GEOLOGY OF THE MOONLIGHT VALLEY PORPHYRY COPPER DEPOSIT, LIGHTS CREEK, PLUMAS COUNTY, CALIFORNIA

thesis submitted in partial fulfillment of the requirements for a Master of Science degree

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ABSTRACT

The Moonlight Valley porphyry copper deposit contains 250 million tons of 35% copper and minor but important gold and silver, occurring within a cupola-like body adjacent to the quartz monzonitic Lights Creek stock. The principal ore mineral is chalcopyrite, but most ore zones are coincident with the presence of bornite and/or primary chalcopyrite. The sulfides are zoned from chalcocite-bearing cores outward to pyrite-bearing fringes. Pyrite is subordinate in quantity and extent of occurrence as compared to magnetite, indicating a low sulfur system. Potassic, sericitic, and propylitic alteration types are present, but are low in intensity and are telescoped over the same rock volume rather than being cylindrically arranged. The style of mineralization and alteration indicate that the deposit is more magmatic than hydrothermal in nature.

The nature of the mineralization in Moonlight Valley, and the Lights Creek area as a whole, compares to mineralization in widely distributed areas throughout the world that are directly related to island arc magmatism and genesis. Because of the location within a Jurassic island arc terrain, and the existence of other known Jurassic deposits in this same terrain (e.g., Yerington), the Moonlight Valley deposit is considered to be Jurassic in age. It is not considered to be directly related to the adjacent Cretaceous Sierra Nevada batholith.
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INTRODUCTION

The Moonlight Valley porphyry-type copper deposit is located in the Lights Creek stock in Plumas County, California, about twelve miles north of the town of Taylorsville (see Figure 1). The area has in the past produced copper from the old Engels and Superior Mines, which are at the northern end of what has been referred to as the "Plumas Copper Belt" (Smith, 1970). Current interest has turned from these previously developed areas of high grade mineralization to areas of related but lower grade mineralization. These areas of current interest include the Moonlight Valley and Superior deposits; the Moonlight Valley area is newly discovered while the Superior deposit consists of low grade mineralization associated with the previously mined high grade mineralization.

Vegetation and Climate

The 3800' to 7500' above sea level elevation range in the Lights Creek area, together with approximately 25 inches per year of precipitation, makes the area indigenous for vegetation characteristic of the Transition and Canadian life zones. The lower elevation Transition zone is characterized by yellow pine, sugar pine, Douglas fir, white fir, incense cedar, and black oak. The higher elevation Canadian zone is characterized by lodgepole pine, Jeffrey pine, and red fir. The vegetation in general prospers in...
Figure 1. Location map showing the Lights Creek area (Plate 1) of Plumas County, California. (after Smith, 1970)
moderately developed soils; thus bedrock exposure is often poor.

Most precipitation occurs in the form of winter snow. The upper elevations tend to be covered with snow continuously for most of the winter, while the lower elevations tend to have intermittent winter snow.

The general appearance of the area can be seen in Figures 2 and 3.

Mining History

Probably the first mineral exploration in the Lights Creek area occurred during the early 1850's as a result of the original California gold rush. Some placer gold was removed from the streams of the area and Tertiary auriferous gravels in the Moonlight vicinity were mined sporadically during the period 1887 to 1907 (Diller, 1908).

While there was minor copper development elsewhere in Plumas County before 1900, interest in the Lights Creek vicinity first began in 1901 with incorporation of the Engels Copper Mining Company, whose principal undertaking was the development and exploitation of properties along Lights Creek. Mine development activity began immediately, but it was not until the construction of milling facilities in 1915 that actual production began. From 1915 to 1930, at which time the facilities were shut down due to low copper prices, the Engels and Superior Mines together produced 160 million pounds of copper from 4.7 million tons of ore.
Figure 2. View looking west to Moonlight Peak from Moonlight Valley.

Figure 3. View of the old Engels mill along Lights Creek Canyon. Mill is adjacent to the old Engelmine townsite.
for an average grade of about 1.70% Cu.

In 1922 the California Copper Corporation was formed to acquire and hold shares of Engels Copper Mining Company. These two companies then merged in 1936 to form the California-Engels Mining Company, which still owns 8 unpatented and 36 patented claims. Also controlled by the Engels Copper Mining Company was the subsidiary Indian Valley Railroad, formed in 1916. The rail ran from the Engelminte townsite (now abandoned, population then about 3000) to Paxton, on the Feather River, where it joined the Western Pacific Railroad. The railroad has since been disbanded. (Norman A. Lamb, Vice President, California-Engels Mining Company, per. com., 1979)

Interest in the Lights Creek area waned until 1962, when, as a result of sampling in the old Superior Mine workings, American Exploration and Mining Company (now Placer Amex, Inc.) decided that they were probably working with a porphyry type system. Subsequent drilling of anomalies determined by stream sediment and soil sampling led to the discovery of the Moonlight Valley deposit in August, 1966. In the late 1960's the deposit was probably a viable mining project and was extensively drilled, but with the deteriorating economic conditions surrounding the copper industry in the 1970's, the deposit is at present merely being held until economic conditions again improve. Most mineral property in the Lights Creek area is now controlled by Placer Amex, Inc., either by claim or sub-lease of prop-
property owned by California-Engels Mining Company. (L. O. Storey, Placer Amex, Inc., per. com., 1979)

Previous Literature

While Diller (1892) and Hyatt (1892) did early geologic work in the Taylorsville area, the first published literature on the general geology inclusive of the Lights Creek area was produced in 1908 by Diller. At the time there was only minor interest in the copper mineralization in the Lights Creek area. The first literature pertaining to the Engels Mine was published in 1914 by Turner and Rogers, and was chiefly a microscopic study of the ores and the wall rock. This first description ignited a minor controversy in the literature pertaining to the magmatic versus hydrothermal/pneumatolytic origin of the chalcocite-bearing bornite ores, and also brought into focus the neighboring Superior Mine. Papers in this published debate include Head (1915), Tolman and Rogers (1916), Graton and McLaughlin (1917), Tolman (1917), and Graton and McLaughlin (1918).

The first publication dealing with geology beyond the scope of just the sites of ore deposition in the Engels Mine is Knopf and Anderson (1930), followed closely by a somewhat repetitive publication by Anderson (1931) that dealt more with the ores of the Superior Mine. A subsequent paper by Knopf (1933) dealt with the Lights Creek area as it relates to the "Plumas Copper Belt."

Since the closure of the Engels and Superior Mines, no
literature has been published on the ores of these mines. However, Crickmay (1933) and McMath (1966) produced important papers dealing with the stratigraphy and structure of the Taylorsville area.

Smith (1970) and Putman (1972, 1975) later published papers dealing at least in part with trace element distribution in the Lights Creek stock. Putman (1975) and Storey (1978) are the only works that recognize the recently discovered Moonlight Valley porphyry type deposit. Storey (1978) is the only publication to date that deals directly with the Moonlight Valley deposit and gives any genetic interpretations.

Scope of Present Study

Within the Lights Creek area there is a very large range of problems that could be studied. The general area of interest encompasses approximately 30 square miles and contains such a complexity of intrusives, pre-intrusive rock section, post-intrusive rock section, and mineralization that it is necessary to limit the scope of this study.

Placer Amex, Inc., drilled and then made available over 200,000 feet of core from several areas of mineralization in the Lights Creek area. It was decided to take advantage of the core availability and provide a detailed examination of the Moonlight Valley mineralization and to show its relationship to the geologic framework of the Lights Creek area as a principal objective of this thesis.
The Moonlight Valley deposit and Lights Creek area in general will then be compared and contrasted with other porphyry copper occurrences throughout the world to show the nature of the Moonlight Valley deposit in a perspective that could be applicable to exploration for other deposits of a similar nature.

REGIONAL GEOLOGIC SETTING

The Lights Creek stock and associated intrusives are located within a sequence of Jurassic volcanic-sedimentary rocks, immediately adjacent to the Sierra Nevada batholith to the east. These and other pre-Cenozoic rocks of the Sierra Nevada geological province are located just south of the edge of the extensive Tertiary volcanic cover of the Cascade and Modoc Plateau geological provinces. The area of Honey Lake, just east of the batholithic rocks, is considered an extension of the Great Basin structural-geological province, with probable structural relationships to the Walker Lane zone of right lateral movement. (See Figure 4)

As described by McMath (1966), there are four informal sequences of lithologies in the Taylorsville area. The oldest is a sequence of slates (phyllites), cherts, and sandstones, with minor limestones and felsitic tuffs contained in the Silurian Taylorsville Formation and the Carboniferous Shoo Fly Formation. These are directly correlative with the Calaveras Formation of central Califor-
Figure 4. Map of northern California showing the locations of the various geological provinces. (From Bailey, ed., 1966)
nia and are interpreted by McMath (1966), to represent a
miogeoclinal continental shelf or slope environment, though
a eugeoclinal environment might be arguable by his descrip-
tion.

Unconformably overlying these is the pyroclastic
sequence. These rocks are a volcanic succession of dacite,
andesite, latite, basalt or andesite, and dacite or sili-
ceous andesite. They are included in the Grizzly, Sierra
Buttes, Taylor, Peale, Arlington, Goodhue, Reeve, and
Robinson Formations. These formations are considered to
range in age from Mississippian to Permian. (McMath, 1966)

The third, or Triassic, sequence consists of only two
formations: the Hosselkus Limestone and the Swearinger
Formation. The Hosselkus is composed of limestone and calc-
arenite; the Swearinger of black hornfels, argillaceous
limestone, and quartz sandstone. This sequence lies uncon-
formably upon the pyroclastic sequence. The upper boundary
is not exposed, but it is probably unconformable with the
younger Jurassic sequence.

The Jurassic sequence is the only of these four
sequences exposed in the Lights Creek area, where it con-
sists of fourteen formations that total over 13,000 feet
in stratigraphic thickness. They, in general, consist of
various andesitic to dacitic volcanic flows, pyroclastics,
and intercalated clastic sediments including shales, mud-
stones, and volcaniclastic conglomerates and graywacke
sandstones. These formations are Early to early Late
Jurassic in age and have generally been metamorphosed to the
greenschist facies.

Following the deposition of these four sequences there
was a period of compressional activity during the inception
of the Nevadan orogeny that produced overthrusting and
folding in the Taylorsville area. This was closely followed
by Cretaceous batholithic plutonism of the Sierra Nevada.

GEOLOGY OF THE LIGHTS CREEK AREA

In the Lights Creek area there are three major time-
rock categories. These include (1) the Jurassic volcanic-
sedimentary sequence, (2) plutonic rocks of Jurassic (?) and
Cretaceous age, and (3) post-plutonic (Tertiary) sediments
and volcanics. Of these, the plutonic rocks are here given
the most attention since they host the ores. Others are
described in more general terms.

Jurassic Sequence

Rocks of this sequence consist primarily of andesitic
to dacitic pyroclastics with lesser flows and various inter-
calated clastic sediments. Best exposure of these rocks
in the area mapped is in the upper prism of the road along
Moonlight Creek (southwestern portion of Plate 1).

While Diller (1908), Smith (1970), and Storey (1978)
made some lithologic distinctions, the rocks are here not
broken down into units and mapped, though differing lith-
ologies were noted. The most abundant rock types consist of various volcanic agglomerates, breccias, and tuff-breccias. These are highly variable in nature, with clasts ranging from very angular to well rounded, from less than one centimeter to slightly less than one meter in size, from dacitic to andesitic in composition, and with matrix percent ranging from near zero to almost 75. Some flows are present that range from dacitic to andesitic in composition, but these are subordinate in quantity to the pyroclastics.

Clastic marine (?) sediments are found chiefly in one distinct area along Moonlight Creek near its juncture with Lights Creek (Plate 1). The chief lithology is a poorly sorted volcanioclastic graywacke sandstone that locally contains zones of graded bedding, conglomerate, and tuffaceous material. Also present are significant quantities of reddish hued silty shales or mudstones that grade into the sandstones. In fact, the general character of most of the sediments includes a reddish coloration, probably indicating oxidizing conditions of deposition. These beds generally strike northwest and dip gently to the southwest, with graded bedding indicating that the beds have not been overturned. In mapping the perimeter of the Lights Creek stock, sediments were generally not encountered except along Moonlight Creek. No fossils were found.

Definite correlation of these Jurassic lithologies to known formations as described by Crickmay (1933) and McMath (1966) was not made. A general column consisting of por-
phyritic andesitic breccias with minor graywacke at the base, the succession of reddish hued clastic sediments in the middle, and an upper unit of chiefly volcanic agglomerates was noted along Moonlight Creek, but these do not exactly correlate to previously described formations in the Taylorsville area. The best correlations seem to be with the sequence of Northridge Formation, Foreman Formation, and Cooks Canyon Formation. These correlations are tentative and not representative for the entire Lights Creek area.

Though previously referred to in the literature as Jurassic-Trassic in age, the pre-plutonic section of the Lights Creek area is here designated as Jurassic. The character of Triassic rocks in the Taylorsville area is decidedly non-volcanic, as it is on the North Fork American River where Late Triassic (?) limestones are overlain unconformably by the Lower Jurassic Sailor Canyon Formation containing basal andesitic tuffs with overlying siltstones, graywackes and conglomerates (Clark, et al., 1962). This lithologic difference between Jurassic and Triassic rocks has also been noted by Schweickert and Cowan (1975).

Two Jurassic terrains have been recognized by Schweickert and Cowan (1975), Kemp and Garcia (1976), Schweickert (1978), and others. These both generally trend north-by-northwest and are divided into the eastern and western belts, of which the Taylorsville-Lights Creek area belongs to the eastern belt. The rocks of the Taylorsville area
have been correlated by Rogers, et al., (1974), Schweickert and Cowan (1975), and Schweickert (1978) with rocks of the North Fork American River, the Peavine Sequence west of Reno, Jurassic rocks of the Carson City, Nevada, area, Jurassic rocks of the Pine Nut Range, Nevada, and Jurassic rocks in pendants in the eastern side of the southern portion of the Sierra Nevada batholith. As seen in Figure 5, these rocks delineate a zone that crosses the Sierras obliquely from northwest to southeast.

The high fragmental content and the nature of the intercalated sediments of the volcanic rocks of this Jurassic terrain fit the criteria of Garcia (1978) that establish it as a volcanic island arc in origin.

In the Lights Creek vicinity, all of the Jurassic sequence has been regionally metamorphosed at least to the greenschist facies. In the area between the Lights Creek stock and the Engels gabbro-quartz diorite metamorphism has achieved the pyroxene hornfels facies.

Mesozoic Plutonic Rocks

Within the Lights Creek area there are four major plutonic units. Three of these are stock-like bodies; the fourth is a part of the Sierra Nevada batholith. The distribution of these units in the Lights Creek area is shown on Plate 1. The exact age and relationship of all these units to each other are not thought to be nearly well enough understood at this time, and shall be discussed more
Figure 5. Map showing the distribution in east-central California and west-central Nevada of Jurassic volcanic-volcaniclastic rocks of the eastern belt of island arc terrain in relationship to the Sierra Nevada batholith. (From Schweickert and Cowan, 1975, and Stewart and Carlson, 1978)
Figure 6. Quartz-alkali feldspar-plagioclase ternary diagram used for plutonic rock classification. (from Bateman, 1977)
Figure 6 gives the plutonic rock classification used in this discussion.

Descriptions of Rock Units

The rocks of these plutonic units have previously been described by Knopf and Anderson (1930) and Anderson (1931). Subsequent works by Smith (1970), Putman (1975), and Storey (1978) examine more closely the quartz monzonite of the Lights Creek stock because of the mineralization which it hosts. These descriptions are here given to provide a clearer perspective of the geologic conditions surrounding the copper mineralization.

Engels gabbro-quartz diorite. This unit of gabbro and quartz diorite was the rock of original interest in the area, being the host of the Engels Mine copper mineralization. These two rock types are intimately associated in the northeast portion of the area mapped and are differentiated on Plate 1.

The gabbro is of variable texture and lithology but is most commonly a hornblende gabbro. Oscillatorily and normally zoned subhedral plagioclase of grain size averaging .75mm constitutes approximately 70% of the rock. The average composition is about An54 (labradorite), though more sodic rims are approximately An36 (andesine). Hornblende comprises approximately 20% of the rock. The hornblende tends to be ophitic with respect to finer, earlier
formed plagioclase. Hornblende grain size averages 2 to 3 mm with plagioclase inclusions averaging .1 mm. Hornblende, with minor biotite and chlorite, forms as alteration of previously formed pyroxene (usually augite) that may constitute a significant proportion of the hornblende crystal, but is generally present only in traces. Accessory minerals include magnetite, sphene, apatite, and sericite. Figure 7 shows a typical example of this rock type in thin section.

Variations in the hand specimen appearance of the gabbro result chiefly from variations in the percent of hornblende in the rock and in size variation of the hornblende crystals. The hornblende percentage may vary up to 5% either way from the average, while crystal size may vary from 1 mm to several centimeters. In some areas the gabbro displays magmatic banding, and thin sections sometimes show sub-parallel alignment of plagioclase crystals.

The quartz diorite is typically a biotite-hornblende quartz diorite containing 65% plagioclase, 10% quartz, 15% hornblende, and 5% biotite with accessory chlorite, sericite, magnetite, apatite, and sphene. The normally zoned plagioclase has an average composition of An44 (andesine) with rims averaging An42. The form is in subhedral crystals averaging 1 mm in length. Quartz fills interstitially to plagioclase. Hornblende, averaging 1 mm in crystal size, at times shows ophitic relationships to finer, earlier formed plagioclase. Pyroxene is rare and apparently most hornblende is primary and not an alteration of pyroxene. While
some biotite forms at the expense of hornblende, some is also primary. Chlorite is found as an alteration product of both biotite and hornblende. A typical example of the quartz diorite in thin section is shown in Figure 8.

The quartz diorite contains some pegmatitic segregations that, as described by Graton and McLaughlin (1917), contain associated copper sulfide minerals. By the descriptions of Graton and McLaughlin (1917), it can be argued that both the pegmatitic minerals and the copper minerals migrated directly from the crystallizing quartz diorite.

As described by Knopf and Anderson (1930) from underground observations, the quartz diorite was definitely later in forming than the gabbro.

**Quartz monzonite of the Lights Creek stock.** This unit, centrally located on Plate 1, is the most important to this study, being the source and host of mineralization in both the Moonlight Valley and Superior deposits as shall be discussed later. Hand specimens from all areas of the stock generally have a very similar appearance, being fine grained, equigranular, and pinkish to salmon in color. Microscopic examination of thin sections does, however, reveal both textural and mineralogical variations within the stock.

While Storey (1978) shows a lithologic division of the stock derived by plotting and then contouring variations in the potassium feldspar/plagioclase ratios, there are textural variations present which could also be contoured.
Figure 7. Photomicrograph of a typical ophitic Engels gabbro thin section. p=plagioclase, h=hornblende, b=biotite, (Nicols crossed)

Figure 8. Photomicrograph of a typical Engels quartz diorite thin section. p=plagioclase, h=hornblende, b=biotite, q=quartz (Nicols crossed)
Neither compositional nor textural variations, however, can be readily mapped in the field.

Three main textural variations are recognized here that are found in the stock. The first shall be referred to as the "quartz latite" type (Putman, 1975), the second as the "semi-perthitic" type, and the third as the "semi-graphic" type. The "semi-graphic" type is best developed in areas of mineralization.

The "quartz latite" (Figure 9) is the one variety of quartz monzonite that is recognizable in the field, and is shown in the southeast portion of the stock on Plate 1. This rock type was previously recognized by Putman (1975) and is interpreted as a chilled margin of the stock, though it is not located peripherally to the entire stock. The rock is composed of 20 to 25% subhedral, unzoned plagioclase (An\textsuperscript{n3}3, andesine) with an average grain size of .75mm in a very finely intergrown (less than .05mm) matrix of quartz, potassium feldspar, and plagioclase(?). Sericite and minor chlorite highly alter most plagioclase, especially in the cores, and are present as matrix material. Chlorite also forms .3mm to 1.0mm crystals that are probably the result of the alteration of earlier formed biotite, which is still present as shreds, or of hornblende. Chlorite is also associated with 1.5mm wide clots of randomly oriented .3mm plagioclase crystals. Calcite may be present in minor amounts with chlorite. Of interest is the presence of .2mm garnet crystals in the matrix of some of the rock. Mag-
netite and rare sphene are accessory minerals.

The "semi-perthitic" quartz monzonite variety (Figure 10) is characterized by the presence of very fine intergrowths of feldspars that are here termed "semi-perthite," in reference to the appearance that perthitic exsolving began to develop, but for some reason did not fully develop. The mineral is petrographically difficult to distinguish and may also be possibly referred to as cryptoperthite. Some perthite is also present. One millimeter semi-perthite and potassium feldspar crystals compose 40 to 70% of the rock and are often intergrown with quartz (25 to 35% of the rock) in very vague graphic intergrowths that may be slightly dendritic in form. Plagioclase is usually present in quantities of less than 10%. More mafic minerals are present in this quartz monzonite variety than in the others and include actinolitic hornblende, hornblende, biotite, and chlorite in combined quantities of less than 15% of the rock. The actinolitic hornblende and biotite are usually shredded in appearance and at least partially altered to chlorite. Tourmaline in 0.2 to 3.0 mm radiating "suns" is relatively abundant. Other minerals present in varying quantities include sphene, magnetite, apatite, zircon, epidote, and sericite. The mineralogy and textures of this variety can in places be seen to be transitional with those of the "semi-graphic" variety.

The third and most important variety, "semi-graphic," is typified by microphenocrysts of plagioclase within a
Figure 9. Photomicrograph of a typical thin section of "quartz latite". Sericitically altered plagioclase microphenocrysts are within a very fine quartz, potassium feldspar, and sericite matrix. Also present are chlorite and tourmaline. (Nicols crossed)

Figure 10. Photomicrograph of well developed "semi-perthite" variety of quartz monzonite. Present are perthite, "semi-perthite", quartz, and tourmaline. (Nicols crossed)
matrix of finer plagioclase and semi-graphically intergrown potassium feldspar and quartz. The 1 to 2mm, subhedral, unzoned plagioclase microphenocrysts are An<sub>36</sub> (andesine) in average composition. The microphenocrysts are commonly observed in "clots" of several crystals, forming an aggregate of up to 3mm across. The clots are readily distinguishable in hand specimen and are shown in Figure 11 and 12. Finer (0.2 to 0.5mm) groundmass plagioclase is usually subhedral, but occasionally euhedral, and of An<sub>28</sub> (oligoclase) composition. Plagioclase microphenocrysts are sometimes partially resorbed and then filled by quartz to leave a patchwork of plagioclase remaining.

Potassium feldspar in the semi-graphic phase (orthoclase) is present as cloudy pink colored crystals ranging from 0.1 to 0.4mm in size. The feldspar is found bordering and to varying degrees filling resorbed plagioclase, and within quartz. Potassium feldspar that borders plagioclase projects out euhedrally into quartz, and that within quartz is often in euhedral laths except where there is a mutual boundary between two potassium feldspar crystals (see Figures 13 and 14). The quartz, non-undulatory in nature and containing abundant bubble-bearing fluid inclusions, surrounds plagioclase and potassium feldspar and extends out up to 3mm around included feldspars in an almost poikilitic relationship. The textural relationship between quartz and potassium feldspar is usually verging on graphic (semi-graphic); however, in some small (1 to 3cm) zones and as
.25 to 1cm envelopes around some veinlets the texture is graphic, sometimes in a dendritic arrangement. The feldspar-quartz relationships can be observed in Figures 15 and 16, with the true graphic texture in Figures 17 and 18.

Tourmaline (schorlite) is a common component of this rock variety. It occurs as 0.5mm to 1cm radiating clusters ("suns") that form either totally within earlier formed plagioclase, associated with zones or veinlets of late forming quartz, or interstitial to rock forming plagioclase, potassium feldspar, and quartz (see Figures 19 and 20). In some areas chlorite is relatively abundant and occurs in association with earlier plagioclase and biotite, though biotite is rarely seen. Chlorite does occur in veinlets, but usually, in direct association with magnetite, it forms interstitially to and at the expense of plagioclase in "clots" (see Figures 21 and 22). Sericite is usually present in varying quantities and occurs as mild to intense alteration of plagioclase (only rarely of potassium feldspar), as interstitial filling to quartz-potassium feldspar, in veinlets with quartz, and in the same areas typical of chlorite but in the absence of chlorite. Calcite is often abundant and occurs in areas and veinlets in association with chlorite, sericite, tourmaline, and quartz. Epidote, rarely found in veinlets, is at times found as very fine grains within plagioclase.

Accessory minerals include sphene, zircon, and magnetite. The magnetite includes varying amounts and/or
Figure 11. Photomicrograph of a portion of a plagioclase "clot" with randomly oriented plagioclase (p) crystals. Also present are tourmaline (t) and sericite (s) interstitial to the clot, and quartz (q) and potassium feldspar (k). (Nicols crossed)

Figure 12. Same as Figure 11, in plane polarized light.
Figure 13. Photomicrograph showing potassium feldspar (k) and quartz (q) filling the edges of a slightly resorbed, isolated plagioclase (p) crystal that is moderately altered to sericite. Some potassium feldspar projects euhedrally into quartz. (Nicols crossed)

Figure 14. Same as Figure 13, in plane polarized light. Note distinct cloudy appearance of potassium feldspar.
feldspar (k) in a nearly poikilitic relationship with quartz (q). There is also minor quartz filling resorbed potassium feldspar. Interstitial tourmaline (t) is present with sericite. (Nicols crossed)

Figure 15. Photomicrograph showing euhedral potassium feldspar (k) in a nearly poikilitic relationship with quartz (q). There is also minor quartz filling resorbed potassium feldspar. Interstitial tourmaline (t) is present with sericite. (Nicols crossed)

Figure 16. Same as Figure 15, in plane polarized light.
Feldspar in a dendritic form. Also present are tourmaline(t) and sericite(s). (Nicols crossed)

Figure 17. Photomicrograph of graphic quartz-potassium feldspar in a dendritic form. Also present are tourmaline(t) and sericite(s). (Nicols crossed)

Figure 18. Same as Figure 17, in plane polarized light.
Other tourmaline associations can be seen in Figures 11, 12, and 15-18. Also note sericite altering the core of the plagioclase. (Nicols crossed)

Figure 19. Photomicrograph of tourmaline(t) forming at the expense of an isolated plagioclase crystal. Other tourmaline associations can be seen in Figures 11, 12, and 15-18. Also note sericite altering the core of the plagioclase. (Nicols crossed)

Figure 20. Same as Figure 19, in plane polarized light.
Figure 21. Photomicrograph showing chlorite (c) and magnetite (m) in the interstices of a plagioclase clot. Pyrite and sometimes chalcopyrite may at times be located in this association. (Nicols crossed)

Figure 22. Same as Figure 21, in plane polarized light.
intergrowths of ilmenite, titanomagnetite, hematite, and leucoxene altering from these. Associated ore minerals shall be discussed later. All described textures for "semigraphic" rocks are best developed in areas containing copper mineralization.

All quartz monzonite varieties discussed above grade into one another, and in addition to the textural variations, may range compositionally from granite to granodiorite. For any described texture the ratio of plagioclase to potassium feldspar may vary significantly.

Another unit found within the Lights Creek stock is represented as Jdi on Plate 1. This hornblende diorite is found as small bodies that are interpreted to be autoliths that formed early in the magmatic event responsible for the quartz monzonite stock.

*China Gulch granodiorite.* This unit has variously been referred to as alaskite, granite, and granodiorite by previous workers, but is most correctly termed a biotite granodiorite (Figure 23). This unit is readily identifiable in the field as a generally light colored rock bearing 5 to 10% biotite, and is shown in the southwestern portion of Plate 1. This unit also has two very closely associated pegmatite-aplite units shown as Kpa on Plate 1.

The bulk of the rock is composed of 40% plagioclase, 25% quartz, and 20% microcline, all in crystals ranging up to 1.5mm in size. Plagioclase is euhedral to subhedral in form with both oscillatory and normal compositional
Figure 23. Photomicrograph of a typical thin section of China Gulch granodiorite. Present are quartz (q), microcline(f), and plagioclase(p). Sericite alters the cores of plagioclase. (Nicols crossed)

Figure 24. Photomicrograph of a typical thin section of Sierran granodiorite. Present are plagioclase (p), microcline(f), quartz(q), biotite(b), and hornblende(h). (Nicols crossed)
zoning that gives an An$_{28}$ (oligoclase) core and an An$_{23}$ (oligoclase) rim. The plagioclase tends to be altered to sericite at the core and sometimes has myrmekite formed on the rims. Microcline and quartz are both found anhedrally, with the quartz forming later than both the plagioclase and the microcline. One millimeter biotite is found evenly distributed throughout the rock. The biotite is somewhat altered to chlorite and is sometimes shredded in appearance. Sphene occurs as an accessory mineral. As discussed later, this unit is considered to be a portion of the Cretaceous Sierra Nevada batholith.

Undivided granodiorite of the Sierra Nevada batholith.

Along the eastern margin of the Lights Creek area is the western edge of the Sierra Nevada batholith (Kgd on Plate 1). Though consisting of multiple intrusive lithologies, the most commonly occurring rock is a medium grained, non-porphyritic hornblende-biotite granodiorite often considered typical of batholithic granodiorites. The rock composition averages 30 to 50% plagioclase, 20 to 30% potassium feldspar (mostly microcline), 10 to 20% quartz, 10% biotite, and 5% hornblende with accessory apatite, zircon, magnetite, and sphene. The major constituent minerals are generally equigranular in the 1 to 3mm range, though quartz is usually finer. Feldspars are usually subhedral to anhedral, with resorption of the earlier formed minerals by the later forming minerals being apparent. Figure 24 shows a representative specimen of this rock type.
Age Relationships Between Plutonic Rock Units

Anderson (1931) lists the relative ages of the plutonic units from oldest to youngest as follows:

1. Gabbro (Engels)
2. Quartz Diorite (Engels)
3. Quartz Monzonite (Lights Creek stock)
4. Granite (China Gulch)

The granodiorite of the Sierra Nevada batholith was not mentioned. The relationship of the gabbro and the quartz diorite of the Engels Mine was determined from excellent underground exposures and cannot be easily argued. Anderson (1931) claimed dikes of quartz monzonite were observed intruding into the Engels units to establish a younger relationship. This observation was not duplicated here, but owing to the very similar style of mineralization in both, and the more acidic composition of the quartz monzonite, it would follow that the units are related, with the quartz monzonite being younger. Anderson also claimed that dikes of the China Gulch "granite" were observed intruding both the quartz monzonite and the Engels units, but again this observation was not duplicated.

Storey (1978) lists the relative ages of the plutonic units from oldest to youngest as follows:

1. Gabbro (Engels)
2. Quartz Diorite (Engels)
3. Granodiorite (main batholith)
4. Quartz Monzonite (Lights Creek stock)
(5) Granite (China Gulch)

The units are described by Storey (1978) as batholithic differentiates and differ from Anderson's (1931) interpretation only by the insertion of the Sierra Nevadan batholithic granodiorite into the sequence. Evidence for the given age sequence was not given.

On the basis of field work and research accomplished for this thesis the favored interpretation for the sequence of intrusion is as follows:

1. Gabbro (Engels)
2. Quartz Diorite (Engels)
3. Quartz Monzonite (Lights Creek stock)
4. Granodiorite (main batholith)
5. Granodiorite (China Gulch)

The only positive evidence of age relationship observed in the field was the chilled margin of the China Gulch granodiorite being in contact with the batholithic granodiorite, indicating the younger age of the China Gulch granodiorite. The intimate occurrence of the Engels gabbro and quartz diorite would indicate a very close time interval, with the quartz diorite being assumed to have been formed slightly later. The extreme similarity of copper mineralization in the Engels units and in the Lights Creek quartz monzonite would seem to indicate a very close genetic relationship, with the quartz monzonite probably being younger on the basis of composition. If, as stated by Anderson (1931), the China Gulch granodiorite is younger
than the Lights Creek quartz monzonite, the only ambiguity that remains is the age relationship of the batholithic granodiorite to the Engels and Lights Creek units. On the basis of the above given information it could be placed at any relative age older than the China Gulch granodiorite.

The selection of the relative age of the batholithic granodiorite being younger than the Engels and Lights Creek units is based on the assumption that there must have been two periods of magmatic activity in the region: (1) magmatism associated with Jurassic volcanism, and (2) magmatism that was responsible for the creation of the Sierra Nevada batholith that was dated near Honey Lake by Evernden and Kistler (1970) as Cretaceous in age. The interpretation here is that the Engels and Lights Creek plutonic units are subvolcanic intrusives of Jurassic age within a coeval island arc volcanic-volcaniclastic pile; the batholithic granodiorite and related China Gulch granodiorite are later and Cretaceous in age and are related to a different magmatic process (e.g., partial melting vs. anatexis?).

The presence of the Cretaceous batholithic magmatism can be little debated, though some pulses of the Sierra Nevada batholith have been dated as Jurassic by Evernden and Kistler (1970). The designation of a Jurassic age for the gabbro, quartz diorite, and quartz monzonite is based upon the following:

(1) Units of similar composition, size, and distribution, as described by Hietanen (1973, 1976), are Jurassic
in age and are contained within a coeval volcanic-volcaniclastic terrain of island arc origin.

(2) On a world-wide basis, the intrusive rocks that contain copper mineralization of the character of that found within the Engels and Lights Creek units are usually found within coeval volcanic-volcaniclastic piles of island arc origin, and are not directly associated with major batholithic plutonism.

(3) The only mineralization normally considered to be associated with batholithic plutonism is the tungsten skarn type. As discussed by Newberry and Einaudi (1981), tungsten skarns probably form at greater depths and temperatures than do copper skarns and related porphyry deposits. It would therefore be implied that the Lights Creek plutons and mineralization formed under different conditions and at a different time than did the batholithic rocks.

(4) The geochemical relationships discussed below tend to indicate two separate magmatic episodes, though the age relationships are not necessarily indicated by that data.

**Geochemistry of the Plutonic Rock Units**

Smith (1970) listed the results of whole rock geochemical analyses for four samples of Lights Creek quartz monzonite and one sample of the Engels quartz diorite. Three whole rock analyses, one each of the Engels gabbro, Engels quartz diorite, and China Gulch granodiorite, were obtained for the purposes of this study. The above data, together
with data on typical Sierra Nevadan batholithic rocks given by Carmichael, et al. (1974), are included in the Appendix as Tables 1, 2 and 3.

The alkali-iron-magnesium ratios for the Lights Creek plutonic rocks were first plotted on an AFM ternary diagram (Figure 25). All plots fall easily within the field of calc-alkaline magmatism typical of convergent tectonic plate margins. This geochemical trend is prevalent worldwide in plutonic and volcanic rocks of both island arc and batholithic association.

The normative quartz-orthoclase-albite ratios for both the Lights Creek plutonic rocks and the typical Sierra Nevadan batholithic plutons were then plotted on a Q-or-ab ternary diagram (Figure 26). Two distinct fields are apparent and outlined on the diagram. One field is represented by all Lights Creek plutons analysed EXCEPT the China Gulch granodiorite; the other is represented by the Sierra Nevadan batholithic rocks AND the China Gulch granodiorite. The interpretation here is that even though both fields are calc-alkaline by the AFM diagram definition, there is a basic geochemical variation that indicates the probability of separate magmatic events. The Jurassic (?) Lights Creek plutonic sequence (Engels gabbro-quartz diorite, Lights Creek quartz monzonite) represents a shift away from the quartz-orthoclase (SiO2-K) end members and towards the albite (Na) end member as compared to the Cretaceous Sierra Nevadan batholithic rocks that would include the China Gulch
Figure 25. Alkali-iron-magnesium (AFM) ternary diagram containing sample plots for the Lights Creek area rocks. The distribution is typically calc-alkaline. (Sample numbers refer to analyses in Appendix)
Figure 26. Quartz-orthoclase-albite (Q-or-ab) ternary diagram containing sample plots of normative contents for Lights Creek area rocks (x) and typical batholithic rocks (o). Batholithic rocks and the China Gulch granodiorite fall into one field, while all other Lights Creek rocks are in a separate field. (Sample numbers refer to analyses in Appendix)
Another distinction may also be realized by examining the MnO values of all analyses. Typical MnO values for the batholithic rocks AND the China Gulch granodiorite are well below those of the Lights Creek rocks EXCEPT the China Gulch granodiorite.

Tertiary Units

The northwestern area shown on Plate 1 is unconformably overlain by a series of Tertiary sedimentary and volcanic units. The earliest units are sedimentary, followed in time by the deposition of a volcanic unit. All are followed by a later coarse gravel deposition.

The base of the Tertiary section is defined by a reddish-brown, hematitic ochre-bearing unit of uncertain origin that may or may not contain a high percentage of lithic fragments at any given point. The lithic fragments, which may constitute 0 to 70% of the rock, are, in relative order of abundance, volcanic fragments, altered granitic fragments, quartz and crystalline hornblende probably derived from granitic rocks, metallic hematite, and miscellaneous unidentifiable fragments. The fragments are sub-rounded to very angular and range in size from less than 1mm to more than 7cm. The matrix, and sometimes the whole rock, is composed of reddish-brown hematitic ochre that gives the rock its distinctive color that makes it an excellent field marker unit. The thickness ranges from 0 to
approximately 200 feet, but is usually present at a thickness of approximately 40 to 50 feet. The environment of deposition is interpreted as being high energy and highly oxidizing fluvial (?) with a short distance of load transportation.

The basal unit grades conformably upward into a 400 to 500 feet thick unit best termed an arkosic quartz sandstone, though variations occur. The composition is predominantly quartz (60 to 90%) with lesser and varying proportions of mica, feldspar, and other mafics. The clasts are usually sub-rounded to rounded. Though typically a friable medium to coarse sandstone, a conglomerate to siltstone size range is well represented. In some of the siltstone and fine sandstone facies organic material is preserved including thin (5cm) coal seams and well preserved leaf fossils. The unit is given an Eocene age (Lyndon, et al., 1960), which is also the probable age of the underlying basal unit. A typical exposure of this unit is shown in Figure 27.

Overlying the sedimentary units is a dacitic to andesitic volcanic flow that was not extensively studied. This volcanic unit has not been dated more specifically than Tertiary. Another Tertiary volcanic unit, present just south of the Moonlight Valley deposit, is an andesitic to basaltic plug. The exact relationship of this plug to the flows of the area is not known.

The last episode of Tertiary deposition (Pleistocene?) produced rounded to well rounded, unconsolidated gravel and
pebble deposits at scattered locations in the Lights Creek area (see Plate 1). The gravels are found deposited unconformably on most of the previously described units of all ages.

STRUCTURE

Due to poor exposure and the generally irregular outcrop boundaries of most of the rocks dealt with in the Lights Creek area, no detailed structural analyses were attempted. A few minor magnitude faults were recognized and are shown on Plate 1, but considering the large number of shears encountered in drill cores, there are probably a great number of faults present that could not be recognized on the surface. Faults shown on Plate 1 are post-magmatic and probably post-mineral, and some are obviously post-Eocene. Shears containing mineralization within plutonic rocks, not shown on Plate 1, are interpreted to have formed in the very late stages of magmatic crystallization or at a magmatic-hydrothermal boundary.

Within the Jurassic sequence southwest of the Lights Creek stock the dominant rock attitude can be generalized as a northwest strike with a southwest dip, with deviations being commonplace. If post-intrusion tilting has not been significant, this may represent doming and shouldering aside of the country rock during intrusion by the Lights Creek stock, though this cannot be verified on all sides of
Figure 27. A typical exposure of Tertiary arkosic sandstone.
the stock. In addition to this apparent doming, some stopping took place as evidenced by xenoliths of Jurassic volcanics that range in size from a few inches to several hundred feet that occur within the quartz monzonite.

Post Eocene tilting has probably taken place as evidenced by the general N45E, 12NW attitude of the arkosic quartz sandstones. This post-magmatic tilting would be insufficient to account for the attitudes described for the Jurassic section; thus the doming effect described is probably true.

GEOLOGY OF THE MOONLIGHT VALLEY DEPOSIT

The Moonlight Valley porphyry copper deposit is located in an area of subdued topography in the southeastern portion of the Lights Creek stock (Plate 1). Due to the extremely poor exposure, the only means of studying the deposit in any detail is to examine drill core. Drill core was examined from 28 selected holes that provided data for the three cross-sections through the deposit. These drill hole and cross-section locations are shown on Plate 2.

Drill core was logged at the scale of 1" : 10' for lithology, ore mineralogy, alteration mineralogy, gangue mineralogy, style of mineralization (disseminated vs. fracture filling), and structure. Fifty foot composite copper assays were available from Placer Amex, Inc. From this accumulated data, three variables have been interpreted for
each cross-section line: (1) zones of copper grade, (2) ore mineralogical zones, and (3) alteration mineralogical zones. These three aspects of each of the three cross-sections, together with the lithologies present, are given on Plate 3.

The Moonlight Valley deposit contains published reserves of 250 million tons of 0.35% copper (0.20% cutoff). Significant and recoverable amounts of gold and silver are also present. Molybdenum is negligible. (Storey, 1978)

Host Rock

The majority of copper mineralization, and all high grade mineralization, is within "semi-graphic" intrusive rock of granite and quartz monzonite composition in what is almost a small cupola on the west side of the Lights Creek stock (Plate 1). As described earlier, the primary features of this rock include small (1-2mm) plagioclase (oligoclase) microphenocrysts bounded by potassium feldspar and/or quartz. A number of plagioclase crystals may be associated together in clots (Figures 11, 12, 21, 22). The potassium feldspar is finer grained (0.1-.4mm) and often borders portions of earlier formed plagioclase or may occasionally fill resorbed portions of it (Figures 13, 14, 19, 20). Quartz forms in optically continuous, unstrained areas up to 3mm across that enclose potassium feldspar and/or plagioclase crystals. Late forming minerals that include tourmaline, sericite, chlorite, calcite, and magnetite tend to be found as fillings interstitial to the earlier formed minerals, though
Mafic alteration of the earlier minerals is also present. Mafic minerals, excepting chlorite, are rare.

The semi-graphic granite/quartz monzonite that hosts the Moonlight Valley deposit is interpreted here as having crystallized in a very quiet state. The early forming plagioclase crystals were in a quiet state that allowed most to crystallize before crystallization of the other minerals began, and gave an interval of time that permitted freely "floating" crystals to be statically attracted together into the described clots. The quiet state continued as the potassium feldspar began crystallizing evenly and finely as mantles on the plagioclase (with some occasional minor resorption) and as often euhedral crystals within the residual fluid. Quartz then began crystallizing in large anhedral crystals that encompassed both plagioclase and potassium feldspar, with some resorption of the plagioclase. Sometimes potassium feldspar and quartz grew simultaneously in a probably aqueous rich phase to form a true graphic intergrowth (Figures 17, 18). The continued quiet crystallization at the quartz forming stage is evidenced by the totally unstrained appearance of the quartz. As a final stage, late forming tourmaline, sericite, chlorite, and other accessory minerals filled in remaining interstices and to varying degrees altered earlier formed minerals, especially plagioclase. At this latest stage, and to a lesser degree during the quartz-potassium feldspar stage, minor fracturing developed in varying degrees that permitted
migration of later stage minerals to form veinlets. These latest stages of crystallization are technically hydrothermal, though directly related to the magmatic process.

In addition to the granite/quartz monzonite host, some copper mineralization is also present in portions of the Jurassic volcanic section. This mineralization was not studied in detail, but it is assumed that the mineralization would prefer more permeable and receptive lithologies containing pyroclastics rather than flows, as is true in the Ingerbelle deposit of British Columbia (Macauley, 1973). Some mineralization is located at the contact of the granite/quartz monzonite with the Jurassic volcanics.

Sulfide Mineralogy and Zonation

Sulfide mineralogy and the zonational relationships between sulfide minerals were noted in detail and are shown on Plate 3. Minerals encountered include chalcocite, bornite, chalcopyrite, pyrite, tennantite, covellite, and digenite. All but covellite and digenite, both of which are minor components, are represented on the cross-sections of Plate 3.

Inspection of the cross-sections shows a distinct zonational distribution of chalcocite, bornite, chalcopyrite, and pyrite. A generalized description of this distribution depicts a core containing primary chalcocite that grades outward into a zone containing bornite, which in turn grades outward into a chalcopyrite-bearing zone.
The chalcopyrite zone then grades into a pyrite fringe zone. These zones usually overlap adjacent zones, but only rarely does chalcocite coexist with chalcopyrite, or bornite with pyrite. Coexistence of chalcocite with pyrite is extremely rare. Drill holes which show well this zonal distribution include ML-505 on cross-section C-C', ML-378 on A-A', and ML-45 on B-B'. This zoning represents a high Cu/Fe+S core grading out into a low Cu/Fe+S fringe.

The cross-sectional morphology of high grade chalcocite/bornite cores is undulatorily tabular. This crudely tabular body, over most of the area of the cross-sections, is generally striking N10W and dipping 17SW. In the southwest portion of the deposit the body begins to plunge at a much steeper dip. The average thickness of the chalcocite-bornite zone is 300', while the total copper sulfide zone is near 1000'. These thicknesses persist for a strike length of 2600'. In dip length, the body extends from the area of drill holes ML-505 and ML-346 for at least 1800' to the southwest, where the absolute bottom of the mineralization has apparently not been established. The parallel relationship of the ore body to the Jurassic volcanic-quartz monzonite contact to the southwest indicates that the tabular morphology of the ore zone may be related to the former presence of a now-eroded roof to the Moonlight cupola.

There is a very distinct relationship between ore mineralogy and copper grade, as can be noted by observing
the respective cross-sections. As a generalization, zones of greater than 0.30% Cu do not occur without the presence of chalcocite and/or bornite, and zones of less than 0.18% are coincident with the occurrence of pyrite. 0.18% to 0.30% Cu zones generally consist of chalcopyrite, the most abundant copper mineral in the deposit, with variable amounts of pyrite or bornite. The highest grade encountered was 3.00% Cu and was coincident with a high percentage of disseminated chalcocite. (Copper grade zones are derived from 50' composite assays provided by Placer Amex, Inc.)

In logging the core, it was noted that chalcocite, bornite, chalcopyrite, and pyrite all occurred as both disseminations and fracture fillings. Of the fracture fillings, most are microfractures (less than 1mm thick). Disseminated chalcocite, bornite, and often chalcopyrite tend to occur associated with sericite within radiating tourmaline "suns" distributed fairly evenly throughout the rock. Disseminated pyrite and sometimes chalcopyrite tend to occur closely associated with chlorite and magnetite within plagioclase clots.

Microveinlet mineralization generally contains the same minerals that occur in a given zone as disseminations. In some instances very fine microveinlets (less than .5mm) bearing sulfides, usually chalcopyrite, are observed to connect to disseminated sulfides, thus representing indigenous veining. Only in the larger veinlets (1 to 3cm) was there observed to be any radical mixing of sulfide types,
i.e., chalcocite with pyrite.

The preponderance of copper mineralization found as disseminations and apparent indigenous microveinlets, together with a lack of intense alteration (to be discussed), is an indication that the mineralization is magmatic in nature and has migrated little from its original site within the magmatic melt source. Mineralization was simply the last stage of the crystallization sequence that may have involved minor hydrothermal activity at the very end.

Tennantite-bearing zones were identified in drill holes ML-5 (A-A', C-C') and ML-41 (A-A'). The tennantite was always found within fractures in association with quartz and in the macroscopic absence of other copper minerals. The exact nature of the tennantite mineralization as it relates to the other copper mineralization is not understood, for it tends to cut off otherwise correlative copper zones. It is most likely that it represents a slightly later hydrothermal episode that cut and altered or flushed earlier mineralization more magmatic in nature. This later hydrothermal episode, by tennantite mineralogy, would represent a system more enriched in arsenic and probably zinc and silver than would have been present during the more magmatic stages. Storey (1978) suggests that the tennantite may be argentiferous.

The microscopic study of polished sections revealed that all sulfides, including chalcocite, are primary in
nature. No secondary sulfides were positively identified. The primary nature of all chalcocite is revealed by the presence of classic exsolution and granophyric intergrowths with included bornite (see Figure 28). This texture is present even in zones that might be expected to be coincident with supergene sulfide formation. All chalcocite logged was of the steely variety, and not sooty. This texture is considered magmatic and not hydrothermal in origin (Bastin, 1950).

The more copper rich minerals tended to form later than the iron rich minerals. Chalcopyrite surrounds euhedral pyrite crystals and fills fractures within it, indicating the chalcopyrite is later. Chalcopyrite present with chalcocite and/or bornite usually shows evidence of having been replaced by those minerals (Figure 29). Where bornite and chalcocite did not crystallize simultaneously in exsolution intergrowths, the bornite appears to have formed earlier and to have been somewhat replaced by chalcocite (Figure 30). The rare covellite that was observed is very fine and feathers the edges of other copper sulfide minerals, indicating a later time of formation (Figure 31). Probably the latest mineral to form was tennantite. Figure 32 shows minor bornite and chalcopyrite within the tennantite that has apparently undergone some replacement by the tennantite.

The rise in the Cu+As/Fe ratios in later sulfide-forming phases is due to the greater solubilities of copper and arsenic as compared to that of iron. The Cu+Fe/S ratio
Figure 28. Photomicrograph of exsolution textured chalcopyrite (cc) and bornite (b) that can be seen grading into a granophyric texture. Euhedral laths are probably sericite. (Plane polarized reflecting light)

Figure 29. Photomicrograph showing apparent minor replacement of earlier copper poor minerals by later copper rich minerals. chalcopyrite=cp, bornite=b, chalcocite=cc, (Plane polarized reflecting light)
Figure 30. Photomicrograph showing minor replacement of bornite (b) by later forming chalcocite (c) in an area of granophyric texture. (Plane polarized reflecting light)

Figure 31. Photomicrograph showing very minor covellite (cv) associated with disseminated chalcopyrite (cp). Also present is magnetite (m). (Plane polarized reflecting light)
Figure 32. Photomicrograph of a tennantite (tn) microveinlet showing some replacement of bornite (b) and chalcopyrite (cp) by the tennantite. (Plane polarized reflecting light)
of the sulfide minerals tends to increase with time throughout the sulfide-forming phases. This is due to the fact that the available sulfur in this sulfur deficient system is used up earlier in the sulfide-forming phases. The total sulfur deficiency of the system is evidenced by the low content of sulfur in minerals of all phases, from earlier sulfur-lacking magnetite to later sulfur-poor chalcocite.

Alteration Mineralogy and Zonation

Two main silicate alteration types are shown on the cross-sections of Plate 3. These are sericitic and propylitic (chlorite, magnetite, and/or epidote) and usually occur in mutual exclusion of each other. In addition, tourmaline and calcite are alteration minerals, but due to their ubiquity to most of the stock, no zonations are outlined. There do tend to be increases of tourmaline and quartz within the sericitic zones and an increase of calcite in the propylitic zones.

Examination of the cross-sections of Plate 3 shows a high coincidence of sericitic alteration with high grade chalcocite-bornite-chalcopyrite mineralization, and a coincidence of propylitic alteration with low grade chalcopyrite-pyrite mineralization. (Note— the cross-sections indicate pervasivity of alteration only, and not intensity.)

The sericitic zones are typified by the presence of sericite in interstitial rock sites, in veinlets, and as an
alteration of earlier formed plagioclase. It is commonly associated with tourmaline, quartz, and sulfide minerals both interstitially and in veinlets; in these sites the sericite is technically not an alteration mineral because it alters nothing except maybe theorized chlorite. As an alteration mineral it falls far short of the intensity described by Lowell and Guilbert (1970), as typical for porphyry deposits. In the Moonlight Valley deposit, the sericite rarely alters plagioclase 100%. It is found as a 5 to 90% alteration of plagioclase, with the usual percentage range being 20 to 60%. Potassium feldspar has very minor alteration to sericite (less than 5%). A typical Lowell and Guilbert (1970) model sericitic (phyllitic) zone has all plagioclase and all potassium feldspar altered 100% to sericite +/- quartz.

Propylitic minerals, usually chlorite and magnetite +/- epidote, also occur at interstitial sites, in veinlets, and as an alteration of plagioclase, though they are considerably rarer in veinlets than in sericite. Pyrite and sometimes chalcopyrite may be associated with the propylitic minerals. The wider distribution of the propylitic mineral assemblage, the apparent cutting nature of the sericitic zones through the propylitic zones, and the lack of propylitic minerals in veinlets indicate the propylitic assemblage to be slightly earlier in formation than the sericitic assemblage.

Ubiquitous to the Moonlight Valley area, but not to the
entire stock, are abundant potassium feldspar envelopes about veinlets and small (1 to 3 cm) zones identical to the envelopes. Potassium feldspar envelopes are shown in Figures 33 and 34. These are typical of the potassic zones described by Lowell and Guilbert (1970), but are here not considered to be alteration or to occur in a specific zone. Microscopically (Figures 7 and 8) these occurrences are graphic intergrowths of quartz and potassium feldspar with associated tourmaline that are observed to alter or replace nothing. Lowell and Guilbert (1970) interpret the potassic cores of porphyry deposits as being more magmatic in nature than the outer hydrothermal ore shells. The ubiquity of potassium feldspar envelopes to the Moonlight Valley deposit thus gives further impetus to the magmatic interpretation of the deposit. (For the sake of consistency, the potassic envelopes shall still be referred to as an alteration type).

The above alteration occurrences together form an alteration scenario that is not a true zonal arrangement over a given space. It is instead an alteration arrangement superimposed or telescoped over the same space in a sequence of time, and again reflects the more magmatic rather than hydrothermal nature of the deposit. The time sequence includes the early crystallization of a static magma that ends with the formation in an aqueous rich phase of some graphically intergrown quartz/potassium feldspar, evenly distributed throughout the area of the deposit. The still static residual fluids then overprinted propylitic minerals
Figure 33. Photograph showing potassium feldspar envelopes about sulfide and non-sulfide bearing veinlets. Specimens are from Superior Mine dump, but are identical to what is observed in Moonlight Valley core.

Figure 34. Photograph of rocks after yellow staining to emphasize the presence of potassium. Note that potassium feldspar zones are not always associated with visible veinlets. Specimens again from the Superior Mine dump.
with some pyrite and chalcopyrite upon the previously crystallized fraction. As a very last stage the aqueous rich, volatile rich residual portion of the original magma produced sericite, quartz, tourmaline, copper sulfides, etc., that in restricted areas overprinted all previous mineralogies and formed the ore zones. The very last stage was still relatively static, as evidenced by the abundant occurrence of disseminated ore minerals, though small scale fracturing and veinlet forming did occur. The fracturing was probably hydrostatic in nature.

The changing alteration effects with time are directly related to the progressive chemical evolution of the residual fluids of the magma. After the initial crystallization of the main rock forming minerals composed of silica, alumina, calcium, sodium, and potassium, the iron, magnesium, hydroxal, carbonate, and sulfur enriched fluids produced the propylitic alteration effects. The further depleted residual fluid would then be relatively enriched in potassium, sodium, silica, boron, hydroxal, copper, and sulfur, all contained in an aqueous rich phase. This last phase produced the sericitic alteration effects, together with the most important copper mineralization.

Because of the regional greenschist metamorphism, a propylitic alteration halo cannot be used as an exploration guide for the Moonlight Valley area. However, as noted in drill hole ML-15 of cross-section B-B' (Plate 3), there is some tourmalinization of the Jurassic volcanics that could
be used as an exploration guide. This was noted over a considerable area southwest of the Moonlight Valley ore body and is occasionally accompanied by minor copper staining. This aspect of the deposit was not studied in detail.

Supergene Effects

The surface over the Moonlight Valley deposit has been weathered to a depth ranging from 40' to 140', as noted on the cross-sections of Plate 3. This weathering is typified by the only argillic alteration noted, with both kaolinite and montmorillonite altering from most minerals except quartz and sometimes tourmaline. Most copper sulfides are totally oxidized in the weathered zone, except some primary chalcocite which was slightly more stable and persistent in the zone of weathering.

Supergene enrichment is restricted to oxide enrichment and does not include sulfide enrichment. This can be noted on the cross-sections of Plate 3 by the coincidence of noted copper oxide occurrences with slightly higher assay values than might be expected, including some in the Jurassic volcanics. Noted copper oxide minerals include malachite, azurite, and some native copper.

The lack of sulfide enrichment in the Moonlight Valley deposit can be attributed to the following factors:

1. the lack of abundant pyrite for acid formation
2. the lack of fracturing for permeability
3. the lack of intense sericitization for permeability
(4) an apparent lack of Tertiary weathering, to which most supergene enrichment is usually attributed.

The Quaternary age of the weathering is evidenced by unweathered quartz monzonite at the base of the Tertiary section in cross-section A-A'. The Moonlight Valley area seems to have been undergoing erosion and deposition during the Tertiary rather than just simply being weathered.

### Relationships to Other Mineralization

Other mineralized areas that bear relationships to the Moonlight Valley deposit include the Engels Mine, Superior Mine, Sulfide Ridge area, Blue Copper area, and the Ruby Mine. These can all be found located on Plate 1. The Engels Mine is the most remotely related of the above; the others can be considered to be directly related.

The Engels Mine mineralization differs from that related to the Lights Creek stock in the gabbro-quartz diorite host and a higher proportion of mineralization in shears and fractures. The mineralization still reflects a low sulfur system favorable to bornite-chalcocite formation that probably developed as a late magmatic segregation and involved little hydrothermal activity.

The other mineralizations are directly related to the Lights Creek stock. The Superior Mine differs from the Moonlight Valley deposit only in the high proportion of large scale vein development within the zone of disseminated mineralization, and in the presence of very minor sphalerite
and galena. The Sulfide Ridge and Blue Copper areas of very low grade mineralization (Storey, 1978) are almost purely disseminated in nature and have a higher proportion of pyrite and chalcopyrite. The sulfur content is still relatively low, but the copper content is proportionately lower.

The Ruby Mine is not within the stock, but is a small fissure vein in Jurassic graywacke that is directly related to the Lights Creek stock. Dump specimens contained chalcopyrite, bornite, tetrahedrite, tennantite, digenite, enargite, covellite, sphalerite, and arsenopyrite.

Summary of the Moonlight Valley Deposit

The Jurassic(?) Moonlight Valley mineralization is the result of the very end stage of static magmatic crystallization of a quartz monzonitic magma within a coeval volcanic-volcaniclastic pile, and not the result of convective mobilization of metals in the intrusive at depth with hydrothermal deposition at higher levels as described by Henley and McNabb (1978). The non-convective system produced a non-intense alteration assemblage that is temporarily telescoped over the same volume of rock rather than being spatially zoned. The system is low in sulfur and produced a mineral assemblage with primary chalcocite, bornite, and magnetite and a lower proportion of pyrite than described by Lowell and Guilbert (1970) as typical. Indeed, the "dry system" of Guilbert and Lowell (1974) may be in effect here. Positive effects on the deposit by supergene activity
have been almost negligible. The principal value of the deposit is in its primary copper content, with significant quantities of gold and silver, and negligible molybdenum.

MINERALIZATION ANALOGIES

The highly referenced paper by Lowell and Guilbert (1970) has often been considered the standard model or characterization for porphyry copper mineralization. More recently, however, some authors, especially Hollister (1975) and Titley (1975), have recognized that many porphyry copper deposits associated with island arc terrains do not fit exactly into the characterizations of Lowell and Guilbert (1970) to the extent of technically being improperly termed "porphyry copper."

On a world-wide basis, deposits from many areas can be shown to have characteristics that compare well to those of the Lights Creek area and contrast with the model of Lowell and Guilbert. These include deposits from simple oceanic island arcs such as Panama (Kesler, et al., 1977) and the Caribbean area (Kesler, et al., 1975, Cox, 1973, Bradley, 1971) and deposits from island arcs associated with evolving continental margins or mini-continents such as the Southwest Pacific area (Titley, 1975) and the Philippines (Wolfe, 1973). Also included are deposits from ancient island arcs now totally accreted to continental masses such as the western Cordillera of British Columbia (Hollister,
1975, Field, et al., 1974, Dickinson, 1975) or some intra-continental areas of Russia (Smirnov, 1977).

Important general characteristics derived from the literature on the island arc associated deposits that are consistently present include the following:

(1) A country rock consisting of dacitic to andesitic volcanics, including large proportions of pyroclastics, with intercalated clastic sedimentary units. All are of island arc origin and are often regionally metamorphosed to the greenschist facies.

(2) An intrusive rock that is usually quartz diorite or granodiorite in composition and often lacks a porphyritic phase. The intrusives may occur along batholithic trends, but rarely are batholiths themselves. Also, the intrusives are nearly always coeval with the enclosing volcanic-volcaniclastic country rock.

(3) An alteration assemblage that may weakly resemble that described by Lowell and Guilbert, but will more often be a potassic assemblage only, or a telescoped alteration sequence of different varieties over the same rock volume. Also, albitization may be an important alteration process.

(4) An ore suite that consists mostly of chalcopyrite with important bornite and lesser chalcocite and covellite, all being primary minerals. The minerals occur evenly distributed between disseminations and
fracture fillings. Associated pyrite is low in quantity in comparison with magnetite, indicating low sulfur systems.

(5) An important and economic content of gold and silver, with a usually negligible molybdenum content.

(6) A normally unimportant role of local structure on mineralization except possibly for ground preparation for some mineralization in the country rock. Breccia pipes are rare. Regional and continental structures are important in the overall formation of an island arc.

(7) A range in time of formation from Pleistocene to Devonian, and maybe even into the Archean in the case of Timmins, Ontario (Davies and Luhta, 1978).

(8) A consanguinity that includes copper-magnetite skarns and gabbroic associated deposits such as the Tertiary Sooke deposits of Vancouver Island (Carson, 1969), and Volkovskoye deposits of the Russian Urals (Smirnov, 1977).

The above characteristics contrast with the generalizations of Lowell and Guilbert:

(1) A country rock of Pre-Cambrian crystalline rocks or Paleozoic to Mesozoic platform sediments, usually of continental origin.

(2) An intrusive rock that is generally quartz monzonitic in composition and almost always contains
a porphyritic phase. Spatial association with batholithic bodies is rare.

(3) A well zoned cylindrical alteration assemblage grading outward from potassic to phyllic (sericitic) to argillic(?) to propylitic.

(4) An ore suite that consists predominantly of chalcopyrite with lesser molybdenite and almost rare bornite, all usually in a fracture stockwork though disseminations may be locally important. Pyrite is extremely abundant in some zones, comprising up to 10% of the rock, while magnetite is rare. Supergene chalcocite is important.

(5) An omnipresent molybdenum content and sporadic gold and silver values.

(6) An important structural role in the localization of mineralization, especially in the case of breccia pipes.

(7) A range in time of formation from 30 million to 200 million years.

(8) A consanguinity with copper skarns and major lead-zinc vein deposits.

Of these two contrasting generalized characterizations, the Moonlight Valley deposit and the Lights Creek area as a whole compare very well to the characterizations of deposits associated directly with irrefutable magmatic island arcs. In fact, the only possible divergence from the island arc model is the quartz monzonite rather than grano-
diorite to quartz diorite intrusive composition, but there is not a porphyrytic phase involving potassium feldspar phenocrysts. Specific deposits to which the Moonlight Valley deposit favorably compares, excepting age, include Cerro Colorado, Panama (Kesler, et al., 1977), Rio Vivi, Puerto Rico (Kesler, et al., 1975), Panguna, Bougainville (Fountain, 1972), Marcopper, Philippines (Louden, 1972), Mt. Washington, Vancouver Island (Carson, 1969), Valley Copper, British Columbia (Guilbert and Lowell, 1974), and Kal'makyr, U.S.S.R. (Smirnov, 1977).

In the Cordillera of the western United States, the Yerington (Moore, 1969) and MacArthur (Heatwole, 1978) deposits, Nevada, some deposits near the Snake River on the Oregon-Idaho border (Field, et al., 1974), and some described occurrences in the Peavine Sequence near Reno, Nevada (Hudson, 1977), also compare very favorably with the deposits of irrefutable island arc affinity and genesis, and also with the Moonlight Valley deposit. The Yerington (135 million years), MacArthur (161 million years), Snake River, and Peavine(?) occurrences have all been dated as Jurassic in age. This gives further impetus to the Jurassic-island arc interpretation of the Lights Creek deposits as opposed to the Cretaceous-batholithic differentiate interpretation of Storey (1978).
CONCLUSIONS

The Moonlight Valley porphyry copper deposit is hosted by a portion of the Jurassic(?) aged, fine grained, quartz monzonitic Lights Creek stock that crystallized in a static environment and is enclosed in a section of Jurassic volcanic-volcaniclastic country rock. Chalcopyrite is the principal ore mineral, though primary bornite and chalcocite are important in forming the ore zones that create the 250 million ton ore body of 0.35% Cu with important gold and silver, and negligible molybdenum. The ore minerals are zonally arranged from high Cu/Fe+S chalcocite-bearing cores outward to a low Cu/Fe+S pyrite-bearing fringe. Pyrite is less abundant in the deposit than magnetite, indicating an overall low sulfur system.

Potassic, sericitic, and propylitic alteration types are recognized in the deposit, but are not arranged in a cylindrical, spatial zonation. Instead, they are telescoped or superimposed over the same rock volume. The intensity of all alteration types is generally low.

The Moonlight Valley porphyry deposit essentially represents magmatic mineralization with only minor hydrothermal activity. Of no apparent importance to the Moonlight Valley mineralization have been the roles of structure and supergene enrichment.

On a basis of world-wide comparison, the Moonlight Valley deposit and Lights Creek area as a whole compare
favorably to deposits considered to be the subvolcanic expression of ancient volcanic island arcs, as described by Hollister (1975). The Moonlight Valley deposit contrasts with deposits of continental origin, as described by Lowell and Guilbert (1970). Any exploration for deposits similar to the Moonlight Valley occurrence would need to take into account the terrain and local geological conditions listed as characteristic of island arc related occurrences, although it must be remembered that the Lowell and Guilbert model deposits may also be found in island arc terrains. The two models should be considered end members of a range of possible settings for porphyry copper mineralization.
Because of the necessarily restricted scope of this study, there are several potential areas of study in the Lights Creek area that could lead to a better understanding of the mineralization in the area. These include the following:

1. A detailed study of the stratigraphy, correlation, and petrology of the Jurassic section.
2. A detailed petrologic, petrographic, and geochemical study of all the intrusive rocks of the area to establish their exact relationships to each other.
3. A fluid inclusion study, particularly of ore hosting intrusives.
4. Isotopic age dating of all intrusive units in the area.

These are listed here to acknowledge that all geological facets of the Lights Creek area are not yet fully understood.
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### APPENDIX

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Geochemical data on some Lights Creek plutonic rocks. Analyses by Technical Service Laboratories, Mississauga, Ontario, using the argon plasma emission method.

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| Co            | 50                    | 15                               | 40                            |
| Ni            | 34                    | 20                               | 34                            |
| Mo            | 1                     | 1                                | 1                             |
| Ag            | 0.4                   | 0.6                              | 0.5                           |
| Cr            | 174                   | 148                              | 210                           |
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TABLE 2.

Geochemical data on Lights Creek plutonic rocks from Smith (1970). Major elements only, given in percent.

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<td>0.56</td>
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<td>0.70</td>
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<td>100.25</td>
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Geochemical data for some typical Sierra Nevadan batholithic rocks (from Carmichael, et al, 1974, p. 580). All are major elements, given in percent.

<table>
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<tr>
<th></th>
<th>B-1 (gabbro)</th>
<th>B-2 (quartz diorite)</th>
<th>B-3 (granodiorite)</th>
<th>B-4 (quartz monzonite)</th>
<th>B-5 (quartz monzonite)</th>
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<td>SiO₂</td>
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