only double proportions. One explanation to this problem is that which has been put forth by Giordano and Barnes (1981), who state that "the contribution of chloride and sulfide complexing is subordinant to the total concentration of lead in brines". They go on to suggest that there may be other inorganic complexes which could transport Pb, and these include: $\text{SO}_4^{2-}$, $\text{CO}_3^{2-}$, $\text{HCO}_3^-$, $\text{NH}_3^-$, and $\text{Br}^-$, and the ion pairs $\text{NaPbCl}_3^0$ and $\text{NaPbCl}_4^-$. 

**Gold Solubility**

Gold constitutes a potential economic member of the Great Excelsior deposit. It averages approximately 0.047 oz/ton throughout the deposit. Silver/gold ratios average 133:1 which indicates Au is probably depleted with respect to Ag (Krauskopf, 1967).

The complexes of Au evaluated here are $\text{Au(HS)}_2^-$ and $\text{AuCl}_2^-$ (Seward, 1973; Casadevall and Ohmoto, 1977; Barnes, 1979). From Figure 37d it can be seen that $\text{Au(HS)}_2^-$ is by far the dominant complex for the given solution chemistry. This is in accordance with Seward's (1973) determination that chloride complexes of Au are negligible relative to Au sulfide complexes at temperatures below 400°C. Even though the activity of $\text{Au(HS)}_2^-$ may seem relatively low compared to the base metals, the commercial value of Au is an obvious enrichment factor. Helgeson and Garrels (1968) suggest that through geologic observations and thermodynamic considerations, less than 0.02 ppm Au in solution is
sufficient to result in a major Au deposit. Weissberg (1969) agrees with this and goes on to say that high concentrations of Au are not necessary in the ore-forming solution, but rather an effective precipitation mechanism is the foremost requirement.

Even though the average Au content at Excelsior is considered low grade, its presence will play an important role in the future economics of the deposit.

**Silver Solubility**

Silver is the most important metal present in the Great Excelsior deposit from an economic standpoint. In the Big Stope Zone, Ag averages 3.41 oz/ton, in the Lower Tunnel Zone 5.75 oz/ton, and in the Lower Zone 3.40 oz/ton. For the entire deposit Ag averages 4.67 oz/ton using a 1.5 oz/ton Ag cutoff.

The complex Ag\(\text{Cl}_2^-\) has been the only one evaluated here since it is the dominant species at temperatures greater than 270° C (Seward, 1976). The sulfide complexes of Ag are very poorly known and therefore data is meager concerning these (Barnes, 1979).

Figure 38 shows the solubility of Ag as Ag\(\text{Cl}_2^-\). In the region of interest, Ag concentrations slightly over 0.1 ppm are possible. This is more than adequate when considering the average Ag content of 4.67 oz/ton for a 4 million ton deposit. In the unlikely event that the solution were completely saturated with respect to Ag, it would require 5.81 X 10^{12} kg of Ag-bearing solution to make the deposit. If an
Figure 38. Solubility of Ag at 300° C and \( a_{\text{Cl}^-} = 10^{-0.82} \) M. The complex \( \text{AgCl}_2^- \) is represented here by the solid contours. Stipled area represents the ore solution.
average discharge rate similar to that measured for Wairakei (Weissberg, 1969) were considered, it would take 415 years to deposit all of the silver. Since this may be an unreasonably short lifespan it is very likely that the annual discharge rate at Excelsior was at least two orders of magnitude lower than that for Wairakei. More important, however, is the relative amount of time it would require to deposit all of the Ag compared to that of the Zn. For any given discharge rate, the time required to deposit all of the Ag will be nearly one order of magnitude more than that of Zn. This may be good indication that the hydrothermal solution was probably greatly undersaturated with respect to the base metals while being closer to saturation with respect to Ag.

Precipitation Mechanisms

Since it has been assumed that metal transport was related to chloride and/or sulfide complexes, there are a limited number of precipitation mechanisms which could have been responsible for concentrating the ore metals. These mechanisms have been summarized in Barnes (1979) and include: 1) cooling, 2) decrease in the activities of the complex-forming ligands, 3) increase in total sulfur activity, and 4) change in pH. Processes that may have been responsible for these effects include; mixing with a second solution, reaction with host rocks, and boiling.

From the previous section it seems reasonable to assume that the dominant mode of metal transport for the Excelsior deposit was by chloride complexes. For weakly acidic solutions, such as is the case here, a general reaction may be written which represents the precipita-
tion of sulfides from chloride-complexed metals (Me$^{2+}$).

\[
\text{MeCl}_2(aq) + H_2S(aq) \rightleftharpoons \text{MeS} + 2\text{Cl}^- \quad \text{(Barnes, 1979)}.
\]

From this equation it can be seen how saturation of metals in a fluid can occur, or to what extent precipitation will take place. For example, an increase in $H_2S$ concentration will drive the reaction to the right, thereby depositing sulfide. This can be brought about by the reduction of sulfate, reaction with organics, or mixing with sulfide solutions (Barnes, 1979). Likewise, an increase in pH will also bring about sulfide deposition. The two most common processes which result in a pH shift are; reaction with host rocks (especially feldspars and carbonates), and boiling. A change in pH equal to +1.0 will result in the precipitation of nearly 99% of the metal in solution (Barnes, 1979). Therefore boiling, which results in the loss of volatiles (e.g. $H_2S$ and $CO_2$), and accompanying rise in pH, can be a very powerful precipitation mechanism.

Finally, a decrease in chloride activity will cause precipitation of sulfide. This can be brought about by dilution resulting from the mixing of the hydrothermal fluid with a second fluid such as meteoric water or sea water, or by reactions adding strong Cl$^-$-ion-pairing cations such as Ca$^{2+}$.

Barnes (1979) feels that dilution is a moderately effective precipitation mechanism based on the fact that the efficiency of dilution increases as the $n$th power where $n$ is the stoichiometric coefficient for Cl$^-$. This means that dilution is much more effective for the MeCl$_4^{2-}$ stoichiometry than for MeCl$_2^-$. He points out that for MeCl$_2^-$, in an
initially saturated sulfide solution, a 1:1 dilution with Cl\textsuperscript{-}-free water will result in 85\pm10\% precipitation of sulfide, other conditions remaining constant. However, a decrease in temperature often accompanies dilution. This may add to the effectiveness of precipitation, as a temperature decrease of 100\,^\circ C may deposit up to 90\% of the metal in solution (Barnes, 1979). Mixing also has the effect of increasing the solution pH, fO\textsubscript{2}, and zS. This, in combination with a temperature decrease and dilution, may be a very important factor in ore deposition (Large, 1977).

Large (1977) believes that mixing of the hydrothermal fluid with sea water was the primary mechanism of precipitation for submarine volcanogenic polymetallic sulfide deposits. For the Great Excelsior deposit, however, this mechanism is not completely satisfying.

The Great Excelsior deposit appears to lack a clear-cut metal zonation pattern as one might expect if precipitation was brought about by mixing with a second solution. Also, the Excelsior ore solution was relatively dilute to begin with, quite close to the salinity of ordinary sea water. This would tend to rule out the role of dilution. The lack of sulfate minerals and Fe oxides is indicative of a relatively low fO\textsubscript{2} environment which also argues against mixing.

Precipitation of the Excelsior sulfides was probably in response to boiling of the hydrothermal solution and/or reaction with the host rocks. Extensive carbonate replacement in many of the host rocks suggests that boiling occurred throughout much of the deposit. This
carbonate replacement probably resulted from the rapid precipitation of calcite upon the loss of CO$_2$ to the vapor phase during the boiling process. Also, the presence of both liquid-rich and vapor-rich primary two phase fluid inclusions in quartz-calcite-sulfide veins verifies that the solution was boiling in at least one locality in the Big Stope Zone. Reaction with host rocks could have also played an important role in sulfide precipitation. The intimate relationship of precious and base metal sulfides with euhedral pyrite suggests that precipitation could have been brought about, at least in part, by the reaction between the relatively oxidizing hydrothermal solution and the relatively reducing pyrite-bearing host rocks.
GENESIS OF THE GREAT EXCELSIOR Ag-Au DEPOSIT

From field and petrographic evidence the Great Excelsior deposit appears to have been formed in an environment similar to the ore-forming environment(s) of Kuroko-type deposits which have been described by numerous writers (e.g. Kajiwara, 1973a & b; Lambert and Sato, 1974; Large, 1977; Henley and Thornley, 1979; Solomon and Walshe, 1979; Hattori and Sakai, 1979; Franklin et al., 1981). It was likely deposited in a submarine environment based on the presence of fine grained bedded sediments, subrounded chert clasts, rounded massive pyrite clasts, and radiolarians found in the footwall sediments. Furthermore, the mineralization is associated with rhyolitic to dacitic pyroclastics and breccias proximal to a volcanic center.

There are two major differences between this deposit and typical Kuroko-type deposits. One is the obvious lack of massive stratiform ore, and another is the lack of appreciable base metal concentrations which are so characteristic of Kuroko deposits.

The Great Excelsior deposit is closely associated both in space and time with a felsic volcanic center. The mineralization is confined to at least three vertically separated zones, all of which exhibit some stratigraphic control. The uppermost zone (Big Stope Zone) is primarily confined to a felsic volcanic breccia, whereas the two lower zones are contained within fine-grained sediments, tuffaceous graywackes, and felsic tuffs.
Summary of Depositional History

In the early stages of volcanism, voluminous submarine lava flows of andesitic (keratophyric) composition were erupted (Lower Volcanic Unit). These were generally thick, massive lavas displaying porphyritic-aphanitic textures. Subordinant flows of basaltic-andesite with pilotaxitic and locally amygdaloidal textures were also present. Immediately following this was a local volcanic hiatus which allowed the undisturbed deposition of black shales (Slate Unit) in a quiet, relatively deep marine environment. These were later metamorphosed to slates.

Continued volcanic activity accompanied by uplift (possibly related to resurgence) produced intermediate to felsic vitric and lithic tuffs (Lower Green Tuff). The presence of subangular to angular welded tuff clasts in many of these tuffs suggests that these rocks were probably deposited near on-going subaerial volcanism and possibly in relatively shallow water.

Following the deposition of these vitric tuffs was a period of sporadic, explosive felsic volcanism (Fragmental Tuffaceous Graywacke Unit) accompanied by regional subsidence. The reappearance of bedded sediments (Dark Sediment Unit) containing subrounded clasts of chert together with the absence of any indication of terrestrial volcanism (welded tuff clasts, etc.), are suggestive of a moderate to deep marine environment. This activity is characteristic of resurgent caldera complexes such as have been described by several writers and is summarized by Franklin and others (1981). For instance, in the
Hokuroku Basin of Japan, vertical movements associated with resurgence of a submarine caldera caused part of the basin to change from terrestrial to deep submarine (>2000 m) conditions prior to the deposition of Kuroko ores (Franklin et al., 1981). It is not unrealistic to assume the same processes were in effect here.

During the waning stages of volcanism, just prior to the mineralization, was the submarine extrusion of a rhyodacitic dome. The dome itself has not been seen and has probably been removed by erosion. The felsic volcanic breccia probably represents a dome-flank facies composed of auto-breccias, blocky talus, tuff-breccias, unstratified and minor stratified acid hyaloclastites (Pichler, 1965). Capping this unit locally, is a siliceous cherty breccia (Felsic Volcanics Unit) which may represent viscous glassy extrusions of rhyolitic lava which were auto-brecciated and later devitrified (Fig. 24).

Just prior to, and possibly also syn-depositional with hydrothermal alteration, was the deposition of a rhyolitic to dacitic tuff (Gray Siliceous Tuff Unit). This unit probably represents the position of the sea water/rock interface at the time of mineralization, as it is the uppermost unit to have been affected by hydrothermal alteration.

After sulfide mineralization, volcanic activity continued but emanated from a source more distant from the mine area. Voluminous andesitic to dacitic tuffs and very minor flows overlie the deposit (Upper Green Tuff Unit). These have been completely unaffected by hydrothermal alteration. Eventually, volcanic activity became very
distant, and regional subsidence took place. This resulted in the deposition of the marine volcaniclastic sediments of the Nooksack Group.

Model for Sulfide Deposition

As previously mentioned, the Great Excelsior deposit is similar in many ways to Kuroko-type deposits. Knowing this, a review of the factors governing the deposition of Kuroko ores may be helpful.

Base and precious metal zoning of Kuroko ores have been described by numerous writers, including excellent summaries by Large (1977) and Franklin and others (1981). Typical zoning patterns include Cu-rich bases to Zn±Pb-rich tops with Ag generally occurring with Zn and Pb. The lowermost zone consists of a Cu-rich siliceous stringer (stockwork) ore which was deposited below the sea water/rock interface. Above this is a zone known as the lower massive ore (Large, 1977), which is composed dominantly of chalcopyrite-pyrite. This ore is thought to have been deposited just below the sea water/rock interface and/or around the orifice of the hydrothermal vent. The uppermost zone is generally composed of pyrite-sphalerite±galena±Ag which were deposited around the flanks of the hydrothermal vent directly onto the sea floor. Further from the hydrothermal vent, cooling solutions moving along the sea floor reached the silica saturation point and deposited silica and pyrite or hematite to form siliceous (cherty) pyritic or hematitic tuffs.

Kajiwara (1973a) and Large (1977) proposed thermochemical models for the transport and deposition of Kuroko ores. These models call for the transport of the metals to be related primarily to chloride com-
plexes, and deposition to be in response to physicochemical changes related to mixing with sea water. In this way, Large (1977) explains metal zoning patterns by the use of temperature-log fO₂ diagrams depicting sulfide deposition along certain mixing paths.

The role of boiling, however, may have profound effects on sulfide deposition. The deposition of massive stratiform ore on the sea floor will occur only if the system is at a sufficient sea water depth so as to prevent the hydrothermal solution from boiling as it ascends through the volcanic pile (Ridge, 1974). Ridge (1974) points out that if boiling occurs the solution will likely deposit most of its metal content before it reaches the sea water/rock interface resulting in a subsurface replacement and/or open-space filling deposit.

Finlow-Bates and Large (1978) also emphasize the importance of sea water depth in massive sulfide deposition. They point out that the depth of sea water will, in effect, determine whether a particular system will deposit metal in the subsurface or only on the sea floor. Since Cu is deposited at higher temperatures than either Zn or Pb in this type of system, the water depth can also determine where Cu minerals will be deposited. At maximum depths, boiling will not occur, thereby allowing Cu minerals to be deposited only in the stratiform ore (no Cu-rich stringer ore). At medium depths an extensive Cu-rich stringer zone will be developed, and at shallow depths Zn, Pb, and Cu will likely be present in the stringer zone (Franklin et al., 1981).

In the case of the Great Excelsior deposit, boiling is known to
have occurred and may have been fairly extensive as suggested by the degree of carbonate replacement throughout the mineralized zones. Since there is no known massive stratiform mineralization it is possible that all of the metals were deposited below the sea floor as in case three of the preceeding paragraph. What may have happened in this case is that the hydrothermal solution(s), upon ascending through the volcanic pile, encountered zones of high permeability and began to boil. This resulted in the precipitation of metals as subsurface replacement and open-space fillings. Upon reaching the sea water/rock interface the solution was devoid of base and precious metals leaving only silica and Fe to be deposited. The apparent enrichment of Ag to Pb and Zn by a factor greater than 1.0 is, at the moment, seemingly enigmatic.

An alternative explanation for the absence of a massive stratiform ore could be that the hydrothermal solution(s), being less dense than sea water, formed a plume upon emanating from the vent(s) and this plume was dispersed by current action. According to Solomon and Walshe (1979) a hydrothermal solution of this type (300°C and 0.6 M NaCl) would be 25 percent lighter than sea water as it emerged onto the sea floor.

Either of these mechanisms is adequate for explaining the absence of a massive stratiform ore but it fails to explain the low base metal/Ag ratios. As previously mentioned, in Kuroko deposits Ag is generally associated with Zn and Pb, occurring in the uppermost portions of the massive ore. Typical Pb/Ag and Zn/Ag ratios for Kuroko-type deposits are 66.7 and 250, respectively (Lambert and Sato, 1974). Comparing
these values with those present at Excelsior (0.55 and 0.82, respectively) one can immediately see a radical difference. This difference of 2 to 3 orders of magnitude is not easily explained.

The occurrence of Ag and Au in the absence of commercial base metal concentrations is not uncommon in some types of deposits. Weissberg (1969) states that base metals are relatively rare in epithermal deposits associated with high geothermal gradients. He contends that the absence of base metals in the Au, Ag zones of the active geothermal systems of the Taupo Volcanic Zone, New Zealand is related to different precipitation mechanisms. At Broadlands and Waiotapu, Cu, Pb, and Zn occur at a much greater depth than do Au and Ag. Weissberg (1969) argues that all of the metals were transported primarily by sulfide complexes and that Cu, Pb, and Zn sulfides were deposited at depth in response to incipient boiling of the hydrothermal solution. He states that Au and Ag did not precipitate with the base metals because they form much more stable sulfide complexes. He goes on to say that this incipient boiling actually enhanced the solubility of Au and Ag by increasing the pH, which in turn caused an increase in the activity of HS\(^{-}\) and S\(^{2-}\).

A strong zonation between base and precious metals also exists in the Neogene Vein deposits of Japan. These deposits occur in Tertiary volcanic and sedimentary rocks which were deposited in a submarine environment (Hattori, 1975). Here, a zonation similar to that of Broadlands and Waiotapu exists between Pb, Zn and Au, Ag. Hattori (1975) suggests that the metals were transported by sulfide complexes
and that Pb and Zn were deposited at depth in a reducing environment in response to a shift in pH. She contends that under these conditions Pb, Zn-sulfur complexes become unstable while the "solvent power" for Au and Ag remained sufficiently high. She argues that Au and Ag remained in solution until a more oxidizing environment was encountered at higher structural levels. This caused the oxidation of the reduced sulfur species bringing about the precipitation of Au and Ag.

It is difficult to determine if the same mechanisms governing the transport and deposition of base and precious metals at Broadlands, Waiotapu, and the Japanese Neogene Vein deposits were also in effect at Excelsior. Solution transport of the metals could have been by either chloride or sulfide complexes, or both. The base metals appear to be more soluble as chloride complexes but sulfide complexes are clearly adequate given the low concentrations in which the base metals are found. Precipitation appears to have taken place in response to boiling and reaction with the pyrite-bearing host rocks. Whether or not commercial concentrations of Cu, Pb, and Zn ever existed at Excelsior is problematic. It is possible that these metals could have been concentrated in a more central portion of the system at higher temperatures. Stratigraphic evidence indicates that the volcanic center was located somewhere to the northeast of the Big Stope and has since been removed by erosion. Assuming that the central portion of the hydrothermal system coincides with the volcanic center (Fig. 39) then the base metals, if present, could have been eroded away.

An alternative explanation could be either the hydrothermal
Figure 39. Schematic diagram and cross section representing the volcanic environment and mineralization at the Great Excelsior Mine (upper diagram after Horikoshi, 1969). Arrows in the upper diagram indicate the presumed direction of fluid movement. See Plate 4 for location of cross section B-B'.
solution was ineffective in leaching the base metals from the source rocks, or the base metals were not present in sufficient amounts within the source rocks. This would render the hydrothermal solution greatly undersaturated with respect to Cu, Pb, and Zn resulting in insufficient concentrations to form an economic deposit.
SUMMARY AND CONCLUSIONS

The Great Excelsior Ag-Au deposit shares several features common to typical Kuroko-type deposits. The mineralization is associated with rhyolitic breccias and pyroclastics, it was deposited in a submarine environment, fluid temperature and composition are similar to those of Kuroko fluids, and it was deposited in an island arc tectonic setting. The major differences between the Great Excelsior deposit and Kuroko-type deposits is the absence of massive stratiform mineralization, sulfate mineralization, and commercial base metal concentrations.

The absence of massive stratiform mineralization can be explained by extensive boiling of the hydrothermal solution causing subsurface precipitation of metals. This caused the solution to become devoid of base and precious metals by the time it reached the sea floor. Alternatively, since the hydrothermal solution must have been lighter than sea water, a plume could have developed several hundred meters above the sea floor. This plume could then have been dispersed by current action.

The absence of commercial base metal concentrations remains problematic. At least three explanations can be put forth to explain this anomaly: 1) the base metals were deposited in the central portion of the system which coincides with the volcanic center, and has since been removed by erosion, 2) the hydrothermal solution was vastly undersaturated with respect to Cu, Pb, and Zn due to either an inability to leach these metals from source rocks, or an inadequate supply of these metals in the source rocks, or 3) the base metals were flushed through
the system and were dispersed. There is no concrete evidence to support or deny any of these explanations. All are possible, but the only thing that is certain is that part of the deposit has been removed by erosion, and with it valuable clues which could help to answer the uncertainties relating to the genesis of the deposit.
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## APPENDIX I

### Selected Equilibrium Constants

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Log $K_{300^0}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2S + 2O_2(g) = SO_4^{2-} + 2H^+$</td>
<td>48.55</td>
<td>a</td>
</tr>
<tr>
<td>$H_2S(aq) + 2O_2(g) = HSO_4^- + H^+$</td>
<td>55.61</td>
<td>a</td>
</tr>
<tr>
<td>$H_2S(aq) = H^+ + HS^-$</td>
<td>-8.12</td>
<td>a</td>
</tr>
<tr>
<td>$H^+ + HS^- = HSO_4^-$</td>
<td>-7.06</td>
<td>a</td>
</tr>
<tr>
<td>$SO_4^{2-} = S^{2-} + 2O_2(g)$</td>
<td>-64.26</td>
<td>a</td>
</tr>
<tr>
<td>$3NaAlSi_3O_8 + 2Cl^- + K^+ = KAl_3Si_3O_10(OH)_2 + 6SiO_2 + 3Na^+$</td>
<td>9.57</td>
<td>b</td>
</tr>
<tr>
<td>$3KAlSi_3O_8 + 2H^+ = KAl_3Si_3O_10(OH)_2 + 6SiO_2 + 2K^+$</td>
<td>8.4</td>
<td>c</td>
</tr>
<tr>
<td>$2KAlSi_3O_10(OH)_2 + 2H^+ + 3H_2O = 3Al_2Si_2O_7(OH)_4 + 2K^+$</td>
<td>5.44</td>
<td>c</td>
</tr>
<tr>
<td>$5CuFeS_2 + S_2(g) = Cu_5FeS_4 + 4FeS_2$</td>
<td>6.40</td>
<td>c</td>
</tr>
<tr>
<td>$FeS + kS_2(g) = FeS_2$</td>
<td>5.81</td>
<td>c</td>
</tr>
<tr>
<td>$2FeS_2 + 3/2O_2(g) = Fe_2O_3 + 2S_2(g)$</td>
<td>28.19</td>
<td>c</td>
</tr>
<tr>
<td>$3FeS_2 + 2O_2(g) = Fe_3O_4 + 3S_2(g)$</td>
<td>33.93</td>
<td>c</td>
</tr>
<tr>
<td>$3FeS + H_2O_2(g) = Fe_3O_4 + 3/2S_2(g)$</td>
<td>51.39</td>
<td>c</td>
</tr>
<tr>
<td>$2Fe_3O_4 + 2O_2 = 3Fe_2O_3$</td>
<td>14.35</td>
<td>c</td>
</tr>
<tr>
<td>$PbS + SO_4^{2-} = PbSO_4^2 + S^2-$</td>
<td>-7.87</td>
<td>a</td>
</tr>
<tr>
<td>$PbS = Pb^{++} + S^{2-}$</td>
<td>-18.31</td>
<td>a</td>
</tr>
<tr>
<td>$Pb^{++} + 2Cl^- = PbCl_2$</td>
<td>3.9</td>
<td>a</td>
</tr>
<tr>
<td>$PbS + 2H_2S = Pb(HS)_2(SH_2S)(aq)$</td>
<td>-4.38</td>
<td>d</td>
</tr>
</tbody>
</table>
### Appendix I (cont.)

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Log $K_{300^\circ}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BaSO}_4 = \text{Ba}^{2+} + \text{SO}_4^{2-}$</td>
<td>-11.49</td>
<td>a</td>
</tr>
<tr>
<td>$\text{CaSO}_4 = \text{Ca}^{2+} + \text{SO}_4^{2-}$</td>
<td>-9.05</td>
<td>a</td>
</tr>
<tr>
<td>$\text{CaCO}_3 = \text{Ca}^{2+} + \text{CO}_3$</td>
<td>-14.10</td>
<td>a</td>
</tr>
<tr>
<td>$\text{HCO}_3^- + \text{H}^+ = \text{H}_2\text{CO}_3(aq)$</td>
<td>8.86</td>
<td>a</td>
</tr>
<tr>
<td>$\text{CO}_3^{2-} + \text{H}^+ = \text{HCO}_3^-$</td>
<td>11.83</td>
<td>a</td>
</tr>
<tr>
<td>$\text{H}_2\text{CO}_3 + \text{H}_2\text{O}(1) = \text{CH}_4(aq) + \text{2O}_2(g)$</td>
<td>-69.74</td>
<td>a</td>
</tr>
<tr>
<td>$\text{C}(\text{graphite}) + \text{O}_2(g) = \text{CO}_2(g)$</td>
<td>35.96</td>
<td>c</td>
</tr>
<tr>
<td>$\text{C}(\text{graphite}) + \text{O}_2(g) + \text{H}_2\text{O}(1) = \text{H}_2\text{CO}_3$</td>
<td>34.13</td>
<td>c</td>
</tr>
<tr>
<td>$\text{CuFeS}_2 + \text{H}^+ + \frac{3}{2}\text{O}_2 + \text{Cl}^- = \text{FeS}_2 + \frac{3}{2}\text{H}_2\text{O}(1) + \text{CuCl}$</td>
<td>9.8</td>
<td>c</td>
</tr>
<tr>
<td>$\text{Cu}_5\text{FeS}_4 + 3\text{FeS}_2 + 3/2\text{H}_2\text{O}(1) = 4\text{CuFeS}_2 + 3/4\text{O}_2(g) + \text{H}^+$ + $\text{Cu(HS)}_2^-$</td>
<td>-35.00</td>
<td>c</td>
</tr>
<tr>
<td>$3/2\text{Cu}_5\text{FeS}_4 + 5\text{FeS}_2 + 5/2\text{H}_2\text{O}(1) = 13/2\text{CuFeS}_2 + 5/4\text{O}_2(g) + \text{H}^+$ + $\text{Cu(HS)}_2^-(\text{H}_2\text{S})_2(aq)$</td>
<td>-52.00</td>
<td>c</td>
</tr>
<tr>
<td>$\text{AuO} + \text{H}_2\text{S} + \text{HS}^- = \text{Au(HS)}_2^- + \sqrt{2}\text{H}_2(g)$</td>
<td>1.14*</td>
<td>e</td>
</tr>
<tr>
<td>$\text{H}_2(g) + \text{H}_2\text{O}(g) = \text{H}_2\text{O}(1)$</td>
<td>19.80</td>
<td>f</td>
</tr>
<tr>
<td>$\text{AuO} + 2\text{H}_2\text{S}(aq) + \frac{3}{2}\text{O}_2(g) = \text{Au(HS)}_2^- + \frac{3}{2}\text{H}_2\text{O}(1) + \text{H}^+$</td>
<td>1.97</td>
<td>e</td>
</tr>
<tr>
<td>$\text{AuCl}_2 = \text{Au}^+ + 2\text{Cl}^-$</td>
<td>-6.20</td>
<td>a</td>
</tr>
<tr>
<td>$\frac{3}{2}\text{H}_2\text{O}(1) + \text{Au} = \text{AuO} + \frac{3}{2}\text{O}_2(g) + \text{H}^+$</td>
<td>2.97</td>
<td>a</td>
</tr>
<tr>
<td>$\text{Ag}_2\text{S} + 2\text{H}^+ + 4\text{Cl}^- = 2\text{AgCl}_2^- + \text{H}_2\text{S}(aq)$</td>
<td>0.68</td>
<td>g</td>
</tr>
</tbody>
</table>
### Reactions Log

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Log $K_{300}^0$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Zn}^{2+}+2\text{Cl}^- = \text{ZnCl}_2(aq)$</td>
<td>6.90</td>
<td>a</td>
</tr>
<tr>
<td>$\text{ZnS} = \text{Zn}^{2+}+\text{S}^{2-}$</td>
<td>-18.70</td>
<td>a</td>
</tr>
<tr>
<td>$\text{ZnS}+\text{H}_2\text{S}_2(aq)+\text{HS}^- = \text{Zn(HS)}_3^-$</td>
<td>-2.90**</td>
<td>h</td>
</tr>
<tr>
<td>$4\text{Ag}^0+\text{S}_2(g) = 2\text{Ag}_2\text{S}$</td>
<td>12.19</td>
<td>i</td>
</tr>
</tbody>
</table>

* $K$ value was extrapolated from Seward's (1973) data using a "best fit" curve by least-squares linear regression.

** Log $K$ value is for 200-100°C but Barnes (1979) states that this value is nearly independent of temperature.

- b. Helgeson *et al* (1978)
- c. Crerar and Barnes (1976)
- d. Giordano and Barnes (1979)
- e. Seward (1973)
- f. Casadevall and Ohmoto (1977)
- g. Seward (1976)
- h. Barnes (1979)
- i. Barton (1980)
Mr. Russ Franklin  
U. S. Borax Exploration  
E. 5603 Third Avenue  
Spokane, WA 99212

Nov. 5, 1984

Dear Russ,

Sorry for the long time it took to finally get the dates on the Wells Creek volcanics; but we finally got our broken crushing equipment back on line, putting your sample to the head of the list. The analyses came out very nicely. The common Pb levels are very low and the U contents of the zircons are also low, which usually makes for a high degree of resistance to Pb loss during later, minor thermal events. The two fractions yielded ages very close to concordance (most people would in fact be happy to call them concordant). I feel that the small difference in 206Pb/238 age between the two fractions, and the slightly older Pb/Pb ages may indicate the loss of a very small amount of Pb, however. Thus my interpretation of the actual emplacement age is 175-180 Ma, or Middle Jurassic (Bajocian?) according to the latest DNAG 1983 time scale. Hope this helps in your interpretation of the rocks.

<table>
<thead>
<tr>
<th>fraction</th>
<th>206x</th>
<th>238</th>
<th>208/206</th>
<th>207/206</th>
<th>204/206</th>
<th>6*/8</th>
<th>7*/5</th>
<th>7*/6*</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse</td>
<td>5.652</td>
<td>237.8</td>
<td>0.11663</td>
<td>0.05067</td>
<td>0.000058</td>
<td>174.5</td>
<td>175.3</td>
<td>187±5</td>
</tr>
<tr>
<td>fine</td>
<td>5.328</td>
<td>225.9</td>
<td>0.11973</td>
<td>0.05058</td>
<td>0.000060</td>
<td>173.2</td>
<td>173.7</td>
<td>181±5</td>
</tr>
</tbody>
</table>

notes: 1) * designates radiogenic Pb, corrected for common Pb using 6:7:4:19.0:15.6:1.00
2) Pb isotopic compositions normalized to "absolute" values by correcting for 0.125% per mass unit mass fractionation, based on replicate analyses of NBS Pb standards
3) 6*/8 = 206*Pb/238U age, 7*/5 = 207*Pb/235U age, 7*/6* = 207*Pb/206*Pb age. 6*/8 and 7*/5 ages are precise to 0.2% and 0.3%, respectively. Uncertainties on the 7*/6* ages are calculated individually, and are based on the combined errors in mass spectrometry (chiefly the 204/206 ratio), and in correcting for common Pb.

Best Regards,

James M. Mattinson
APPENDIX III
Activity and Discharge Calculations

Na-Cl-K activities:

The solution contains 3.5 wt.% NaCl equivalent which is equal to 0.6M. The relationship between \( M_{\text{NaCl}} \) and \( a_{\text{Na}^+} \) is by the equation; \( a_{\text{Na}^+} = M_{\text{NaCl}} \times y_{\text{NaCl}} \) (Daniels and Alberty, 1975), where \( M_{\text{NaCl}} \) is 0.6M and \( y_{\text{NaCl}} \) is the stoichiometric mean activity coefficient for NaCl at 300° C for a 1M NaCl solution. From Helgeson (1969), \( y_{\text{NaCl}} = 0.25 \).

--- \( a_{\text{Cl}^-} \) will be equal to \( a_{\text{Na}^+} \) by the relation \( \text{NaCl} = \text{Na}^+ + \text{Cl}^- \) (Helgeson, 1969), for each mole of \( \text{Na}^+ \) released, an equal number of moles of \( \text{Cl}^- \) must also be released.

--- Albite---Adularia in equilibrium

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

\( K_{300^\circ \text{C}} = 6.17 \) (Helgeson, 1969)

\[
\frac{a_{\text{Na}^+}}{a_{\text{K}^+}} = \frac{0.15}{6.17} = 0.02M = 10^{-1.70M}
\]

Discharge Rates:

Assuming a projected reserve of 4 million tons with an average Zn value of 294 ppm there will be \( 1.07 \times 10^9 \) grams of Zn in the entire deposit. The average discharge rate for Wairakei has been calculated by Weissberg (1969) to be \( 1.6 \times 10^6 \) kg(H₂O)/hr, which is equal to \( 1.4 \times 10^{10} \) kg(H₂O)/yr. If the solution were saturated with respect to Zn (1 ppm), there will be \( 10^{-3} \) g(Zn)/kg.
Assuming a saturated solution and a discharge rate comparable to that of Wairakei, 1.4 $\times$ 10$^7$ g(Zn) is capable of being deposited each year. To deposit the total amount of Zn which is present at Excelsior (1.07 $\times$ 10$^9$ g), it would require 76 years (1.07 $\times$ 10$^9$ g(Zn)/1.4 $\times$ 10$^7$ g(Zn)/yr) and 1.07 $\times$ 10$^{12}$ kg(H$_2$O).