THE GEOLOGY AND ALTERATION OF THE SIATE CREEK BRECCIA PIPE, WHATCOM COUNTY, WASHINGTON

by

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STATEMENT BY AUTHOR

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APPROVAL BY THESIS DIRECTOR

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ABSTRACT

The Slate Creek breccia is a 200- by 260-meter oval, nearly vertical pipe formed by late-Miocene igneous activity. Genetic association with an S-type granite, the intrusive quartz-eye porphyry, is evident from the presence of quartz-eye porphyry as matrix, clasts, and dikes in the breccia. The breccia has both intrusion and explosion features. Venting is possible, but erosion prevents verification of the pipe's upper features.

Crenulated quartz, quartz-eye rhyolite, barren quartz veins, quartz-magnetite veins, and quartz-molybdenite veins within 300 meters of the breccia pipe are similar to rocks and textures found near the Henderson orebody, a Climax-type molybdenum deposit. Within the breccia, base-metal sulfide mineralization, phyllic alteration, and granitic intrusive associations all bear resemblances to the Redwell Basin prospect, also a Climax-type deposit. Fluid inclusion data also support comparison of the Slate Creek breccia and host rocks with Climax-type deposits.
CHAPTER 1

INTRODUCTION

The Slate Creek breccia pipe is mid-Tertiary molybdenum prospect located in Whatcom County, Washington. The prospect occurs in the Slate Creek mining district in the North Cascade range. Sporadically active since the late 1870's, the Slate Creek district is known for its placer and lode gold production, but the district has produced only minor copper and no molybdenum. In the late nineteenth century when it was known as the Great Northern prospect, miners drove three adits into the Slate Creek breccia to investigate its potential, but low gold, silver, and copper values made the breccia an unfavorable target. More recently, investigation of the breccia pipe as a molybdenum target by the Duval Corporation has progressed to the detailed evaluation stage with ongoing mapping, sampling, and drilling. The presence in drill core from the breccia pipe of rounded fragments of quartz-molybdenite veins of the Climax-type promotes continued interest in the breccia and surrounding rocks. The source of these Climax-type mineralized fragments is unknown but is presumably subjacent to the breccia pipe that samples it. This in-depth appraisal of information concerning the breccia pipe is essential to the determination of its future.
Purpose

This thesis provides an accurate and modern description of the Slate Creek breccia pipe. The account includes determination of igneous rock association and classification of deposit type. Comparisons of the Slate Creek occurrence with other breccia pipes and evaluation of possible genetic models of formation indicate that the Slate Creek prospect is similar to Climax-type molybdenum deposits. A comparison of fluid inclusion data from quartz-molybdenite veins and quartz-molybdenite vein breccia fragments provides additional information which supports the comparison of the Slate Creek breccia pipe with Climax-type deposits.

Method of Treatment

Mapping of the breccia pipe was conducted during the 1981 summer field season, extending from June through August. Although weathered, the pipe is well exposed in the steep walls of Slate Creek Canyon. A brunton and topofil survey provided control for the 1:1200 scale mapping, rock chip sampling, and a magnetometer survey. Subsurface information is available from drill holes and adit maps. Approximately 1220 meters of core from two diamond drill holes outline the subsurface character of the pipe. Three short adits, totaling 120 meters in length, aid in constructing the subsurface geology.

Laboratory investigations add to surface and subsurface knowledge of the breccia. Thin sections were used to ascertain the breccia matrix composition and the mineralogy of vein and alteration
assemblages. Doubly-polished slabs provide fluid inclusion data for quartz-molybdenite veins. Both thin sections and doubly polished slabs are on file with the Duval Corporation in Tucson, Arizona. Chemical analyses of grab samples combined with assay information from the two drill holes provide data for element zonation maps and cross-sections of copper, molybdenum, lead, zinc, tungsten, and fluorine occurrences. Age determinations using the potassium-argon isotope dating method also aid in construction of the total description of the Slate Creek breccia pipe.

**Location and Accessibility**

The Slate Creek breccia pipe is located in the remote southeast corner of Whatcom County, Washington (Figure 1), shown on the Slate Peak, Washington, 7-1/2° Quadrangle. Only one narrow gravel road serves the rugged area. U. S. Highway 20 and the outpost of Mazama are 40 kilometers to the east over Harts Pass via the Chancellor Road. The area mapped occupies the SW 1/4 of section 3, T. 37 N., R. 17 E. More precisely, the breccia pipe crops out on the south side of Slate Creek Canyon one kilometer upstream from the junction of Slate Creek and the South Fork of Slate Creek. Weather in the region is unpredictable and both U. S. Highway 20 and the Chancellor Road are closed during the winter months. U. S. Highway 20 opens in May. The Chancellor Road, on the other hand, does not open until June or early July even with bulldozer clearing of the snow-drifts. Even during the summer, rain and snow storms in the higher elevations can make access difficult.
Figure 1. Location map of the Slate Creek prospect.
Terrain in the Slate Creek area is rugged. The elevation of Slate Creek in the prospect area is approximately 1200 meters, with the glaciated Slate Creek Canyon providing approximately 600 meters of relief. Where mapping was conducted, the canyon walls slope at 30-45 degrees with a few cliffs; the slopes are thickly vegetated at most elevations except over the breccia pipe, most of which is barren of vegetation.

**Previous Work**

Outside of information collected by Duval Corporation, very little previous work has been carried out on the breccia pipe. Around the turn of the century, miners drove five adits into and adjacent to the breccia, but there is no record of production. Two more-recent reports are entitled *Mines and Mineral Deposits of Whatcom County, Washington* by Moen (1969) and *Reconnaissance Economic Geology and Probable Future Mineral Activity Target Areas on the Okanogan National Forest, Washington* by Grant (1982).

The regional geology has been discussed by J. D. Barksdale in a number of papers (1941, 1947, 1948, 1956, 1958, 1960, 1975) dealing with glaciation, sedimentation, and structural deformation, as well as general geology. Dissertations and theses from Washington State University also aid in understanding the area. M. E. Tennyson (1974) studied Jurassic and Cretaceous sediments in the Harts Pass area. The Black Peak batholith, located south of the Slate Creek prospect, was described by J. B. Adams (1961). Other work from Washington
universities includes R. J. Stull's study of the southeast part of the Golden Horn batholith (1969) and K. B. Riedell's (1979) and D. M. Orazulike's (1979) work on the Fawn Peak stock, both of which occur in the area. The United States Geological Survey has also been active in evaluating land for National Park or Wilderness Area designation. Geology of both the Pasayten Wilderness Area (Staatz et al., 1971) and the northern part of the North Cascades National Park (Staatz et al., 1972) has been reviewed. On a broader scale, P. Misch (1952, 1966) studied and reported on the entire Cascade region. Tennyson and Cole (1978) interpret the significance of Methow-Pasayten Belt rocks, and other papers address the structural and tectonic development of the entire region (Davis et al., 1978; Hamilton, 1978).

The present study draws on past work for regional geology, structure, and age determinations. However, previous investigations shed almost no light on the details of the Slate Creek breccia pipe which will be developed herein.
CHAPTER 2

REGIONAL GEOLOGY

Geologic knowledge of the region surrounding the Slate Creek prospect is important to the description and interpretation of the Slate Creek breccia pipe. The prospect is located within the Methow-Pasayten Belt, a major northwest-trending graben-like feature of north-central Washington and south-central British Columbia. The nature of the graben is contested, but it is a fault-bounded, linear, depositional basin. The graben has been active from the Jurassic to the Eocene (Barksdale, 1975). A 20,000-meter-thick sequence of Mesozoic and Cenozoic rocks consisting mainly of sediments with locally dominant volcanics fills the graben. In the Slate Creek region, the graben is flanked by metamorphic highlands to the northeast and an intrusive body and metamorphic highlands to the southwest. Intrusions of Cretaceous through Eocene age occur within the Methow-Pasayten Belt. Figure 2 is a bedrock geology map of the area surrounding the Slate Creek prospect.

Surficial Rocks

Newby Group

The Newby Group constitutes the base of the stratigraphic column. In general, the group consists of black shales and interbedded volcanic lithic sandstones with andesitic breccias and
Figure 2. Generalized regional geology, after Barksdale (1975) and Staatz and others (1971).

EXPLANATION

Qal Alluvium
Tmp Monument Peak Stock
Tgh Golden Horn Batholith
Klp Lost Peak Stock
Kfp Fawn Peak Complex
Kpd Pasayten Dike
Kbp Black Peak Batholith
Kmp Midnight Peak Formation
Kvm with Ventura Member
Kw Winthrop Sandstone
Kvr Virginia Ridge Formation
Khp Harts Pass Formation
Kpc Panther Creek Formation
Kgc Goat Creek Formation
Kus Undifferentiated Sediments
K-J Newby Group
n
Cretaceous

Kip Okanogan Batholithic Complex
Kfp Chelan Batholithic Complex

Tertiary

Contacts dashed where inferred

Major Fault
Major Fault Thrust

Kilometers
0 5 10
0 1 5
Miles

Triassic-Jurassic
Figure 2. Generalized regional geology of the Slate Creek area, after Barksdale (1975) and Staatz and others (1971).
flows, but it is divisible into the Twisp and the Buck Mountain Formations. These two formations are of early Jurassic and early Cretaceous age respectively (Barksdale, 1975). Sedimentary rocks of the Newby Group were deposited in a submarine fan environment with a source terrane to the east (Tennyson and Cole, 1978).

The Twisp Formation is dominated by argillic shales in 2-to-10-centimeter thick beds and is generally dark gray to black in color. Locally interbedded in the shales are volcanic siltstones and lithic sandstones in thicknesses of a few centimeters to two meters. The Twisp Formation is intricately folded and faulted. Outcrop-scale deformation and poor exposure make it impossible to estimate the thickness of the formation (Barksdale, 1975), but it is at least 1200 meters thick.

The Buck Mountain Formation overlies the Twisp Formation along an erosional unconformity. Characterized by a more volcanic nature, the upper formation of the Newby Group consists of interlayered flows and volcanoclastic rocks of andesitic composition grading upward to lithic sandstones, siltstones, and black shales. The black shales commonly contain lenses of conglomerate. Rocks of the Newby Group crop out along the margins of the Methow-Pasayten Graben and strike to the northwest, generally dipping steeply to the east or west (Barksdale, 1975). The Buck Mountain Formation is approximately 4,400 meters thick.
Harts Pass Group

The Harts Pass Group was deposited in early to mid-Cretaceous time. Similar to the Newby Group, the Harts Pass Group is marine in nature, but was deposited in a more proximally volcanic environment than the older Newby Group. Rocks of the Harts Pass Group consist of arkose, argillite, and minor granite-bearing conglomerates (Tennyson and Cole, 1978). The three formations within the group are the Goat Creek, the Panther Creek, and the Harts Pass.

The early Cretaceous Goat Creek Formation unconformably overlies the Newby Group. No fossils have been found to give a more precise age for the 1,500-meter-thick well-bedded arkose and argillite formation. The rocks are immature with large amounts of plagioclase and accessory minerals, including biotite. Outcrop of the Goat Creek Formation is restricted to the northeast corner of the regional map area. In that area, the beds strike northwest and dip from vertical to steeply overturned to the northeast (Barksdale, 1975).

The early Cretaceous Panther Creek Formation conformably overlies the Goat Creek Formation. Unlike previously described formations, the Panther Creek Formation contains distinctive interbeds of granitic clast conglomerates within the stratigraphically dominant black shales. The conglomerates are unusual in that they tend to be poorly sorted, yet all clasts, pebble to boulder in size, are well rounded. Also, little or no shale is incorporated in the conglomerates. Away from the type section, arkose beds become increasingly important as the conglomerate units diminish in number.
and thickness (Barksdale, 1975). The Panther Creek Formation crops out in the center and in the northeastern parts of the regional map area, and is about 1,500 meters thick with strikes to the northwest at variable dips.

The Harts Pass Formation is of particular interest because it is the host of the Slate Creek breccia pipe. This mid-Cretaceous formation conformably overlies the Panther Creek Formation, and consists of massive marine arkoses with interbeds of argillite. The formation can be divided into three members on the basis of the amount of argillite present. The lower and upper members contain only minor argillite as interbeds within massive arkose, and the middle member has nearly equal arkose and argillite. The entire formation is well indurated with two generations of cement; the first is dominated by chlorite and the second is of late silica and carbonate which fill remaining pore space. Harts Pass rocks crop out to the northeast as pendants to the Monument Peak stock and in the central area adjacent to the Golden Horn batholith. In the type section, the formation is 2,400 meters thick. As with the previous formations, bedding in the Harts Pass Formation strikes to the northwest and dips to the northeast or southwest (Barksdale, 1975).

Virginia Ridge Formation

After a gap in deposition, the mid-Cretaceous Virginia Ridge Formation was deposited unconformably over the older formations. Black shales dominate the formation, but chert-rich sandstones and
pebble conglomerates occur abundantly. Granitic clasts do not occur in the conglomerates. The Virginia Ridge Formation crops out through the center of the map area, outlining the Goat Peak syncline and ranging from 330 to 3540 meters in thickness (Barksdale, 1975). Unlike the formations described earlier, the Virginia Ridge Formation was deposited from the west and thins to the east (Tennyson and Cole, 1978).

Winthrop Sandstone

The late-Cretaceous Winthrop Sandstone intertongues with the Virginia Ridge Formation along a gradational contact. The fluvial Winthrop Sandstone is generally light colored and poorly bedded and contains plant fragments (Tennyson and Cole, 1978). It is composed of arkosic sandstones and shales; both have poor cementation and are nonresistant in outcrop. In the type section the Winthrop Sandstone is 4,100 meters thick, but it thins and disappears to the west, with outcrop controlled by the Goat Peak syncline (Barksdale, 1975).

Midnight Peak Formation

The Midnight Peak Formation is divisible into the lower Ventura red bed, sandstone, and shale member and the volcanic member. This formation was derived from the east and ranges in age from late Cretaceous to early Tertiary (Tennyson and Cole, 1978). Except for recent glacial and alluvial deposits, the Midnight Peak Formation contains the youngest rocks in the regional map area.
The lower Ventura Member conformably overlies the Winthrop Sandstone, and is easily recognized by its red to purplish outcrop colors and good bedding. Sandstones dominate this member, but it also contains beds of siltstone and lenses of conglomerate. Total thickness of the Ventura Member is 620 meters (Barksdale, 1975).

The upper volcanic member consists of volcanic breccias, flows, and tuffs ranging from dacite to pyroxene andesite in composition. Dark greenish-gray colors characterize the upper member throughout its 3,170 meter thickness (Barksdale, 1975). Both members of the Midnight Peak Formation crop out through the core of the Goat Peak syncline and in fault blocks in the southeast corner of the map area.

**Intrusive Rocks**

Pasayten Dike

The Pasayten stock-dike is a late Cretaceous intrusion of dominantly quartz dioritic composition, locally ranging to a grandioritic composition. Its isotopic age of 86 million years is given in Table 1, a summary of isotopic and geologic age data for intrusive units. This thick, tabular dike contains plagioclase of intermediate composition, quartz, potassium feldspar, biotite, and hornblende, in decreasing order of abundance. Accessory minerals include titanite, apatite, and magnetite, with plagioclase crystals locally rimmed by albitic myrmekite (Staatz, et al., 1971). For ease of comparison, the igneous classifications and the ages of the
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<td>Allanite</td>
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Table 1. - continued

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<th>Mineral Dated</th>
<th>Composition</th>
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<td>Biotite</td>
<td>Granite</td>
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<tr>
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<td>Potassium Feldspar</td>
<td>Quartz-Rich Granitoid</td>
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<tr>
<td>Breccia Pipe Alteration</td>
<td>25 ±0.7my</td>
<td>Sericite</td>
<td>See text Chapter 3</td>
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**Geologic Age Evidence**

<table>
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<tr>
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<th>Cut by Monument Peak Stock</th>
<th>Quartz Monzonite</th>
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<td>Probably associated with Golden Horn Batholith and Monument Peak Stock</td>
<td>Variable Granitic</td>
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<tr>
<td>Numerous Diorite Porphyry Dikes</td>
<td>Cut by Breccia Pipe Probable mid-late Cretaceous Age</td>
<td>Diorite to Quartz Diorite</td>
<td>3</td>
</tr>
</tbody>
</table>

**Sources for age dates:**

1. P. Misch, 1964
2. R. Tabor et al., 1968
4. K. Riedell, 1978
5. J. Engels, 1976
6. C. Naeser, 1970
7. Laboratory of Geotectonics, University of Arizona
Pasayten dike and other known intrusive rocks in the region are listed in Table 1, pages 14 and 15. The Pasayten dike is composed of a medium-grained, gray rock with hypidiomorphic granular texture. Mafic minerals within the dike are partially altered to chlorite, but otherwise the dike is unaltered. Rocks around the intrusive have been metamorphosed to the hornblende hornfels facies (Barksdale, 1975). The dike, which is elongate to the northwest, is resistant to weathering and is well exposed in the north central portion of the regional map area (Figure 2, page 8).

Black Peak Batholith

The problematic 88 million-year old Black Peak batholith is located in the southwest portion of the region. This quartz dioritic batholith intrudes Newby Group volcanics and Twisp Valley Schist on the north and east boundaries and is, in turn, intruded by the Golden Horn granite. On the south and west boundaries, however, the Black Peak batholith is in gradational contact with gneisses of the Chelan Metamorphic Complex (Barksdale, 1975). To the northeast, textures are distinctly igneous: for example, zoned plagioclase crystals, subhedral to euhedral crystal forms, sharp intrusive contacts, a lack of foliation, and a half-mile wide contact aureole are found. Contacts to the south and west are indistinct and best recognized by the development and increase of foliation. The compositions of the late Cretaceous Black Peak batholith ranges from dioritic to granodioritic except along the contact with the Twisp Valley Schist,
where the composition grades from hornblende quartz diorite to hornblendite. Essential minerals in the Black Peak batholith are plagioclase, quartz, biotite, and hornblende, with microcline-microperthite filling interstitial space (Adams, 1964). The Black Peak batholith is located in the southwest part of the regional map area (Figure 2).

Lost Peak Stock

The Lost Peak stock is a light-gray to pinkish-gray hypidiomorphic granular intrusion with compositions ranging from granodiorite to quartz monzonite. The rock is fine-to-medium-grained and major minerals present include plagioclase, quartz, potassium feldspar, hornblende, and biotite with accessory sphene, zircon, ilmenite, magnetite, and allanite. The Lost Peak stock intrudes arkoses and argillites and exhibits a well-developed aureole. The Lost Peak stock is itself intruded by the Monument Peak stock and as a consequence, minor potassium feldspar flooding has occurred along the contact with this younger intrusion (Staatz et al., 1971). Moderately resistant to weathering, the Lost Peak stock is located in the northeast corner of the map area. The age of this stock is not known.

Fawn Peak Stock

The Fawn Peak stock is especially noteworthy as it is the site of a low-grade disseminated copper occurrence. The well-jointed stock is composed of large amounts of calcic andesine, hornblende, biotite, and minor quartz with magnetite and apatite as the dominant accessory
minerals. Chlorite, muscovite, tremolite-actinolite, and hematite comprise the alteration assemblage which is most intense in the southern portion of the intrusive (Barksdale, 1975). Compositionally, the Fawn Peak stock is a diorite, although locally it ranges to quartz diorite in composition. The stock is generally coarse-grained with a locally porphyritic border phase. Magmatic biotite gives an isotopic age of 87 million years. The Fawn Peak stock is located about 30 kilometers west-southwest of the Slate Creek prospect.

Golden Horn Batholith

The Golden Horn batholith, along with the Monument Peak stock, are two unique alkaline granitic intrusions occurring within the dominantly calc-alkaline terrane of the North Cascades. The Golden Horn granite is a northwest-trending body intruded along the southwest margin of the Methow-Pasayten belt. The mid-Eocene batholith was forcefully intruded, shouldering aside the Harts Pass Formation arkoses and brecciating the Black Peak batholith along the intrusive contact (Barksdale, 1975). Isotopic ages vary, but the intrusive is about 48 million years old.

The Golden Horn batholith consists of three different phases (Stull 1969): a two-feldspar biotite granite, a one-feldspar biotite granite, and a sodic amphibole-bearing alkaline granite. The granites vary from fine-to-coarse-grained, gray to pink on fresh surfaces, and weather to yellow or orange. The two-feldspar-granite contains perthitic orthoclase, plagioclase, quartz, biotite, hornblende, and
minor aenigmatite, and the one feldspar granite is composed of perthite and quartz with rare albite, while the alkaline phase is comprised of perthitic orthoclase with exsolved albite, quartz, sodic amphibole, and rare pyroxene and biotite. Accessory minerals in the granites include apatite, magnetite, zircon, fluorite, and carbonates. Both miarolitic cavities and rapakivi textures are common in these granites.

Monument Peak Stock

The Monument Peak stock is circular and about eleven kilometers in diameter. As with the Golden Horn granite, the 48 million-year old Monument Peak granite shouldered aside sediments during intrusion (Tabor et al., 1968). The Monument Peak stock consists of perthitic microcline, quartz, and plagioclase, with biotite. Accessory minerals include sphene, zircon, and apatite. The Monument Peak stock developed textural zoning during crystallization and as a consequence is fine-grained and porphyritic near its margins and medium-grained in the interior. Fresh outcrop color is yellowish-pink while weathered outcrops are orange.

Additional Intrusive Rocks

Two other groups of intrusive rocks common to the region are quartz porphyry dikes and diorite porphyry dikes. The northwest-trending quartz porphyry dikes are common in the area between the Monument Peak stock and the Golden Horn batholith. These Felsic dikes are resistant to weathering, and stand out as yellow to orange ribs on
steep valley walls. The quartz porphyry dikes contain subhedral to euhedral phenocrysts of quartz, potassium feldspar, and plagioclase, with minor biotite. The phenocrysts comprise 10-50% of the rock and are surrounded by an aphanitic, potassium-rich matrix. Compositionally, these dikes range from rhyolite to rhyodacite (Tabor et al., 1968).

Diorite or plagioclase porphyry dikes are scattered throughout the region. These dikes contain phenocrysts of plagioclase, potassium feldspar, quartz, hornblende, and biotite in a fine-grained groundmass of similar composition. Magnetite is the major accessory mineral and calcite and chlorite occur as alteration products (Staatz et al., 1971). The light to dark gray dikes range from diorite to granodiorite in composition. Both the quartz porphyry and the diorite porphyry dikes are too numerous to be shown in Figure 2.

**Metamorphic Rocks**

The Methow-Pasayten belt is adjoined on both sides by metamorphic rocks. To the northeast lies the Okanogan Batholithic Complex and to the southwest is the Chelan Batholithic Complex. The Okanogan Complex is predominantly leucocratic in appearance and composed of quartz, feldspar, and biotite, with weakly developed gneissic foliation (Barksdale, 1975). The rocks of the Okanogan Complex have both metamorphic and igneous textures. Granulated quartz, wavy micas, and rotated plagioclase crystals appear to be metamorphic in origin, while zoned plagioclase and hypidiomorphic
crystals indicate an igneous origin. Barksdale (1975) suggests that the rocks are the products of shearing and metamorphism acting on leucocratic quartz diorites or trondhjemites which date from Triassic-Jurassic time (Tennyson and Cole, 1978).

The Chelan Batholithic Complex flanks the Methow-Pasayten belt on the southwest. Several compositionally and texturally distinct units comprise the pre-Tertiary Chelan Complex, although in the regional map area only two units are present; the low grade rocks of the Twisp Valley Schist east of the Black Peak batholith and the low to high grade Skagit Gneisses west of the Black Peak batholith. The Twisp Valley Schist ranges in composition from quartzitic to micaceous to calcic and was probably derived from sedimentary and volcanic rocks (Barksdale, 1975). The Skagit Gneiss is generally quartz dioritic in composition in this area. The oldest rocks in the Chelan Complex are late Cretaceous in age.
CHAPTER 3

DETAILED GEOLOGY

This chapter describes the detailed geology of the late Oligocene Slate Creek breccia pipe and the adjacent host rocks. The steeply southward-dipping breccia pipe cuts through arkose, diorite porphyry, quartz-magnetite altered rock, and quartz-eye rhyolite (Figure 3, in pocket). At its southern extreme, the breccia severs a diorite porphyry dike, while massive arkose adjoins the pipe on its west and southeast sides. Quartz-magnetite altered rocks are adjacent to the pipe from the north to the east and grade northward into quartz-eye rhyolite and eastward into arkose. At the southernmost extent of the quartz-magnetite rock, an irregular outcrop of quartz-eye rhyolite is cut by the breccia. One additional rock type, crenulated quartz, crops out near the pipe, but is not cut by it. This unique rock occurs north of the pipe beyond the outcrops of quartz-eye rhyolite.

In addition to outcropping rocks, drill holes 1 and 2 intersect several other rock types. Drill hole 2 is oriented S 3.5° E, plunging 55°, and is located about 10 meters north of the breccia pipe. In this hole, numerous argillite beds, one conglomerate layer, and one quartz-eye porphyry dike are encountered, besides the more abundant arkose and a diorite porphyry dike, all of which occur beyond the breccia. Drill hole 1 is vertical and traverses quartz-magnetite
altered rock to a depth of approximately 490 meters, where quartz-eye porphyry is encountered and is present to the bottom of the hole. Each of these lithologies will be described in successive sections to follow.

Host Rock Petrology

Argillite and Arkose

The most common rock type bordering the breccia pipe at the surface is massive Cretaceous arkose, with rare interbeds of argillite. At depth, where drill hole 2 passes out of the breccia, arkose is still the dominant rock type (Figure 3), but argillite beds are more common and one chert-pebble conglomerate layer occurs. Both arkose and argillite are well indurated and weather to light gray; fresh surfaces are dark brownish gray. These sedimentary rocks are part of the 2,400 meter-thick, mid-Cretaceous Harts Pass Formation. Bedding is difficult to discern in the massive arkose and surface outcrops of argillite are rare, complicating the task of obtaining information on bedding attitudes.

Thin section observations offer additional information about both the arkose and argillite. The arkose is composed of medium-grained quartz and feldspars of modal composition as follows: 40-55% quartz, 25-30% plagioclase, 15-20% orthoclase, and 5-10% lithic fragments consisting of chert, volcanics, and quartzite. The grains are poorly sorted and angular, although locally they range to sub-rounded. A biotite-dominated matrix constitutes 5-15% of the arkose
with montmorillonite, sphene, zircon, magnetite, quartz, and calcite also present.

The argillite is composed of very fine-grained quartz, biotite, and clays. The modal composition of the argillite is 50% quartz, 20-35% biotite, 10-15% montmorillonite, 2-5% magnetite, < 5% chlorite, and 1% calcite, with trace amounts of zircon, apatite, and tremolite.

Diorite Porphyry

Diorite porphyry occurs in steeply dipping north-to-northwest trending dikes (Figure 3). The diorite is gray on fresh surfaces and weathers to light gray. The rock consists of 1-4 mm phenocrysts of 25-30% plagioclase, 5-10% hornblende, and 1-3% biotite, with rare quartz and orthoclase. The remaining 65% is composed of a very fine-grained groundmass of intermediate composition containing plagioclase, quartz, magnetite, apatite, zircon, and chlorite. Similar dikes of middle to late Cretaceous age are common throughout the northern part of the North Cascades.

Quartz-Eye Rhyolite

An undated quartz-eye rhyolite is present in several irregular outcrops near and in contact with the breccia pipe. It is white to cream colored on fresh surfaces, weathering rusty orange. The rhyolite consists of 3-6 mm, generally euhedral and locally embayed quartz phenocrysts in an aphanitic groundmass. Rare phenocrysts of orthoclase and biotite are also present. Phenocrysts constitute only
5-10% of the rhyolite. Its pod-like surface outcrops and occurrence in drill hole 1, where it is cut by quartz-magnetite alteration, suggest that the rhyolite is an intrusive rock in this area.

Quartz-Eye Porphyry

The quartz-eye porphyry (QEP) is closely associated with the breccia pipe. The porphyry occurs both as matrix and clasts within the breccia and in two cases as dikes cutting the breccia. No outcrops of the QEP occur in the area surrounding the breccia pipe, but it is intersected in both drill holes. Drill hole 1 bottoms in barren, relatively unaltered QEP. Drill hole 2 intersects mineralized and phyllic-altered QEP within and in a lone dike outside of the breccia.

The QEP contains about 45% phenocrysts composed of 15-20% quartz, 10-15% orthoclase, 15-20% low-anorthite plagioclase, 3% hornblende, 2% biotite, and 1% muscovite, all with a size range of 2-6 mm. The remaining 40-45% is a fine-grained felsic groundmass. The matrix of the dike occurrences has a consistently finer grain size than that of the massive intersection of QEP in drill hole 1. A single whole-rock analysis of the QEP and Barth norm composition are listed in Table 2. Both norm and mode indicate that the porphyry is a granite (Figure 4).

Crenulated Quartz

One of the most extraordinary rock types near the breccia pipe is that of crenulated quartz, or "brain rock", found in several small
### Table 2.

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* - All Fe as Fe₂O₃

A - Quartz-Eye Porphyry (Granite)

B - Crenulated Quartz (Quartz-rich Granitoid)
* - Crenulated Quartz (Quartz-rich Granitoid)

# - Quartz-eye Porphyry (Granite)

Figure 4. IUGS (1973) plutonic rock classification of quartz-eye porphyry and crenulated quartz.

Plag. - Plagioclase
A.F. - Alkali feldspars
Qtz. - Quartz
outcrops north of the breccia pipe. While it does not occur as clasts in the breccia, it is cut by quartz-magnetite veins which do occur as clasts in the breccia (Figure 5).

The crenulated quartz rock consists of alternating bands of quartz and felsic porphyry. The 1-5 mm thick, monomineralic bands contain medium-grained, subhedral quartz crystals. The bands are smooth on one side and have crystal growth faces protruding on the opposite side. It has been proposed that this texture indicates a facing or growth direction with the jagged euhedral quartz crystals pointing inward to a crystallizing magma body (Shannon et al, 1982). At Slate Creek, the facing direction of quartz bands is consistent on the handsample scale, but the bands are intricately folded and no consistent facing direction is apparent on the outcrop scale. The quartz bands constitute 30-40% of the brain rock. The intraband area is filled with pink felsic porphyry consisting of 10% quartz, 5-10% orthoclase, 5-10% plagioclase, and rare biotite, with a fine-grained felsic groundmass. A single whole-rock analysis and Barth norm composition for the crenulated quartz is listed in Table 2. Based on the whole rock normative composition, the crenulated quartz classifies as a quartz-rich granitoid (Figure 4). Both the QEP and the crenulated quartz were analyzed using wet geochemical methods at Skyline Laboratory, Tucson, Arizona. The potassium-argon isotopic age of orthoclase in the crenulated quartz is 24 ± 0.6 million years.
Figure 5. Crenulated quartz cut by quartz-magnetite veins. The sample was collected from outcrop 125 meters north of the breccia pipe.
Tuff

A small outcrop of tuff occurs 30 meters southwest of the breccia pipe (Figure 3). The white rock is platy and very porous. The tuff consists of quartz, sericite, clays and fragments which may have been glass. Lithic fragments of quartz and sutured quartz are also present. A second tuff of presumably limited occurrence is present outside the detailed map area but within one kilometer of the breccia. It is a gray to white colored crystal-lithic-garnet tuff with eutaxitic texture. Subhedral crystals of quartz, plagioclase, and rare garnet of unknown composition are accompanied by lithic fragments of arkose and sutured quartz in a fine-grained matrix.

Structure

The area immediately around the breccia pipe is structurally uncomplicated. The arkose strikes northwest and dips steeply to the northeast. Diorite porphyry dikes trend north to northwest and dip nearly vertically. Jointing around the breccia pipe occurs in a nearly orthogonal set, with northwesterly directions ranging from N35-50W and northeasterly directions from N15-45E. In both cases, dips are near vertical. The northwest-striking joints have densities of six to twelve joints per meter, while the northeast-striking joints range from twelve to eighteen joints per meter. In traverses away from the pipe, no variation in joint orientation or density is apparent. The pipe's long dimension trends northeast, in opposition to the arkose bedding orientation and strikes of the diorite porphyry
dikes. The plunge of the pipe is not precisely known, but drill hole and adit intersections of the pipe-wall contact indicate an 80-85° south-to-southwest plunge. No mappable faults were observed in the area.

**Breccia Pipe Geology**

The Slate Creek breccia pipe stands out as a large orange color anomaly on the south side of Slate Creek Canyon. It is egg-shaped, with long and short dimensions of 260 meters and 200 meters (Figure 3) with the long dimension striking N 35 E. At the surface, the strong limonite staining is accompanied by manganese oxide staining (Figure 6). Although the breccia is weathered, fresh sulfides can be identified where a small stream cuts the pipe. Quartz-molybdenite vein clasts of the Climax-Urad-Henderson veinlet type are also present at the surface.

**Clasts**

Clasts in the pipe include all the host rocks, with the exception of the crenulated quartz, along with rare fragments representing a previous breccia event which is unexposed at the surface or in drill holes. Clasts occurring in the breccia pipe are, in decreasing order of abundance: arkose, argillite, diorite porphyry, quartz-magnetite rock, quartz-eye porphyry, quartz-eye rhyolite, quartz-feldspar porphyry, quartz-molybdenite vein fragments, rare clasts of sulfides, and rarer clasts of a previous breccia event. The subangular to subrounded clasts range in size from several
Figure 6. Weathered outcrop of breccia. For scale, the blue pen is 14 centimeters long.
meters in diameter down to rock flour with an average size of two-to-six centimeters. There is no noticeable clast distribution pattern through the central pipe area, but near the pipe margins the dominant clast type matches the wall-rock type. The wall-rock control on clast distribution is apparent over a two-to-five meter wide interval near the edge of the pipe. Throughout the pipe, phyllic alteration affecting clasts and matrix leads to the characteristic gray-white bleached color of the unweathered breccia.

Matrix

Two types of breccia matrix are found in drill hole 2; rock flour occurs throughout and intrusive quartz-eye porphyry occurs in the intermediate and lower levels. The first consists of small fragments of composition identical to the larger clasts in which clasts make up about 80% of the breccia, with open-space fillings common. The quartz-eye porphyry matrix differs markedly, with distinctive quartz phenocrysts in a fine-grained groundmass. The abundance of clasts in the areas of intrusive matrix is less, as are the open-space fillings. The quartz-eye porphyry matrix differs from the rocks of the dikes which contain few or no clasts.

Contacts

Wall rock-breccia contacts are sharp and distinct at the surface, but less distinct in drill core. In outcrop, the breccia is more easily eroded than the host rocks. No breccia dikes radiate from the pipe, but two breccia dikes occur southwest of the pipe (Figure 3).
The 30-to-45 centimeter-wide dikes are nearly identical to the breccia pipe. Both dikes cut arkose, are filled with phyllic-altered clasts of the same in a rock flour matrix, and have characteristic limonite and manganese oxides resulting from supergene alteration. These dikes are not traceable to the breccia pipe.
CHAPTER 4

ALTERATION AND MINERALIZATION

This chapter describes the style and distribution of alteration and mineralization in and around the Slate Creek breccia pipe; interpretation is kept to a minimum. Information for this description is based on hand-sample and thin-section studies. Element distribution maps for copper, molybdenum, lead, zinc, tungsten, and fluorine are based on assays of drill core composites and surface rock chip samples. Three basic alteration assemblages are present within the detailed map area. Phyllic alteration pervades the breccia pipe and occurs outside the pipe in association with base-metal veins. Penetrative biotite hornfels alteration affects arkose, argillite, and diorite porphyry; in these rocks, secondary biotite replaces mafic and groundmass minerals. The third alteration type, quartz-magnetite alteration, is restricted to an area adjacent to the north side of the breccia pipe.

Besides alteration, a progression of barren and mineralized veins occurs within and around the breccia pipe. The veins are divisible into five sets, in order of decreasing age: quartz, quartz-magnetite, quartz-molybdenite, base-metal sulfides, and calcite. Barren quartz veins cut all rock types except the breccia. Quartz-magnetite veins cut the barren quartz veins and are restricted in occurrence to the quartz-magnetite alteration zone. Quartz-
molybdenite veins cut arkose, argillite, diorite porphyry, and quartz-eye rhyolite; however, cross-cutting relations with quartz-magnetite veins are not clear. Neither quartz-magnetite nor quartz-molybdenite veins cut the breccia. Base-metal sulfide veins cut all rock types and also occur in the breccia as veins, clots, and disseminations. Barren calcite veins comprise the latest event observed.

**Alteration**

**Biotite Hornfels**

Pervasive biotite alteration affects arkose, argillite, and diorite porphyry throughout the detailed map area (Figure 3). The hornfels alteration is also present in the lower extent of drill hole 2, beyond the breccia pipe (Figure 3). The style of hornfels alteration differs significantly in the sedimentary and igneous rocks and will be discussed separately.

In the diorite porphyry, biotite hornfels affected the mafic minerals most strongly. Besides alteration of the mafics, secondary biotite occurs along fractures which are nonpenetrative on the thin-section scale. Biotite, montmorillonite, and sericite are disseminated within the plagioclase phenocrysts and in the felsic groundmass. The primary mafic minerals biotite and hornblende are replaced by fine-grained, light-brown biotite and magnetite. Replaced hornblende crystals are recognized by their lath-like outlines and the rare presence of hornblende cores surrounded by the fine-grained biotite. Actual primary biotite was not observed in diorite porphyry
samples collected near the breccia pipe, but in a relatively unaltered
diorite porphyry sample collected away from the prospect area, medium-
to-coarse-grained, dark-green to brown biotite, quite unlike the fine-
grained alteration biotite, is present. The montmorillonite and rare
sericite present in the diorite porphyry are disseminated through the
felsic groundmass and also occur within plagioclase crystals along
discontinuous fractures. The quartz and rare orthoclase phenocrysts
are generally fresh.

In both the arkose and argillite, secondary biotite of the
biotite hornfels alteration is concentrated in the matrix. The
altered arkose matrix consists almost entirely of fine-grained, light-
brown biotite accompanied by quartz, chlorite, magnetite, and
montmorillonite. The biotite hornfels alteration is generally
pervasive but is locally controlled by nonpenetrative fractures.
Plagioclase grains in the arkose are moderately altered with
montmorillonite and minor sericite partially replacing the grains,
making outlines indistinct, and masking albite-type twinning. As with
the diorite porphyry, quartz and potassium feldspar grains are
generally fresh. The original clay-rich matrix of the argillite is
strongly altered to biotite. The intensity of the pervasive biotite
hornfels alteration in the argillite is commonly controlled by closely
spaced bedding-plane laminations; fractures take on a less important
role in alteration control.
Quartz-Magnetite

The quartz-magnetite alteration zone is restricted in occurrence to the north side of the breccia pipe (Figure 3). The quartz-magnetite zone extends 490 meters in drill hole 1 (Figure 3). The lateral extent of the zone is not known, due to cover, but a magnetometer survey over the detailed map area outlines its extent.

The quartz-magnetite alteration zone is a restricted area of quartz and quartz-magnetite veins. Within this zone, rocks consist almost entirely of sugary quartz with variable amounts of vein-controlled magnetite. Original rock type is not discernible, due to the high density of veins. As the intense quartz-magnetite alteration grades out into quartz-eye rhyolite, quartz phenocrysts common to the rhyolite can be recognized. The gradational contact between arkose and quartz-magnetite is recognized as the quartz-magnetite vein density decreases and inter-vein areas can be distinguished as arkose.

To further delineate the quartz-magnetite zone, a magnetometer survey was conducted over the breccia pipe and surrounding rocks (Figure 7). The breccia pipe forms a distinct magnetic low whereas the quartz-magnetite altered area corresponds to the magnetic high area. Figure 8 (in pocket) provides a transparent geologic overlay keyed to the border of Figure 7.

Phyllic Alteration

Within the breccia pipe, phyllic alteration is pervasive; outside the pipe, it occurs in association with base-metal sulfide
Figure 7. Surface contour map of kriged magnetometer data. See Figure 8 (in pocket) for surface geology overlay of the Slate Creek Breccia area.
veins. The thin base-metal veins and veinlets have alteration halos extending out into the host rock. The bleached halos are weakly silicified and contain greenish sericite and rare chlorite. The potassium-argon isotopic age of sericite in the breccia is $25 \pm 0.7$ million years.

Phyllic alteration within the breccia pipe is characterized by disseminated sericite and siderite, with accompanying silicification and sparse chlorite in areas of rock flour matrix. In addition, magnetite in quartz-magnetite clasts is sulfidized. Throughout the matrix and in most clasts, alteration is strong except in the interior of boulder-sized clasts. In particular, in one three-meter diameter clast of diorite porphyry, alteration intensity decreases inward and is only weak in the core. Alteration mineralogy also changes to sericite, accompanied by montmorillonite and rare zoisite. Plagioclase and hornblende phenocrysts in the core of this large clast are weakly altered.

A similar decrease in phyllic alteration intensity is observed at the breccia-host rock contacts. A thin-section traverse away from the breccia-arkose contact at the surface documents the alteration variation. At 30 centimeters from the contact, sericite is common—partially replacing biotite and chlorite in the arkose matrix. Montmorillonite is more common in plagioclase grains at this location than in the more distant arkose samples. At 1.5 meters from the contact, sericite is sparse and the biotite-chlorite matrix is weakly bleached. Plagioclase grains give no indication of the proximity of
the contact. At 3 meters from the contact, there is no indication of the alteration associated with the breccia pipe.

Vein Mineralization

Quartz Veins

Barren quartz veins are the earliest observed veins in the area of the Slate Creek breccia pipe; they cut all rock types except the breccia. The quartz veins are common, but not abundant, and are generally less than 1 cm. in width. Fine-grained sugary quartz is the dominant constituent of the veins, but where the veins cut biotite-hornfels-altered rocks, chlorite often occurs with the quartz or immediately adjacent to the vein. No mineralization is associated with the veins.

Quartz-Magnetite Veins

Quartz-magnetite veins crosscut only barren quartz veins and are restricted in occurrence to the quartz-magnetite alteration zone, as discussed in the previous section. Fine-grained sugary quartz dominates the veins, with variable amounts of magnetite and sparse chlorite. Adjacent to the quartz-magnetite alteration zone, the veins occur in quartz-eye rhyolite, arkose, and crenulated quartz. In all three rock types, there are weak halos of silicification extending 0-2 centimeters out from the vein edge. In many quartz-magnetite veins there is evidence of repeated magnetite deposition, leading to a layered lit-par-lit texture.
Quartz-Molybdenite Veins

Quartz-molybdenite veins occur in arkose, argillite, quartz-eye rhyolite, and diorite porphyry. These mineralized veins crosscut barren quartz veins, but the nature of the crosscutting relationship with quartz-magnetite veins is not known. Moderate amounts of platy molybdenite occur in the veins, all of which are dominantly composed of sugary quartz. Very weak silicified halos exist around the quartz-molybdenite veins. Molybdenite is also present coating fractures.

The quartz-molybdenite vein set is discussed further in Chapter 5, entitled 'Quartz-Molybdenite Vein Fluid Inclusions'.

Base Metal Sulfide Veins

The base-metal sulfide veins are the most complicated of the vein sets. All rock types are cut by the sulfide veins, as are all other vein sets except for the barren calcite veins. Sulfide minerals in the veins include pyrite, pyrrhotite, sphalerite, arsenopyrite, chalcopyrite, and rare galena and molybdenite. Sphalerite, arsenopyrite and galena tend to be euhedral; pyrite, pyrrhotite, chalcopyrite, and molybdenite are anhedral. Gangue minerals include quartz and dolomite with minor calcite and sericite. Quartz is commonly euhedral while dolomite, calcite, and sericite are subhedral to anhedral. Various combinations of sulfide and gangue minerals occur, but sphalerite, pyrrhotite or pyrite, and quartz are almost always present. Alteration halos around base-metal sulfide veins vary with the rock type cut. Where the veins cut biotite-hornfels-altered
rocks, there are distinctive light green phyllic-altered halos. When quartz-magnetite rock is cut, magnetite adjacent to the base-metal veins is sulfidized. Within the phyllic-altered breccia pipe, no vein-controlled alteration is apparent. Halos are not observed where the sulfide veins cut quartz-eye rhyolite and crenulated quartz.

Calcite Veins

The latest vein set consists of barren white calcite veins. These veins range in size from hairline fractures to veins several centimeters wide. The calcite veins have no alteration halos nor do they contain any accessory minerals.

**Breccia Pipe Mineralization**

Mineralization within the breccia pipe is fairly simple. Sulfides occur in several modes: clots filling open space between the clasts; veins cutting through the breccia; disseminations in the matrix; disseminations in clasts deposited after brecciation; and clasts mineralized before brecciation. Mineralization can be further differentiated by timing and assemblage. A quartz-molybdenite assemblage was present prior to brecciation, while a second event consisting of several or all of the minerals pyrite, sphalerite, pyrrhotite, chalcopyrite, arsenopyrite, galena, molybdenite, quartz, siderite, and sericite occurred after the brecciation event and is directly related to the base-metal mineralization outside of the pipe.

Molybdenum values are derived dominantly from quartz-molybdenite vein clasts. Locally, quartz-molybdenite vein clasts are
abundant (Figure 9), but generally they are sparsely distributed. Very commonly, brecciation has separated the quartz-molybdenite veins from the rocks they originally cut; therefore, no host rock association is apparent. Small amounts of molybdenite also occur with the other sulfides in veins, clots, and disseminations within the breccia. Molybdenite in those occurrences may be either primary or it may represent molybdenite freed through the comminution of quartz-molybdenite vein clasts.

All the other sulfides, including pyrite, sphalerite, pyrrhotite, arsenopyrite, chalcopyrite, and galena, occur together in various combinations. Veins, clots, and disseminations are dominated by sphalerite, pyrite, and pyrrhotite - the characteristic mineralization assemblage in the breccia pipe. Chalcopyrite, arsenopyrite, and galena are variable and less abundant in occurrence.

Some interesting controls on mineralization are apparent in the drill core intersection of the breccia pipe. Throughout the interval, vein density and percent total sulfides remain fairly constant. The contribution to mineralization from the clot mode and the disseminated mode vary greatly. In areas of rock flour matrix, clots are far more important than disseminations. Conversely, in areas of intrusive matrix, clot mineralization is less common and disseminated mineralization is more important. Disseminations in clasts are more constant, but they are controlled by clast outlines. In Figure 10 the three modes of base-metal sulfide mineralization within the breccia pipe are shown.
Figure 9. Fragments of quartz-molybdenite veins in the breccia from drill hole 2 below the weathered zone.
Figure 10. The three types of primary mineralization associated with the breccia pipe. From left to right, the split drill core segments display open space filling, veins, and disseminated mineralization. The samples were collected from drill hole 2 below the weathered zone.
Selected Element Zoning

Contouring based on assay values of copper, molybdenum, lead, zinc, tungsten, and fluorine demonstrates the zoning of these elements in and around the breccia pipe. Zoning information, coupled with a knowledge of geology, provides some insight into the localization of the six elements. Both plan-view and cross-section maps are computer generated. An explanation of the Duval Corporation computer system and background information pertaining to statistics and computer programs used in contouring is not included in the text of this thesis, but is provided in the appendix.

Plan-view maps are based on a 30 meter sampling grid. A brunton and topofil survey was used to locate the sample points and to tie the grid location to a nearby bench mark. Random rock chip samples of outcrop were collected within a 15-meter-radius circle surrounding the sample point. No sample was collected if no outcrop occurred within the 15 meter circle. Samples were analyzed at Copper State Laboratory, Tucson, Arizona. Tungsten concentration was determined by colorimetric methods; copper, molybdenum, lead, zinc, and fluorine concentrations were determined by atomic absorption.

For all six elements, the sixty surface samples conform moderately well to a log-normal distribution. Accordingly, the element grades are contoured after a log to the base ten transformation. The logarithmic mean is labeled as a bold line and the grades are contoured away from the mean; contour intervals were chosen strictly for clarity. Actual assay values for the surface grid
are included in the plot. In order to see the relation between geology and element distribution, a transparent overlay of the geology keyed to the borders of Figures 11 to 16 is included in the pocket (Figure 8).

Geochemical cross-sections are based on data from both the surface sample grid and the two drill holes. The vertical cross-section is oriented south 3-1/2° east and contains both drill holes. As with the surface grid, the drill holes are located with respect to bench mark 3920. Drill hole assay values represent ten foot composites of split drill core. For proprietary reasons, assays of drill core composites are not listed.

The irregular array of data in the cross-section cannot be effectively contoured by normal means, but the process of kriging provides an alternative. A more complete explanation of the kriging process is included in the appendix. Kriging provides an unbiased estimate of grade for contouring. The estimate is based on the variance of the data set being contoured. Although the entire drill hole and surface data set also conforms to a log-normal distribution, untransformed data were used in kriging, since the kriging of log transformed data is of questionable validity (Steve Rooke, pers. comm., 1982). Cross-section geology is shown in Figure 17 (in pocket) and is keyed to the borders of Figures 18 to 23.

The figures of plan view and cross-section element zoning contain additional information concerning the element pictured. In viewing the figures, three points should be kept in mind: first, due
to lack of outcrop, samples do not represent the breccia to the west; second, surface and subsurface data are combined without a weathering correction; and finally, cross-section and surface contouring do not involve interpretation with respect to geology or expected zonation.

The occurrence of the six elements should also be considered. The following list summarizes their occurrence:

1. Copper - dominantly in chalcopyrite deposited after brecciation.
2. Molybdenum - as molybdenite in quartz-molybdenite veins deposited prior to brecciation.
3. Lead - as galena deposited after brecciation.
4. Zinc - in sphalerite deposited after brecciation.
5. Tungsten - no primary mineral identified.
6. Fluorine - no primary mineral identified. Qualitative X-ray diffraction runs indicate it to be present in fluormicas of the alteration assemblage.
Figure 11. Contour map of logarithm of copper concentration at the surface. The log mean is 1.58 (38 ppm) and the log standard deviation (STD DEV) is 0.556. Figure 8 (in pocket) provides a surface geology overlay of the Slate Creek breccia area.
Figure 12. Contour map of logarithm of molybdenum concentration at the surface. The log mean is 1.58 (38 ppm) and the log standard deviation (STD DEV) is 0.426. Figure 8 (in pocket) provides a surface geology overlay of the Slate Creek breccia area.
Figure 13. Contour map of logarithm of lead concentration at the surface. The log mean is 1.52 (33 ppm) and the log standard deviation (STD DEV) is 0.633. Figure 8 (in pocket) provides a surface geology overlay of the Slate Creek breccia area.
Figure 14. Contour map of logarithm of zinc concentration at the surface. The log mean is -1.75 (178 ppm) and the log standard deviation (STD DEV) is 0.597. Figure 8 (in pocket) provides a surface geology overlay of the Slate Creek breccia area.
Figure 15. Contour map of logarithm of tungsten concentration at the surface. The log mean is 1.08 (12 ppm) and the log standard deviation (STD DEV) is 0.426. Figure 8 (in pocket) provides a surface geology overlay of the Slate Creek breccia area.
Figure 16. Contour map of logarithm of fluorine concentration at the surface. The log mean is -0.94 (1150 ppm) and the log standard deviation (STD DEV) is 0.148. Figure 8 (in pocket) provides a surface geology overlay of the Slate Creek breccia area.
Figure 18. Contours of kriged copper concentration; cross-section looking west. Figure 17 (in pocket) provides a cross-section geology overlay of the Slate Creek breccia area.
Figure 19. Contours of kriged molybdenum concentration; cross-section looking west. Figure 17 (in pocket) provides a cross-section geology overlay of the Slate Creek breccia area.
Figure 20. Contours of kriged lead concentration; cross-section looking west. Figure 17 (in pocket) provides a cross-section geology overlay of the Slate Creek breccia area.
Figure 21. Contours of kriged zinc concentration; cross-section looking west. Figure 17 (in pocket) provides a cross-section geology overlay of the Slate Creek breccia area.
Figure 22. Contours of kriged tungsten concentration; cross-section looking west. Figure 17 (in pocket) provides a cross-section geology overlay of the Slate Creek breccia area.
CONTOURS OF KRIGED FLUORINE GRADES. CONTOUR INTERVAL 400.0 PPM. CROSS SECTION LOOKING WEST.

Figure 23. Contours of kriged fluorine concentration; cross-section looking west. Figure 17 (in pocket) provides a cross-section geology overlay of the Slate Creek breccia area.
CHAPTER 5

QUARTZ-MOLYBDENITE VEIN FLUID INCLUSIONS

Fluid inclusion data collected from quartz-molybdenite veins in the breccia pipe walls and from fragments of quartz-molybdenite veins in the breccia serve to compare two fluid inclusion populations. An SGE Inc. stage modeled after a United States Geological Survey design was used for data collection in the Fluid Inclusion Laboratory of the University of Arizona.

Inclusion Type and Size

Quartz-molybdenite veins outside the breccia reveal sparse, very small fluid inclusions ranging in size from 5-10 microns. All inclusions are liquid-rich, show no evidence of boiling, and contain no daughter minerals.

Quartz-molybdenite vein fragments within the breccia are quite different than the unbrecciated veins. Quartz in the breccia fragments is densely populated by small fluid inclusions, many so small as to be unworkable, in the size range of 5 - 10 microns. Many of the inclusions in vein breccia fragment quartz occur along fractures, with no evidence of boiling in the liquid-rich inclusions. Halite rarely occurs as a daughter mineral.
Figure 24. Fluid inclusion homogenization data from quartz in quartz-molybdenite veins (A.), and quartz-molybdenite vein breccia fragments (B.) from the Slate Creek breccia pipe.
Homogenization Temperatures and Salinities

Inclusions in quartz-molybdenite veins outside the breccia homogenized in a range of 140° - 460°C (Figure 20A). The quartz-molybdenite vein breccia fragment inclusions homogenized in a similar range of 160° - 460°C (Figure 20B). A difference between the two fluid inclusion populations was noted during heating for homogenization. Inclusions from the vein breccia fragments commonly burst between 350 - 400°C, making it difficult to homogenize the daughter halite crystals since decrepitation usually occurred before homogenization.

Salinities can be discussed only in a general way for the two fluid inclusion populations. In neither type would inclusions freeze, even with rapid cooling to -130° C. The failure to freeze probably indicates supercooling of highly saline inclusion fluids, but no quantitative statement can be made since the small size of the inclusions may also inhibit freezing. The higher salinity of inclusions from quartz-molybdenite vein breccia fragments is qualitatively documented by the presence of halite. Inclusions containing daughter halite crystals at room temperature have salinities in excess of 23 weight percent NaCl (Potter, et al., 1977).

Comparison with other Quartz-Molybdenite Fluid Inclusion Data

The lack of salinity data reduces comparison to speculation. At the Climax orebody, Hall and others (1974) arrived at a 350°C average inclusion homogenization temperature for quartz-molybdenite
veins. This value agrees well with the Slate Creek quartz-molybdenite vein inclusion data. More recently, White and others (1981) have reported a 400°C average homogenization temperature for the Urad-Henderson deposit quartz-molybdenite veins. These two sources indicate that the Slate Creek quartz-molybdenite fluid inclusions have comparable homogenization temperatures, but little more can be said.
CHAPTER 6

INTERPRETATION AND ORIGIN OF THE SLATE CREEK BRECCIA PIPE

The Slate Creek breccia pipe is a promising mid-Tertiary molybdenum prospect of age, igneous rock association, and style of mineralization that are strikingly similar to other known molybdenum prospects and deposits. The breccia pipe at Slate Creek is closely associated with the granitic quartz-eye porphyry. The breccia has primary base-metal sulfide mineralization, but it cuts through quartz-molybdenite mineralized rocks. These features, along with base-metal mineralization in and around the pipe, indicate that the Slate Creek breccia pipe may be the upper-level-expression of an important molybdenum system. The mode of origin of the Slate Creek breccia suggests that further drilling is indicated.

Igneous Rock Association

The Slate Creek breccia pipe is closely affiliated with the quartz-eye porphyry. The porphyry is present in the breccia both as clasts and as matrix. Compositionally, the quartz-eye porphyry is a granite porphyry. (Figure 3 and Table 2, pages 26 and 27, respectively). This fact places Slate Creek in the "granite molybdenite" system of Mutschler and others (1981). In the same paper, a "composition fingerprint" was calculated. In Table 3, ideal compositions are compared with actual values of the Slate Creek quartz-eye porphyry.
Table 3. Comparison of ideal concentrations of SiO$_2$, Na$_2$O, and K$_2$O with actual values in quartz-eye porphyry.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>SiO$_2$ wt %</td>
<td>$\geq$ 74.0</td>
<td>75.6</td>
</tr>
<tr>
<td>Na$_2$O wt %</td>
<td>$&lt; 3.6$</td>
<td>3.6</td>
</tr>
<tr>
<td>K$_2$O wt %</td>
<td>$\geq 4.5$</td>
<td>3.7</td>
</tr>
</tbody>
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The quartz-eye porphyry conforms to the ideal values except for its low potassium content.

Of additional interest is the classification of the quartz-eye porphyry as an I- or S-type granite as proposed by Chappell and White (1974). According to their characteristics, an S-type classification is favored. Evidence in support of the S-type classification for the QEP includes:

1. High SiO$_2$ - 75.60 wt % in QEP.
2. $> 1\%$ CIPW Normative Corundum - 2.74% in QEP.
3. $> 1.1$, Mol Al$_2$O$_3$/(Na$_2$O + K$_2$O + CaO), actual value = 1.17.
4. No hornblende in QEP.
5. Both biotite and muscovite present in QEP.

Several points of the Chappell and White (1974) classification were not evaluated:

1. Occurrence of garnet, cordierite, sphene, monazite, and apatite.
2. Sr$^{87}$/Sr$^{86}$ values.
3. Irregularity of isochrons and variation diagrams.
4. Timing in intrusive sequence.
The list of evidence leads to the conclusion that the quartz-eye porphyry is an S-type granite.

Comparison to Other Molybdenite Occurrences

Several features of the Slate Creek breccia pipe and the surrounding host rocks are comparable to known molybdenum occurrences. At the surface, quartz-molybdenite veins, a quartz-magnetite alteration zone, rhyolite porphyry, and crenulated quartz are related in both space and time. This rock group was emplaced before the breccia event. A similar occurrence of quartz-molybdenite veins, a quartz-magnetite alteration zone, rhyolite porphyry, and crenulated quartz is noted at the Henderson molybdenum deposit in Colorado, where the rocks are genetically related and form an integral part of the orebody (Wallace et al., 1981).

The breccia pipe itself also shows similarities to other molybdenum occurrences. Base-metal mineralization is common within the pipe, but zoning is apparent only for arsenic. Arsenic is abundant in the upper 65 meters of drillhole 2 and drops off markedly below that depth. Of the 360 vertical meters of the pipe explored at this time, zoning of copper, lead, or zinc is not apparent although base-metal mineralization is clearly centered on the pipe (Figures 11-23).

Redwell Basin, Colorado, is an example of a Climax-type molybdenum prospect associated with a well-developed breccia pipe. The breccia pipe at Redwell Basin has base-metal sulfide
mineralization in its upper 910 vertical meters. In this case, zoning of copper, lead, and zinc is apparent from drill core assays. No arsenic zoning was reported (Sharp, 1978).

There are also negative comparisons to be made. The Slate Creek breccia lacks both high fluorine values and potassic alteration associated with the exposed molybdenum mineralization. These two features are common to other Climax-type molybdenum occurrences (White et al., 1981). The actual role that fluorine plays is not totally understood and its importance in actual molybdenum concentration is questionable (Westra and Keith, 1981). The lack of potassic alteration at Slate Creek, coupled with the low potassium content of the quartz-eye porphyry intrusive, remain as problems.

Breccia Pipe Origin

The cause of some breccias is still speculative, and numerous theories have been proposed to fit the many styles of brecciation. The salient features of brecciation which should be accounted for include:

1. Structural control.
2. Geometry of breccia body.
4. Clast shape, size, and distributions.
5. Alteration style.
6. Type of matrix.
7. Intrusive rock involvement.
At the Slate Creek breccia, basic information on the style of brecciation is available and can be used to constrain or eliminate some models of the mode of breccia formation.

First, the Slate Creek breccia pipe has no apparent structural control. Its northeast-northwest slightly elliptical shape is perpendicular to the northwest-southeast regional structural grain. Drill intersections, adit maps, and the surface map indicate that the breccia is pipelike in shape and extends downward for more than 360 meters. The pipe dips steeply to the south or southwest. In general, breccia-wallrock contacts are sharp with the breccia being more easily eroded.

Secondly, clasts in the breccia are not characterized by any particular shape. Variation in clast size offers little more insight into breccia formation. They range from approximately 3 meters in diameter down to rock flour. In general, distribution of large clasts is random, but in drill hole 2 larger clasts are more common at the margin of the breccia. Distribution of clast type is somewhat more regular. Near the margins, the dominant breccia clasts are of the same rock type as the wall. However, clast types are well mixed through the throat of the pipe.

Finally, the matrix is of a dual nature, consisting of both rock flour and intrusive components, as discussed earlier. The rock flour component indicates grinding and breaking with minimal corrosive chemical activity. The intrusive rock matrix demonstrates close association of brecciation with magma emplacement or post-emplacement
adjustments. Regrettably, there are no marker units with which to
gauge upward or downward movement during brecciation.

Many modes of breccia formation have been discussed in the
literature (Mayo, 1976, Bennett, 1975) and the following list contains
those ideas most commonly proposed:

1. Breccia formation through collapse of rock into a void created
   by either the corrosive action of hydrothermal fluids
   (Sillitoe and Sawkins, 1971, Bryner, 1961), large-scale fault
   fissures (Mitcham, 1974), or by a exsolved vapor bubble from a

2. Brecciation caused by expansive cracking brought about by
   chemical reaction (Sawkins, 1969).

3. Breccia formation by fluidization of a portion of the rock
   column overlying a pluton (Sharp, 1977).

4. Brecciation caused by successive fracturing and
   crystallization of fault or shatter zone conduits by
   hydrothermal fluids from an underlying pluton (Bryant, 1968,

5. Brecciation by either explosive or forceful intrusive action
   associated with emplacement of an underlying pluton (White, et
   al., 1981).

The diagnostic features of the Slate Creek breccia pipe rule out many
possibilities. Rounded breccia fragments associated with corrosive or
solution brecciation do not occur. Features of passive collapse such
as irregular breccia outcrop and platy breccia clasts are not present
either. Only a single brecciation event is recorded in drill core and outcrop discounting theories involving successive fracturing and crystallization. A combination of processes best accounts for brecciation at Slate Creek. Explosive brecciation would generate the generally sharp contacts, the pipelike shape, and the random mixing and equidimensional shape of the clasts. The intimate relationship between breccia and quartz-eye porphyry matrix and dikes clearly shows that intrusive processes were also involved, particularly in the lower portions of the pipe. The interpreted intrusive-explosive combination is in agreement with conclusions drawn by White and others (1981) concerning breccias associated with Climax-type molybdenum deposits.
The Slate Creek breccia pipe formed as the result of late Oligocene granitic igneous activity. Primary mineralization in the breccia is of a base-metal sulfide assemblage, but Climax-type molybdenum mineralization is spatially associated with the pipe. Additionally, Climax-type mineralization is manifest as quartz-molybdenum veins present as clasts in the breccia. The following list summarizes the geochronology of host rock emplacement, brecciation, alteration, and mineralization.

1. Deposition of a late Cretaceous - early Tertiary sedimentary and volcanic pile in the Methow Graben.
2. Intrusion of diorite porphyry dikes prior to approximately 48 m.y. ago.
3a. Intrusion and crystallization of crenulated quartz (24 ± 0.6 my) and quartz-eye rhyolite. Biotite hornfels alteration occurred at or before this time.
3b. Emplacement of barren quartz veins.
3c. Formation of quartz-magnetite alteration zone and emplacement of quartz-molybdenite veins.
4a. Brecciation contemporaneous with quartz-eye porphyry emplacement or during post-emplacement adjustment, with possible venting.
4b. Phyllic alteration and base-metal sulfide mineralization centered on the Slate Creek breccia pipe (25 ± 0.7 my).

The Slate Creek breccia is an explosion-intrusion pipe. The pipe is oval, with dimensions of 200 by 260 meters, extending downward for at least 360 meters and dipping steeply to the south or southwest. The mineralized and altered pipe has a matrix of both rock flour and quartz-eye porphyry. Clasts are as large as 2 to 3 meters, but the most common size is 2 to 6 centimeters.

The breccia pipe is the upper level expression of a granite molybdenum system, a conclusion based on comparisons of the Slate Creek breccia and surrounding rocks with other molybdenum prospects and deposits. The Redwell Basin prospect in Colorado has a base-metal sulfide mineralized breccia pipe that is especially similar to the Slate Creek breccia. Other supporting evidence includes:

1. Granitic rock association.
2. Possible genetic tie with a garnet tuff.
3. Fluid inclusion data.

Certainly many other interesting studies are possible at the Slate Creek breccia. Further drilling clearly provides a means to validate the conclusions drawn in this thesis and uncover mineralization, but it will also supply information applicable to some exploration questions. Answers concerning the nesting of molybdenum deposits and the relation between tuffs, breccias, and intrusives are examples of the application of information from additional drilling.
APPENDIX A

COMPUTER APPLICATIONS

The commercial and in-house software used to generate the element zoning and magnetometer survey maps are proprietary. However, an explanation of the concepts applied in this work provides a means of assessing the validity of the plots produced.

Data from the two drill holes, the surface sample grid, and the magnetometer survey were entered and verified using an in-house data management program. The program provides a standard format consisting of identification number, east-west north-south location and elevation, followed by the data obtained for each location. Initially, these data were reviewed using programs from BMDP Statistical Software, UCLA Los Angeles, California. The BMDP program provides information on arithmetic and logarithmic distribution of data. The mean, median, and standard deviation are also calculated.

Data were contoured using software from CPS-1, Radian Corporation, Austin, Texas. The CPS-1 contouring package takes the raw data and uses it to assign values to an arbitrary grid plane. The arbitrary grid is then contoured. Contouring differs depending on how values are assigned to the arbitrary grid. Several different methods of assigning values to grid nodes are available, but of these, only kriging is capable of handling three-dimensional data.
To use combined surface and drill hole data to produce cross-sections, the kriging routine is necessary. In the kriging process, the user chooses the plane which the arbitrary grid will occupy. Grid values are then assigned according to actual values of $3$ to $10$ surrounding sample points. To obtain the grid values, these sample values are weighted by a function of distance and direction and then added together such that the summation of the weight function for all sample points always equals one. The function is based on the continuity of mineralization through the entire data set. The following graphs of distance versus mathematical variance are used to model the continuity of mineralization and are referred to as semi-variograms. The mathematical variance is a unitless, complex function of the difference in grade between sample points. Distance versus variance is plotted as x's and the points are modeled by a curve to calculate the three constants' range, sill, and $C_0$. The three constants from the semi-variogram are applied to the weighting function and used in kriging. Semi-variograms produced for the magnetometer data and for the combined surface and drill hole copper, molybdenum, lead, zinc, tungsten, and fluorine assays are shown in the following figures (Figures 21-27).

The surface data set of sixty sample points was too small to be used in computing a semi-variogram, so the kriging process could not be used. Instead, the data were reduced to two dimensions for use in contouring. The arbitrary grid plane is then equivalent to the sample plane. Grid values were assigned using a "piecewise linear
least-squares" fit applied to sample points surrounding the node. Sample points are weighted according to a standard exponential distance function. Three references for further information on the subject of geostatistics (David, 1977, Journel and Huijbregts, 1978, Knudsen and Kim, 1978) are included in the reference list.
ALL SURFACE SAMPLES PLUS DRILLHOLE DATA. NATURAL LOG OF COPPER DIRECT SEMI-VARIOGRAM
ANG FROM E = 0.00 DIP = 0.00 WINDOW = 180.00 DISTANCE = 700.00

VARIANCE = 0.73

MOMENT CENTER
6.678E-1
5.009E-1
3.339E-1
1.670E-1

SILL = 0.73
RANGE = 1300.00
CZERO = 0.26

DISTANCE
1.400E+2
9.00E+2
4.200E+2
5.600E+2

Figure 25. Semi-varioagram for combined surface and drill hole copper data.
ALL SURFACE SAMPLES PLUS DRILLHOLE DATA. NATURAL LOG OF MOLYBDENUM DIRECT SEMI-VARIOGRAM

ANG FROM E = 0.00 DIP = 0.00 WINDOW = 180.00 DISTANCE = 400.00

VARIANCE = 1.57

SILL = 1.57
RANGE = 475.00
CZERO = 0.16

DISTANCE

Figure 26. Semi-variogram for combined surface and drill hole molybdenum data.
Figure 27. Semi-variogram for combined surface and drill hole lead data.
Figure 28. Semi-variogram for combined surface and drill hole zinc data.
ALL SURFACE SAMPLES PLUS DRILLHOLE DATA. NATURAL LOG OF TUNGSTEN
DIRECT SEMI-VARIOGRAM
ANG FROM E = 0.00  DIP = 0.00  WINDOW = 180.00  DISTANCE = 400.00

VARIANCE = 1.20

SILL = 1.20
RANGE = 450.00
CZERO = 0.26

Figure 29. Semi-varioagram for combined surface and drill hole tungsten data.
Figure 30. Semi-variogram for combined surface and drill hole fluorine data.
Figure 31. Semi-variogram for surface magnetometer data.
LIST OF REFERENCES


Engels, J. C., 1976, Isotopic and fission track ages, Washington: USGS miscellaneous field studies MF-710, 2 sheets.


References - continued


References - continued


References - continued


FIGURE 3. SURFACE AND CROSS-SECTION GEOLOGIC MAP OF THE SLATE CREEK BRECCIA PIPE.
Figure 8. A geologic overlay of the plan maps of Figures 7, and 11-16, Slate Creek breccia area, Whatcom County, Washington.
Figure 17. A geologic overlay of the cross-sections of Figures 18-23, Slate Creek breccia area, Whatcom County, Washington.