Geology of the Eastern Portion of the Indian Wells Canyon Mining District, Kern County, California

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

by

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Several individuals were helpful in the development and implementation of this study. Some of those who deserve a special thank you are: Mr. Larry Graham and Mr. Ron Marker, principle owners of the Tungsten Peak Mine Company who allowed the collection and retention of data while the mine operated; Dr. Carl Austin, consulting geologist for the Tungsten Peak Mine Company, who provided a tremendous amount of data, guidance, and interest in the author's work while at Tungsten Peak Mine; Mr. Glenn Hatton, Mr. Milford Carlson, and Mr. William Sterling, owners of the unpatented claims in the study area; Dr. Arthur Baker, III, and Dr. Liang-chi Hsu, professors at the Mackay School of Mines, who provided technical guidance and review of this study; and my wife Lorraine, who provided moral support and editorial help.

A special thank you goes to the Geothermal Utilization Division, Naval Weapons Center, China Lake, California and its division head, Dr. Carl Austin, who provided a set of aerial photos and photo enlargements of the study area.

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Metamorphic and metasomatic alteration of fine grained Mesozoic carbonate sediments by a late Cretaceous granodiorite has produced a series of small poorly developed calc-silicate skarns in the southeastern Sierra Nevada Mountains. Tungsten mineralization in the form of scheelite is found in almost all the skarns, but is of great enough concentration in only one skarn to have been extensively mined. This one skarn differs from the others in that it formed in a low-silica tightly folded thin-bedded limestone which provided the necessary host rock and secondary permeability for nearly complete skarn development and mineralization of sections of the limestone.
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PLATES (In Pocket)

I. Geologic Map of the Eastern Portion of the Indian Wells Canyon Mining District, Kern County, California (Study Area)
II. Geologic Map of the HiPeak and Tungsten Peak Mines Area
III. Aerial Photograph of the Study Area (Provided by the China Lake Naval Weapons Center)
INTRODUCTION

Location

Indian Wells Canyon Mining District is a small inactive district located approximately 120 miles north of Los Angeles in the eastern southern Sierra Nevada Mountains. East of the district is the transition from the Sierra Nevada geomorphic province to the Basin and Range geomorphic province which produces some complex geologic problems. Figure 1 is a diagram of the Indian Wells Valley which is the geographic basin east of the Sierra Nevadas in this area. The location of the district and several cultural and geographic features of the area are also shown in the figure.

The study area is located along the eastern edge of the district and includes the two major mines of the district, the HiPeak and Tungsten Peak Mines which were both located in the same scheelite bearing calc-silicate skarn but operated in different parts of the skarn at different times. Figure 2 is an enlargement of the district area as shown in Figure 1 and includes the location of the major prospects and their principle commodities.

Access into the district and study area is via excellent dirt roads which branch off the two major highways, U.S. 395 and State Highway 14, as shown in Figure 3. Two major dirt roads transect the study area in a north-south direction providing excellent access into most of the study area. No roads enter the study area or district from the west because of steep topography.
Figure 1. Location of the Indian Wells Canyon Mining District and Study Area.
Figure 2. Indian Wells Canyon Mining District.
(Study area shaded).
Figure 3. Cultural and Topographic Map of the Study Area. (Topography from USGS Inyokern and Owens Peak 7½' quadrangles).
As shown in Figures 1 and 3, the study area is located at the eastern edge of the Sierra Nevada Mountains which produces an interesting topographic and climatic character. The topography of the area varies from the bajada and alluvial fans at the base of the mountains to rugged granitic spires and peaks west of the study area. An elevation difference of almost 2000 feet occurs across the study area. Topography is controlled primarily by the lithologic units of the region. Climatic variations are extreme in this area of the upper Mojave Desert. Winter daytime temperatures average in the low 50's (degrees Fahrenheit) while summer temperatures generally exceed 100 degrees Fahrenheit. Winter snow storms are relatively rare, but can drop a few feet of snow rather quickly. The majority of the precipitation for the area occurs as spring and summer rain storms. Thunderstorms in the summer can produce flash floods in some of the canyons which extend into the Sierras and have an extensive drainage area.

Study Emphasis

The primary goal of this study is to determine and understand what geological conditions and sequence of events led to the development of the tungsten bearing skarn in which both the HiPeak and Tungsten Peak Mines operated, and to explain why nearby carbonate units and pendants were not developed into skarns or mineralized. Understanding the conditions and processes which led to the development of the HiPeak-Tungsten Peak skarn will assist in the assessment of
skarn potential in other small carbonate units and pendants in the southern Sierra Nevadas.

This study was initiated while the author was employed as mine geologist for the Tungsten Peak Mine Company. Several unanswered questions concerning the origin of the skarn and the geologic framework of the area led to the development of this study. Thus the original goal of the study was to understand the geologic conditions which led to the development of the skarn ore bodies. This goal was later expanded to include an analysis of why other limestone pendants close to the HiPeak-Tungsten Peak Mines roof pendant were not mineralized.

**District History**

Established during the early 1900's as the result of minor gold production, the Indian Wells Canyon Mining District was formed during the boom period of the neighboring Randsburg District, located approximately 20 miles to the southeast. The Indian Wells Canyon Mining District included several gold prospects and two small gold properties, the Nadeau and Magnolia claims (Troxel and Morton, 1962), see Figure 2.

With the advent of World War II and the need for tungsten based alloys for the war effort, the United States government initiated a series of price supports for several strategic minerals including tungsten. A shift to tungsten exploration in the district occurred in the early 1940's (personal communications from several claim owners and prospectors,
1978), and led to the discovery of several tungsten prospects. Skarns and quartz veins containing the calcium tungstate, scheelite \((\text{CaWO}_4)\), were the ore bearing units and were associated with the contact between the igneous intrusions and metasedimentary roof pendants. Small mines, generally small open pits or drifts, were quickly put into production and in most cases were operated by only a few men. Many of the claims which had been previously worked for gold were now worked for tungsten. A small table mill was built in the central part of Indian Wells Canyon in the mid 1940's and operated until the early 1950's when most of the prospects had been worked out.

The largest tungsten producer in the area during this period was the HiPeak Mine, which was located outside of the original district boundaries, see Figure 2, but was included in production records of the district (Troxel and Morton, 1962). Discovered in 1942, and purchased by the U.S. Flare Corporation of Pacoima, California, the HiPeak Mine was started as a crosscut drift in a small roof pendant. The pendant is composed of thin bedded limestones that have been metasomatically altered into a skarn and then mineralized with scheelite. The mine produced fifty tons of ore in the first six months (Troxel and Morton, 1962) and continued development and production through the 1940's. Two levels were developed during this period, the original adit level and a second level fifty feet deeper into the pendant (Erickson and Stopper, 1945). These two levels were connected by an internal shaft which was sunk in ore.

In the early 1950's, the mine was leased by the Hatton and Carlson Mining and Milling Company. Development on a
third level approximately 100 feet below the adit level commenced following the sinking of a 40° inclined shaft from the surface along the western edge of the pendant. This shaft connected all three levels and was used as the main haulage for the mine after several ore passes and raises were developed between the three levels. Mining in the third level showed a general increase in the thickness of the skarn zones within the limestone beds and an increased ore grade. Attempts to sink a winze from the third level were hampered by the water table and were abandoned when the price supports for tungsten ore were removed by the U.S. Government during the mid 1950's. With the reduced ore prices and the production problems, the HiPeak Mine was shut down.

Figure 4 is a plan view of the three working levels of the HiPeak Mine as mapped in 1978. The grid pattern seen in this figure represents a 100 foot survey base established to simplify correlations between working levels. All mapping was accomplished using transit and stadia or brunton-tape methods.

After the removal of price supports for tungsten ore, mining in the district was phased out except for occasional assessment work and weekend prospectors working the gold claims.

In late 1975 a group of local investors hired a consulting geologist, Dr. Carl F. Austin, to study the potential of reactivating the HiPeak Mine. The resulting report indicated a probable extension of the skarn zone beneath the old HiPeak Mine workings and recommended a core drilling program to attempt to intersect this zone. It was
Figure 4. Plan View of HiPeak Mine Workings.
also recommended that a geophysical study of an area just
north and east of the pendant's disappearance under an
alluvial-colluvial cover be conducted. An electrical
resistivity survey using the Schlumberger configuration was
performed by a subcontractor, and interpretations from the
study indicated probable bedrock at depths of less than 100
feet.

The core drilling program was initiated in the summer of
1976 and several ore zones were blocked out to depths of
approximately 100 feet below the lowest level of the HiPeak
Mine. A core hole drilled in the alluvial-colluvial cover
over the geophysical target penetrated 340 feet of alluvium,
ever encountering bedrock, indicating an interpretational
error in the geophysical study. The interesting fact about
this particular hole was that it was drilled approximately
200 feet from an exposed portion of the pendant.

The investment group decided, upon the recommendation of
the consulting geologist, to begin development of these new
ore zones located beneath the old HiPeak Mine. A 15° decline,
projected to reach the bottom of the pendant, was started in
October, 1976. By late November, the decline, now
approximately 600 feet in length, entered the pendant about 40
feet above its root (determined later), and mine development,
by the newly formed Tungsten Peak Mine Company, had begun.
The first ore was shipped in December, 1976 and was produced
from a zone approximately 30 feet above the base of the
decline. Production and development continued laterally, at
first, then upward, until late in 1978 a large stope measuring
approximately 80 feet in height x 50 feet in diameter, and several smaller rooms had been developed. Figure 5 shows the outlines of the various working levels of the Tungsten Peak Mine which were eventually connected into the large stope and rooms. Production work, primarily mining of the existing walls, continued into early 1979 when the easily and safely accessible ore had been exhausted. An underground exploration drilling program had been conducted in early 1978 to explore for additional ore zones in the pendant, but no new major ore zones were identified. This drilling program did result in identifying the boundaries of the pendant in the lower workings which will be discussed later. Figure 6 is an east-west diagramatic cross section of the working levels of the HiPeak and Tungsten Peak Mines and shows the internal connections between the levels and the two mines.

During its operation, the Tungsten Peak Mine produced approximately 200,000 short tons of ore with an average grade of 0.75% WO$_3$ (based on shipping records from Tungsten Peak Mine and assays from Union Carbide Corporation). The ore was shipped as crushed rock to Union Carbide Corporations's Pine Creek Mine located near Bishop, California (a distance of 120 miles). A grab sample was taken from each shipment and assayed by Union Carbide's lab to determine the grade and thus the payment. Ore grades were usually between 0.50% and 0.90% WO$_3$ although grades exceeding 1.00% occurred occasionally. The grade of 0.50% was established as the cutoff grade as Union Carbide would not pay for grades below this level. Ore
Figure 5. Plan View of Tungsten Peak Mine Workings.
Figure 6. Schematic East-West Cross Section of HiPeak and Tungsten Peak Mines.
control in the mining operation was based on visual estimates by the geologist and were usually accurate within 10 to 15 percent.

Previous Work

Very little published data is available for the area, and most publications available are either outdated or reconnaissance in nature. Regional work includes the mineral resources study of Kern County by Troxel and Morton (1962), the 1° x 2° Trona Geologic sheet from the California Division of Mines and Geology (Jennings and others, 1962), a USGS open-file geologic map of the Inyokern 15' quadrangle by Dibblee (1959), and a publication on the geology of the Indian Wells Valley by Zbur (1963) published by the U.S. Naval Ordnance Test Station (now the Naval Weapons Center).

Two studies of the HiPeak Mine were completed by the government during World War II. Both studies are maps of the HiPeak Mine surface area and working levels although the U.S. Bureau of Mines, War Minerals Report by Elliot (1943) does have a small geologic description and production records. The second study, a USGS preliminary map by Erickson and Stopper (1945), is a series of geologic maps of the surface and first two levels of the HiPeak Mine.

Several other publications by the California Division of Mines and Geology during the 1940's referred to production records by district, or were initial geologic studies of tungsten resources, and have been updated in the reports listed in the first paragraph.
The majority of the geologic data used in this study was collected by the author while he was employed at Tungsten Peak Mine. Data collected by the consulting geologist, Dr. Carl Austin, prior to the author's employment, were made available to the author by Dr. Austin.

**Property Ownership**

Several unpatented claims exist in the district and study area. The HiPeak claims, on which the HiPeak and Tungsten Peak Mines are located, originally consisted of four lode claims and one millsite. These were owned by Mr. Glenn Hatton and Mr. Milford Carlson who had obtained them from the U.S. Flare Corporation. Only one claim was maintained with assessment work by Mssrs. Hatton and Carlson during the idle period from mid 1950 to mid 1970's. When the Tungsten Peak Mine Company started operations in the mid 1970's, they staked several peripheral claims in the area to protect the existing HiPeak claim boundaries and to cover possible targets for further exploration in other nearby carbonate units. Figure 7 is the claim map around the HiPeak and Tungsten Peak Mines as it was in 1978.

Approximately one mile northwest of the HiPeak-Tungsten Peak Mines is another roof pendant located at the mouth of Short Canyon. Mr. William Sterling has several lode claims and a few placer claims in this area. Mr. Sterling occasionally works some of the alluvial units on one of his placer claims for tungsten and is somewhat successful using drywash methods.
Figure 7. 1978 Tungsten Peak Mine Claim Map.
In the central portion of the study area and just west of the study area are the two major aqueducts transporting water from Owens Valley to the city of Los Angeles. These are owned and operated by the Los Angeles Department of Water and Power (LADWP). Requests for access to preaqueduct geologic studies were denied by LADWP.

The remainder of the study area is Federal land managed by the Bureau of Land Management with the exception of a few small parcels adjacent to State Highway 14 and U.S. Highway 395 which are owned by the State of California or private individuals. The BLM lands west of the aqueduct which passes through the study area are currently being evaluated for potential wilderness area designation.
Indian Wells Valley is located in an area of diverse and complex geology. This is the result of the area occupying the transition zone between the three major geomorphic provinces in eastern California. These provinces, the Sierra Nevada Mountains, the Basin and Range province, and the Mojave Desert each have characteristic geomorphic and geologic patterns (Oakshott, 1971). Indian Wells Valley reflects these patterns in its diverse and complex geologic character shown in Figure 8.

The valley is a small complex graben bordered by several complex horst blocks. Mesozoic intrusives are the dominant lithologic unit found in most of the ranges bordering the valley, and are associated with the Sierra Nevada batholith and the Nevadan orogeny (Shawe and others, 1971; Nolkebert and Kistler, 1980). Paleozoic and Mesozoic sediments and metasediments are found in the Sierra Nevada and El Paso Mountains. Non-marine sediments are also found in the El Paso Mountains overlying the Paleozoic and Mesozoic units. Late Cenozoic volcanics are found both north and south of the valley and are related to late tectonic development of the area.

Basin and Range extensional tectonics have developed the normal faulting which borders the valley and the translational strike-slip faults found within the valley. The normal faulting found in the basin consists of several parallel and sub-parallel faults which drop the basin in a series of steps.
Figure 8. Generalized Regional Geologic Map.
Most of these faults are buried by the valley fill but have been identified from geophysical work by Zbur (1963). These faults offset the Tertiary non-marine sediments which are found overlying the Mesozoic basement rocks in the valley indicating a late Cenozoic age. Zbur suggests the translational strike-slip faulting absorbed extension in the lithosphere during basin and range development. Where these faults intersect the Sierra Nevada Fault, the trend of the Sierra Nevada Fault shifts farther west. Confusion exists as to why this westerly shift occurred since movement along the translational faults would suggest a shift in the opposite direction. Zbur associates this opposite sense of movement seen in these translational faults to more recent movement along the Garlock Fault, a major left-lateral strike-slip fault south of Indian Wells Valley (fig. 8). Tertiary and Quaternary volcanic fields found overlying some of these translational faults suggest that the faults are deep seated crustal structures which have created a path for upwelling magmas (St. Amand and Roquemore, 1979). St. Amand and Roquemore (1979) propose that much of the tectonic development in the area is late Quaternary as evidenced by the offset of the Coso Formation, a Quaternary fluvial and lacustrine sediment group found both in the Argus Range and the Indian Wells Valley. This idea further substantiates Zbur's (1963) interpretation that most of the tectonic development of the area is late Cenozoic.

The area is as complex lithologically as it is structurally. Late Jurassic and Cretaceous intermediate
intrusives are found in all the ranges bordering the valley (Everden and Kistler, 1970), and are considered to be part of the Sierra batholithic complex (Kistler and others, 1971; Everden and Kistler, 1970). Overlying these intrusives or occurring as septa and pendants within them are Paleozoic and Mesozoic sediments and metasediments which represent lithologies found in a back-arc basin environment (Bond and others, 1977; Noklebert and Kistler, 1980). Metasomatic alteration and tungsten mineralization are found in many of the more calcareous metasediments, but only a few areas have been commercially exploited. Non-marine Cenozoic sediments are found in the El Paso Mountain, overlying the granitic basement in the valley fill (Zbur, 1963), and south of the Garlock Fault in the Mojave Desert (Jennings and others, 1962). They are primarily aeolian sands, ash falls, fluvial and saline lacustrine sediments interbedded within thin basalt flows (Zbur, 1963). Broad pediment surfaces have developed in the southwest and southeast corners of the valley and are suggestive of topography found south of the Garlock Fault in the Mojave Desert area.

Figure 9 is a regional structure map and identifies the three provinces as previously discussed. This map illustrates the variations in structural character between provinces.

Western Tungsten Mineralization Belt

Kerr's (1940) paper on tungsten mineralization in the United States identified two major belts of tungsten mineralization in the western United States. These belts shown
Figure 9. Generalized Regional Structure Map.
(geomorphic provinces shaded).
in Figure 10 are the regions in which tungsten mineralization has been found and the darker zones are major tungsten districts. The western-most belt passes through the Sierran province and western Basin and Range province and shows a characteristic change in mineralization in the Indian Wells Valley area. Tungsten mineralization found southeast of the study area in the Atolia district occurs as large clusters of scheelite (CaWO$_4$) in quartz veins. The tungsten mineralization found in the study area and farther west and north in the belt is the skarn type scheelite deposit which is more common in the Sierra Nevada province. The study area appears to be a transition zone within the belt because both skarn deposits and small vein deposits are found in the district.

**Indian Wells Canyon Mining District**

The Indian Wells Canyon Mining District is located around Indian Wells Canyon, its namesake, which cuts into the eastern face of the Sierra Nevada Mountains, see Figure 1. The major lithologic unit in the district is the late Mesozoic intrusives of the Sierra Nevada batholith. Mesozoic roof pendants trending generally northwest are found along the southern edge and northeast corner of the district. Figure 11 is a generalized geologic map of the district which shows the major lithologic units and the locations of the major mineral properties.

As previously discussed in the section on district history, the major commodity of the district has been tungsten
Figure 10. Western Tungsten Mineralization Belts, after Kerr (1940). (Study area noted by small triangle. Solid areas, major tungsten districts).
Figure 11. Generalized Geologic Map of the Indian Wells Canyon Mining District and Study Area.
occurring as scheelite in skarn and veins deposits along the contact between the intrusives and carbonate units in the roof pendants. Prior to the advent of scheelite production in the 1940's, gold had been the major commodity of the district produced mainly from small veins and fracture zones. Gold production had been sporadic from the late 1800's up until the 1940's when the emphasis changed to tungsten, and gold production became secondary.

Lithology

Two major rock types are found within the district; the Mesozoic metasedimentary roof pendants and the late Mesozoic intrusives. The Mesozoic metasediments are found as roof pendants in the intrusives and are composed of steeply dipping thin-bedded metasedimentary units. The late Mesozoic intrusives are primarily intermediate in composition and cover approximately 70% of the district. A third less important lithologic unit is the alluvial and colluvial material which covers much of the area.

Mesozoic Metasedimentary Units. Found as steeply dipping, northwest trending units in the roof pendants of the Sierra Nevada batholith, these units represent a passive depositional environment similar to a back arc basin (Saleeby and others, 1978, Stanley and others, 1971). Units consist primarily of argillaceous and pelitic thin-bedded, siliceous and calcareous hornfels with lentils and beds of limestone. The complexity of the units, their steeply dipping nature, and
metamorphic alteration has removed any evidence of depositional sequence and stratigraphic order. Evidence that the hornfelsic units may be older than the carbonates is found approximately 40 miles east. The lack of good correlative units between the district and the area 40 miles east only leads to the speculation that they are older.

The hornfels are dark colored, somewhat schistose units with individual beds varying from less than a foot to several feet in thickness. Stratigraphic sections in some of the hornfels show thicknesses of several hundred feet to a few thousand feet. They are generally iron-rich as evidenced by the oxidation of iron in several of the units creating a reddish brown stain.

The limestones are generally light to medium gray in color and bedding ranges from a few inches to several tens of feet thick. Composition varies in the siliceous component of the limestones and for this study the following separation has been made. Limestones which have a siliceous component of less than 25% are classified as low-silica limestones, and those with a larger silica component are classified as high-silica limestones. The siliceous components are detrital quartz and alkali feldspars primarily and are found as intrabeds within the limestones or intermixed with the carbonate minerals. These units have undergone low-grade metamorphism as seen in textural changes, and by the limited regrowth of the calcite.

The roof pendant along the southern ridge of Indian Wells
Canyon is the largest in the district and is several miles in length and over a mile wide at its widest point. Trending in a northwest direction similar to most pendants of the region, the units within this pendant are not as steeply dipping. Dips range from 40 to 60 degrees and are generally to the southwest. A dark, gray, high-silica limestone unit exists within the hornfelsic units and can be followed for several miles. This unit is relatively thick bedded as are most of the high-silica limestones in the area are. Lentils of hornfels within the limestone unit are common. Contacts between this unit and the late Cretaceous intrusives show several poorly developed calc-silicate skarns. Scheelite is associated with most of the skarns but is in economic quantities in only a few moderately developed skarns. These areas are easily identified by the mine and prospect locations shown in Figure 11. Some of these mines and prospects contain scheelite bearing veins illustrating the transitional nature of the district between the vein type scheelite found in the Randsburg-Atolia districts to the southeast and the skarn scheelite deposits found farther west and north.

The group of small roof pendants found in the northeast corner of the district within the study area are generally north-northwest trending and probably are the remnants of a single continuous roof pendant which has been severely eroded. In these pendants, a transition occurs from a siliceous-rich lithology to a carbonate-rich lithology which will be discussed in the section on the study area geology.
Mesozoic Intrusive Units. Ranging in composition from gabbro to granite, several plutons of mid-to-late Mesozoic granitics are found within the district. They are part of the massive Sierra Nevada batholith and are generally similar to other units within the batholith. The more intermediate and acidic units, such as granodiorites, quartz monzonites, and granites, are the most abundant in the district and are the younger units of the sequence. The more basic units such as the quartz diorite and gabbroic rocks are older as evidenced by intrusive contacts and may represent an earlier more basic intrusive episode of late Jurassic age. These more basic intrusives are of similar character and composition to those of the Argus and Coso ranges, to the east and north respectively, which have been dated by Evernden and Kistler (1970) as late Jurassic.

Differential weathering and erosion of the various intrusive units have produced a complex and rugged topographic terrain in some areas while others have been eroded into smoothly contoured terrains. This differential erosion appears to be related to compositional and textural variations within the units. Textures are coarsest in the quartz monzonites and finest in some of the granodiorites and quartz diorites. The finer, less siliceous units are more easily weathered and eroded possibly because of an increase in feldspar weathering. Granodiorite units which have been saturated with post-intrusive potassic feldspathic fluids, probably related to the quartz monzonite, show a greater depth
of weathering and erosion than those units not enriched in feldspars. Some of these weathering profiles are several tens of feet thick in the granodiorite but generally average approximately 10 to 20 feet thick.

Several veins and pegmatites found within the district are generally composed of quartz, calcite, and hornblende. In the northern portions of the district, several potassic feldspar pegmatites are found. Orthoclase and microcline predominate with minor quartz and plagioclase associated with the major minerals. The gold bearing and scheelite bearing quartz rich veins found in the southwest part of the district are similar to other, non-ore bearing, quartz veins in the district. The gold bearing veins found in sections 2 and 11 are less than a foot in width and contain free gold with pyrrhotite, pyrite, and arsenopyrite (Troxel and Morton, 1962). The scheelite bearing veins are found in the gold areas but are generally closer to the contact with the metasediments. Quartz, calcite, and scheelite are found in veins of a few inches to a foot in width. Gold and scheelite do occur in the same vein system but there is a lateral separation of approximately 50 feet suggesting a two phase mineralization sequence (Troxel and Morton, 1962). Age relationships have not been determined and may be difficult to establish because of the nature of the geology of the region.

Cenozoic Units. Alluvium and colluvium units make up the Cenozoic sequence. Two alluvial units have been identified in
the study area and are comparable to the alluvial units in the
district. The older alluvium is generally more conglomeratic
in character and is found above the current drainage systems
indicating a change in base level of the area's drainage. The
younger alluvial units are found in and adjacent to the
current drainages and as the fans and bajada which have
developed along the edge of the Sierras.

Colluvial units are difficult to distinguish from deeply
weathered intrusives, but changes in vegetation cover and
density were used to identify likely colluvial units.
Generally, the weathered intrusives have a less dense
vegetation cover than the colluvium and alluvium units.

Structure

Major structural trends in the district parallel the
northwest trend of the roof pendants and Indian Wells Canyon.
The pendants are elongated in the direction of the trend, and
bedding within the pendants generally parallels the overall
northwest trend of the area. Exceptions to the general trend
are found in the northeast part of the district where bedding
in several small pendants and inclusions do not follow the
overall general trend but are tightly folded and tilted in
several directions. These trends are truncated by the Sierra
Nevada Fault zone which truncates all geologic features
transecting the eastern Sierra Nevada province.

Faulting within the district appears to be primarily of
Mesozoic age exclusive of the faulting associated with the
Sierra Nevada Fault zone. The faults within the metasediments
with few exceptions do not cross the contact with the intrusives indicating a pre-intrusion origin probably tectonically associated with the emplacement of the batholithic complex. Similarly, faults within the intrusive generally do not intersect the pendants making correlations difficult. Faults found within the intrusives and crossing the contacts between the metasediments and the intrusives units are probably related to post intrusive tectonics such as the Sierra Nevada Fault.

The Sierra Nevada Fault and other Cenozoic faults within the area have played a major role in the recent structural development of the area. These faults are associated with Basin and Range tectonics and have developed the current topographic and structural character of the area.

Near the mouth of the Indian Wells Canyon, the trend of the Sierra Nevada Fault changes from a north-northeast trend to a north-northwest trend. This directional change occurs near the intersection of the Sierra Nevada Fault and a northwest trending basement strike-slip fault mapped by Zbur (1963). Several faults radiate outward into the Sierran block from this directional change truncating and changing the trend of some of the pendants. A similar direction change occurs at the intersection of the Sierra Nevada Fault and another northwest trending basement strike-slip fault approximately 20 miles north of the district, see Figure 8. Zbur (1963) interprets this directional change to be a function of the lateral extension of Indian Wells Valley Basin associated with Basin and Range tectonics, and movement of the
Garlock Fault.

Alluvial cover masks most of the Sierra Nevada Fault trace in the district except for a large scarp across the mouth of Indian Wells Canyon. Several small springs known as Indian Wells have developed along this scarp in historic times but none presently exists. In the remaining portions of the district, the fault trace is interpreted by the intersection of the range front and bajada and from gravity surveys conducted by Zbur (1963).

Indian Wells Canyon may be fault controlled as evidenced by two small fault traces along the southern edge and a distinct linearity to the north edge. A series of geophysical cross sections could be developed to further investigate this possibility.
GEOLOGY OF THE STUDY AREA

An area of approximately six square miles was selected as a study area. This areal extent includes the major geologic features close to the HiPeak-Tungsten Peak Mine group. The two previous sections discussed the geologic character of the overall region. In this section, specific conditions or features will be discussed.

The study area covers the eastern edge of the southern Sierra Nevadas in an area where a small north-northwest trending roof pendant complex is apparently truncated by the Sierra Nevada Fault. The overlying sedimentary section has been removed by erosion leaving only small roof pendants and metasedimentary inclusions in the batholith. Mapping of the study area was a combined program including aerial photographs and on the ground techniques and was conducted primarily in the summer of 1979. Data collected by the author while employed at the Tungsten Peak Mine during 1977 and 1978, was also incorporated, and field checking was conducted in the spring and fall of 1980.

The general geology of the area is rather simple at first glance but becomes more complex upon further investigation. A series of Mesozoic metasediments are found in several small roof pendants and as inclusions in the massive batholith complex of the southern Sierra Nevadas. These pendants and inclusions have an overall trend of north-northeast to north-northwest with a major deflection in this trend occurring in
the central portion of the study area. The metasediments are generally thin bedded, argillaceous hornfels and low and high-silica limestones which have been tightly folded and tectonically rotated to near vertical dips. The general strike of the units parallels the overall trend of the pendants and changes where the pendant trend is deflected. The units are generally only slightly metamorphosed, and relict bedding is visible in almost all the units.

Surrounding these metasediments are the granitic intrusives of the Sierra batholith which vary in composition from diorite to granite. The largest intrusive group in areal extent is the granodiorites. These intrusives are generally subdued topographically by extensive weathering which has produced a grus-colluvium cover over much of the area.

Associated with the intrusive units are metasomatic alteration of many of the calcic metasedimentary units. This alteration along with contemporaneous scheelite mineralization produced several small skarn deposits with scheelite mineralization. Only one of these skarns was of sufficient extent and contained enough scheelite to be economical. This skarn is located in the pendant in which the HiPeak and Tungsten Peak mines are found. Cenozoic faulting associated with the development of the Basin and Range province created the Sierra Nevada Fault which truncates the east edge of the pendants and several other major faults within the area.

Figure 12 is a generalized geologic map of the study area which has been derived from Plate I a detailed geologic map of
Figure 12. Generalized Geologic Map of the Study Area.
(Geology modified from Plate I).
of the study area. Figure 13 is similar to Figure 12, but is an interpretation of the probable pendant configuration at a topographic elevation a few hundred feet higher than the current topography.

Lithology

Several different rock types are found in the study area but all can be classified into three groups: metasediments, intrusives, or alluvium and colluvium. The metasediments are found in the small roof pendants and as small inclusions in the intrusives which make up the bulk of the lithology in the area. The alluvium and colluvium are found in the drainage channels and the flank of the range. The colluvium and alluvium units tend to mask some of the contacts, and several of the contacts mapped in Plate I are inferred because of this colluvial cover. This masking in particular created problems in distinguishing the interpluton contacts. Similarities in mineralogy also complicated differentiating between plutons.

Metasedimentary Units

The four major metasedimentary units found in the roof pendants and inclusions are thin-bedded argillaceous and pelitic hornfels, calcareous and calc-silicate hornfels, and high silica and low-silica crystalline limestone. The high-silica limestone occurs as lentils and beds within the more abundant hornfelsic units. Metamorphism has been relatively low-grade as interpreted from several hornfelsic units which have a schistose character and from the limestones which have
Prior to the Erosional Dissection Seen in Figure 12. (Lithology same as in Figure 12).

Figure 13. Interprative Geologic Map of the Study Area Prior to the Erosional Dissection Seen in Figure 12. (Lithology same as in Figure 12).
generally been converted to crystalline limestone. Low-grade metamorphic minerals such as actinolite, wollastonite, and idocrase are found in some of the limestones, and metamorphism has destroyed any primary structures which might have existed in the limestones. Metasomatic alteration has occurred in several of the calcic-rich hornfels and limestones and produced calc-silicate skarns. The degree of development of these skarns appears to be dependent on the calcium content of the host rock and the secondary porosity created by the development of microfractures. No depositional sequence has been determined in the study area, but stratigraphic sections east of the study area suggest the following lithologic sequence.

Argillaceous and Pelitic Hornfels. Fine grained, dark brown to reddish brown, argillaceous and pelitic hornfels are the major metasedimentary unit found in the southern portion of the pendant trend. Relict bedding is evident in most units and is enhanced by low-grade metamorphism which has produced a schistose character in these units. A few units have been metamorphosed into actual schist, but the majority are fine grained, thin-bedded, schistose hornfels.

The hornfels are generally siliceous with mafics of biotite, amphibole, pyroxene, and epidote providing the dark colors. Oxidation of the iron above the water table has produced the red and brown colors. Units which were below the water table prior to mining are darker green to black in color. Iron sulfides and oxides such as pyrite, pyrrhotite,
and magnetite are found in these darker units, but only their
grain molds remain in the weatered section. Textures in these
hornfels are generally aphanitic and can only be distinguished
with a hand lens and microscope. Petrographic studies of
these units show that detrital quartz and feldspars are the
major component in the units as is shown in Figure 14.
Calcite is present in all units varying in abundance from less
than 10% to about 30%. The more calcareous hornfels will be
discussed in the following section.

The occurrence of minerals such as actinolite,
wollastonite, and epidote and textural evidence along grain
boundaries indicates that these units were subjected to low-
grade metamorphism. Metamorphism throughout the units is
relatively uniform and no major changes in grade occur
adjacent to or at the contacts with the intrusives.

The schistose character of many of the hornfelsic units
is primarily a function of the mafic composition and its
realignment by metamorphism. Units with a greater percentage
of biotite and hornblende show a more schistose character than
the units in which pyroxenes are abundant. Alignment of the
mafics by metamorphism is evident in thin section (see fig.
14) but not in hand specimen. Units rich in biotite and fine
grained quartz and feldspars show a major schistose character,
but due to their limited extent were included in the
argillaceous hornfels units in Plate I.

Bedding within the hornfels is relatively uniform
throughout the study area. Relict bedding exists in almost
all the units and ranges from less than an eighth of an inch
a. Argillaceous hornfels. (Crossed nicols).

b. Schistose argillaceous hornfels with biotite (b). (Crossed nicols).

Figure 14. Color Photomicrographs of Argillaceous Hornfels.
thick to a maximum thickness of about eight inches. The majority of the beds are 2 to 4 inches thick. The units themselves as a rule are several tens of feet to several hundred feet thick. The occurrence of upright parabolic folds in many pendants and inclusions gives the appearance that the units are even thicker. This is illustrated in the hornfelsic pendants found in the northwest quadrant of section 15 in Plate I. The occurrence of intrabedded limestone also adds to the overall thickness of many hornfelsic sequences.

Calcareous and Calc-Silicate Hornfels. Dark green to dark reddish brown in color, the calcareous and calc-silicate hornfels are the predominant metasedimentary units found in the central and northern portions of the pendant trends. These hornfels generally cannot be differentiated in hand specimen from the previously discussed argillaceous and pelitic hornfels. Relict bedding is plainly visible in the calcareous and calc-silicate hornfels as it is in the other hornfelsic units and is near vertical.

The calcareous and calc-silicate hornfels are less siliceous than the argillaceous and pelitic hornfels, but quartz and feldspars still comprise a large portion of the total rock. The occurrence of calcite and calc-silicate minerals is the major difference between the two types of hornfels. Mafic minerals are generally similar except that the addition of calc-silicate minerals such as diopside, grossular, and epidote differentiate the two types of hornfels when viewed in thin section. Figures 15a and 15b are examples
a. Epidote (e) in calc-silicate matrix. (Crossed nicols).

b. Diopside (d) and epidote (e) in calc-silicate matrix. (Crossed nicols).

Figure 15. Color Photomicrographs of Calc-Silicate Hornfels.
of a calc-silicate hornfels.

The presence of calc-silicate minerals within the more calcareous hornfels indicates that the metasomatism processes were widespread in the area. Also the occurrence of trace amounts of scheelite and Mo-scheelite shows that the tungsten mineralization was not restricted to only a few localities. The presence of scheelite in the calcareous hornfels is also noted in the two hornfelsic pendants in section 4. All the prospect pits and adits in these pendants, see Plate I, are situated in calcareous hornfels.

In areas where these hornfels are in contact with limestones the calcite component increases towards the contact. The siliceous component in the limestones at some of the contacts is very low indicating an abrupt halt to the deposition of detrital siliceous material.

Bedding in the calcareous and calc-silicate hornfels is very similar to that found in the more siliceous hornfels, but due to a decrease in the mafic component shows less schistosity than the siliceous hornfels. The calcareous and calc-silicate hornfels also are not as intensely folded as those siliceous hornfels found in the southern portion of the pendant trend.

Extensive fracturing occurs in most of the hornfelsic units and these fractures are filled with small veinlets and veins of calcite and quartz. Two groups of veins and veinlets are found in the hornfels; a calcite-quartz group, and a quartz group. The calcite-quartz group are older than the quartz group and are slightly more abundant. Turner and
Verhoogen (1960) explain the occurrence of calcite-quartz veinlets and veins in low-grade schistose metamorphic terranes to be a function of metamorphic differentiation. The absence of these small calcite quartz veins and veinlets within the limestone units except where adjacent to the hornfels indicates such an origin. Tectonic forces associated with the folding of the units and the intrusive episode are probably the major source of the fractures, because the fracture density is greater at the apices of the folds than along the limbs.

The origin of the younger quartz vein and veinlet group is still vague. The lack of similar systems in the major limestone units disputes the theory that they are intrusive related, and the lack of calcite in the system is not explained by the origin discussed by Turner and Verhoogen (1960).

Metasomatic alteration was a regional process in the study area, but the existence of a compatible host rock controlled the degree of alteration. The siliceous hornfels underwent only minor metasomatic alteration as evidenced by the occurrence of minor amounts of amphiboles, pyroxenes, and epidotes. On the other hand, the more calcareous hornfels have been more extensively metasomatically altered. The abundance of epidote and pyroxenes produced a darker colored hornfelsic unit, and several units have poorly developed skarns along their contact with the intrusives. Traces of scheelite are found both in the poorly developed skarns and the calcareous hornfels, occurring as anhedral grains or
clusters generally less than a quarter of an inch across.

**Low-Silica Limestones.** These units are found as small pendants and intrabeds within the calcareous hornfels in the central portion of the pendant trend. They are white or light gray in color, thin-bedded, and fine grained. Low-grade metamorphism has produced a saccharoidal texture in many of these units which is visible on fresh surfaces of the units.

Calcite is the dominant mineral, although some dolomite is found. Recrystallization and regrowths of the calcite are found in almost all the units indicating its metamorphic history. Strained grains also are found in some units indicating some tectonic forces were present during metamorphism. Low-grade metamorphic minerals such as wollastonite, tremolite-actionlite, idocrase, epidote, and grossular are found in varying amounts.

The siliceous component in the low-silica limestones consists primarily of quartz and feldspar detrital grains. As defined in this study low-silica limestones have less than 25% siliceous component. The siliceous components are found as thin laminae or beds, generally less than $\frac{1}{2}$ inch thick, or as random grains in the calcite matrix, as shown in Figure 16.

Metasomatic alteration of these low-silica limestones is more advanced in those beds or units which have a small random siliceous component. These beds also show a greater degree of recrystallization than the more siliceous units in the low-silica limestones.
a. Siliceous and calcareous (calcite, c) laminae contact, with contrasting grain sizes. (See page 84 for explanation).

b. Low-silica limestone. (Note equigranular character of quartz (q) and calcite (c). Crossed nicols).

Figure 16. Color Photomicrographs of Low-Silica Limestones.
High-Silica Limestones. Found primarily in section 15 (see Plate I), these units are coarse to fine grained limestones, light gray to medium gray in color, and have greater than 25% siliceous minerals. They can usually be differentiated from the low-silica limestones by their darker color. Intrabeds of low-silica limestones are found within the high-silica sequences, but are not extensive enough or large enough to separate out.

Calcite and quartz are the dominant minerals with feldspars, clays, and some detrital mafic grains intermixed with the calcite and quartz. Recrystallization is not as extensive as in the low-silica limestones, but regrowths of calcite and quartz are visible in thin section. Low-grade metamorphic minerals such as wollastonite, tremolite-actinolite, and diopside are found in the high-silica limestones but are less abundant than in the low-silica limestones.

Bedding within the high-silica limestones is predominantly thicker and more massive than the low-silica limestones. The bedding is generally several inches thick in the high-silica limestones and in some areas is several feet thick, whereas the low-silica limestones have bedding thickness usually a few inches or less.

Metasomatic alteration is poorly developed in the high-silica limestones. A few skarnified zones are found, but they are only partially developed and too siliceous to be ore grade type skarns.
Skarn Units. Metasomatic alteration was a region-wide process in this portion of the southern Sierras as determined by the occurrence of metasomatic minerals in the hornfelsic and older igneous units. In the study area though, extensive alteration and skarn development only occurred in thin-bedded calcic rich units. Most of the exposed skarns are very small, rarely exceeding volumes of a few hundred cubic feet, and very fine grained. These small skarns and other skarnified zones are generally pyroxene rich skarns with minor amounts of epidote, garnet, quartz, and calcite. The exception is the skarn in which the HiPeak and Tungsten Peak Mines were developed. This skarn is a couple of orders of magnitude larger than the other skarns in the study area and much better developed. Further discussion of this particular skarn will be deferred to the next section.

The greatest number of these small skarns are found in the central portion of the roof pendant trend in sections 10 and the northern part of 15. In this area, all the units including the hornfels and limestone are more calcic compared to the other portions of the pendant. Several small skarns and skarnified zones occur in the units, but only a few are moderately to well developed. A general increase in the abundance of scheelite in these skarns also occurs substantiating the more calcic composition of the area.

These skarns are all pyroxene-rich skarns with a calc-silicate mineral assemblage including diopside hedenbergite, epidote, garnet, and quartz as the major components and
calcite, apatite, fluorite, and sulfides such as pyrite, pyrrhotite, and chalcopyrite as the minor components. Concentrations of these minerals vary greatly within the skarns, but the majority of the skarn contains 30 – 40% pyroxene, and/or epidote, 20 – 30% garnet, 15 – 20% quartz and calcite. Accessory minerals make up the remainder of the skarn. Scheelite was found in all these skarns but only a few skarns have zones of concentrations which could be considered economic. The zones are exclusively restricted to the calcic rich units which are generally limestones and bordered by more siliceous units of limestones or hornfels. Textures are equigranular, fine grained matrices with very minor, well developed grains. Grain size in most is less than one quarter inch and many are aphanitic in character. All are light green to medium green in color with only a few zones of red-brown color identified as grossular garnet.

**Igneous Units**

Several distinct intrusive units can be identified in the region. Compositions range from dioritic to graphic granite and alaskite with more intermediate acidic units such as quartz monzonites and granodiorites being the most abundant. These intermediate type intrusives are typical of the intrusives found in and adjacent to the study area. Three major and several minor intrusive units are found within the study area including an older diorite-quartz diorite series and the younger more acidic granodiorite and quartz monzonite. The age of the two younger intrusive units is late Cretaceous.
based on studies done by Evernden and Kistler (1970) on similar plutonic units west of the study area. A Cretaceous age is interpreted for the diorite-quartz diorite sequence based on intrusive contact data.

In the western portion of the study area, several silicic veins and pegmatites are found in the intrusive units with compositions ranging from quartz, orthoclase, and albite to potassic feldspars. Very few mafic minerals are found in the quartz pegmatities, whereas none are found in the potassic feldspars pegmatities. In the eastern portion, large veins and pegmatites are absent but several small quartz and calcite veinlets and veins do occur. These veins and veinlets are usually associated with the pendants in the eastern portion, and some have traces of scheelite mineralization.

**Diorite - Quartz Diorite Series.** A mafic series of intrusive remnants are found in the study area. These older intrusives are all dioritic to quartz dioritic in composition and are predominately identified as hornblende-biotite diorite and quartz diorites. Several exposures in the eastern portion are more of an epidote-hornblende diorite and quartz diorite with minor pyrite and pyrrhotite. The occurrence of the iron sulfides and epidote is interpreted to be of metasomatic origin rather than intrusive origin because most of the metasedimentary units in the area have similar metasomatic minerals associated with them. Extensive silicification has occurred along some of the contacts with
the granodiorites indicating an influx of siliceous fluids into the unit. This silicification appears to control the quartz component in the quartz diorite end of the series because the quartz diorites generally formed around the perimeter of the more mafic diorites.

This mafic series of intrusives is found only in a few areas within the study area. The large exposures include a hornblende-biotite diorite in the central portion of section 4 and the northeast quadrant of section 9, and a biotite-hornblende quartz diorite with epidote in the eastern portion of the study area in sections 10 and 15. Exposed portions at the surface and near the surface in the mines are extremely weathered which has produced a very friable easily eroded unit.

Similar composition and quantities of the major components in this series indicate a similar origin. Plagioclase, quartz, and hornblende are primarily equigranular in size, less than an eighth of an inch, and are in a fine grained matrix of biotite, hornblende, plagioclase, and quartz. Petrologic studies of these units show that the plagioclase are of labradorite and andesine composition with minor zoning. The hornblende occurs both as a primary mineral and as secondary growths forming at the expense of augite. Some of the biotite appears to have formed at the expense of hornblende. Accessory minerals are apatite and magnetite with minor amount of pyrite. Secondary pyrite and epidote are found in the units within the pendant trend. These are probably associated with the metasomatic alteration of the
region because an occasional grain of scheelite is also found in the series.

Alteration by the later acidic intrusive episodes caused an increase in the alkalinity of the feldspars and quartz, fracturing and silicic alteration along these fractures, and an increase in the silicic component in the older mafic units at the contact with the acidic intrusion. Saturation with silicic fluids can be seen in some of the smaller mafic inclusions indicating that the silicic alteration by the later acidic intrusives was rather wide spread.

**Granodiorite Series.** Covering the largest portion of the study area, the granodiorite series was difficult to study because most of this series has a weathered profile several feet thick. This lack of exposed lithology necessitated several inferences of contact locations and compositional variations within the series. Several outcrops are found in the study area and lithologic studies on these and on core samples collected around and within the HiPeak and Tungsten Peak Mines showed a rather uniform composition with variable textures.

The granodiorite series is the middle intrusive episode of the sequence. Data collected at contacts with the diorite-quartz diorite series indicate that the grandiorites were rather passively intruded into the country rock, the diorite-quartz diorite series and metasedimentary roof pendants. No major shear or cataclastic zones were found along the contacts and the lack of medium and high grade metamorphic minerals at
the contacts indicate a rather cool emplacement. Stresses did occur along the contacts evidenced by gradational recrystallization of the limestones and diorites, and strain and distortion in many of the calcite grains. Similar evidence at the quartz monzonite-granodiorite contacts led to the conclusion that the granodiorites are the middle unit of the intrusive sequences in the study area.

Composition of the granodiorites is relatively uniform with all units being hornblende granodiorites. Plagioclases are the most abundant component of the units and are andesine to albites. Approximately one third of the plagioclase grains shows progressive zonation from andesine to albite. Quartz and plagioclase are subhedral and equigranular, and grain sizes vary from about a half inch to an eighth of an inch. Hornblende and biotite are the mafic minerals with hornblende dominating and comprising about one fifth to one tenth of the rock matrix. Accessory minerals are apatite and magnetite. An occasional grain or grains of scheelite were found in outcrops, but its sequential relationship to the granodiorite was not determined.

Potassium Feldspar-Enriched Granodiorite. In the northeast corner of section 9 an area of granodiorite has been enriched with potassium feldspar. Several potassium feldspar pegmatites and veinlets have permeated the granodiorite with orthoclase and some perthite. This enrichment in potassic feldspars is considered to be post-granodiorite as several of the pegmatites can be traced out of the unit into nearby units.
Generally, the mineralogical make-up of the two types of granodiorites is very similar except that the potassium feldspar enriched unit has orthoclase and perthite present. A small portion of the plagioclase has been depleted during enrichment.

The increased feldspar component of this unit and its saturated nature has produced an extremely easily weathered and friable unit. Competent samples were impossible to collect even in the deep cuts along the aqueduct road.

The potassium feldspar pegmatites and veins which permeate this unit are related to the quartz monzonite sequence and to a potassium feldspar differentiation of the quartz monzonites. Evidence for this relationship exists in the quartz monzonite units west of the study area where the quartz monzonites are rich in potassium feldspar and potassium feldspar pegmatites radiate outward from this area.

Quartz Monzonite Unit. The youngest major intrusive unit in the study area is the quartz monzonite found in the west central portion and southwest corner of the study area. The unit also was found in some of the deeper core holes of the Tungsten Peak Mine but not in surface outcrops.

This unit is the coarsest textured of the intrusive sequence with equigranular and equidimensional textures of about \( \frac{1}{4} \) inch being common. Composition is rather uniform throughout the unit and primarily is a biotite quartz monzonite. Feldspars and quartz predominate in nearly equal
amounts with quartz generally more abundant. Anhedral to subhedral grains of quartz and feldspar are common with the quartz grains generally occurring as the larger of the two. Feldspars are albite and orthoclase with some anorthoclase. The albite and orthoclase are easily differentiated by twinning in the albite. Biotite is the major mafic mineral and is subordinate to the siliceous minerals. Minor amounts of augite and hornblende are subordinate to the biotite. Accessory minerals include sphene, fluorite, and magnetite.

In the study area, the composition of the quartz monzonite is rather uniform, but west of the study area, the potassic feldspars become more prominent creating a pink colored unit. The potassic feldspar pegmatites in the study area appear to be associated with the quartz monzonite rather than the earlier units.

Because of the large quartz component present, the unit is usually very resistant to weathering. The unit forms many ramparts and spires of igneous rock which appear to rise out of the weathered sections of the other intrusives. Some of these ramparts are rugged and dramatically shaped and have been the focal point for several Indian legends developed by local tribes.

*Other Intrusive Units.* Several minor intrusive units and pegmatites are found in the western half of the study area and include small granitic stocks and pegmatites of quartz, calcite, albite, and orthoclase, perthite, anorthoclase, and quartz. These units are limited in areal extent although the
potassic feldspar pegmatites are rather abundant in sections 4 and 9.

The granitic stocks include small stocks of an epidote granite and an orthoclase alaskite and are found along the southern contact of the roof pendant in section 4. Compositions of these units are different from the major intrusive units of the study area and probably represent small differentiated stocks from the plutonic source material. Both units are silica rich with quartz, orthoclase, and microcline being the major components. The epidote granite has an abundance of epidote which is the major non-siliceous component. The epidote is subhedral and exists with minor diopside. Muscovite is common in both units although some minor biotite does exist in the orthoclase alaskite.

Ages of these stocks appear to be post granodiorite, but further age determinations cannot be made because the granodiorite is the only intrusive with which these stocks are in contact. The very acidic composition of these stocks may indicate a late intrusive pulse but the evidence is vague.

The pegmatites can be separated into two groups, a quartz, calcite, albite, and orthoclase group, and an orthoclase, perthite, anorthoclase, and quartz group. These two groups are spatially separated which created difficulty in determining age relationships. The potassic feldspar group is the more abundant of the two and is found in section 4 and the northern half of section 9. They are generally very coarse grained pegmatites with grain sizes of several inches. Textures are anhedral to subhedral with some minor euhedral
growth. Orthoclase and perthite are the most abundant components of the pegmatites and produce a very pink color. Anorthoclase, quartz and muscovite are the minor components and are smaller in grain size than the potassic feldspars. The second group, the quartz, calcite, albite pegmatites are more graphically textured than potassic feldspar pegmatites. The three components are relatively equal in abundance and anhedral to subhedral in texture. Muscovite is the accessory mineral and appears as subhedral to euhedral grains generally about one inch in size. These quartz, calcite and albite pegmatites are found in the area south of the potassic feldspar pegmatites and are not associated. The line of separation occurs just south of the east-west center line in section 9. Because these two pegmatite groups are spatially separated, age relationships between them cannot be determined. However, both groups are found in the youngest intrusive of the area, the quartz monzonite, which suggests a post intrusive age for the two pegmatite groups.

**Alluvial and Colluvial Units**

Three general detrital groups were identified in the study area and include an old alluvium, a young alluvium, and a colluvial unit which covers most of the two older intrusives found in the study area. The young alluvium is a sandy to cobbly alluvial unit found in and adjacent to the present drainage systems of the study area and occurs as the fans and bajada which have developed along the range front. The large clasts and boulders associated with the young alluvium
are angular-to-subangular and are composed of material derived from the units exposed in the region. The old alluvium is a more cobbly unit, and developed soil profiles are visible where the unit has been dissected by a drainage channel. The clasts in the old alluvial unit are subangular and contain a greater percentage of material from the local metasedimentary units. The older alluvium is generally found above the current drainage system which indicates a lowering of the base level of the drainage system (i.e., an uplifting of the range). More iron oxidation is visible in the old alluvium compared to the young alluvial unit which suggests deposition during an earlier, wetter climate. The Holocene period of the area shows little climatic change, but the wetter environments in the Pleistocene are well documented.

The colluvial unit was the most difficult to identify because of the similarities between this unit and the deeply weathered igneous units. A general increase in the vegetation and a weathered horizon of greater than 10 feet were used to identify the colluvial unit. Low-angle light (early morning and late afternoon) seemed to enhance the variations between the colluvium and weathered intrusives. Once an area was studied in air photos and at a distance, on-site surveys were conducted to check the colluvial contact. Most of these contacts showed only minor lithologic variations. Because this technique is very interpretative, the colluvial contacts are mapped as inferred contacts (dashed).

Another problem associated with the colluvial unit was the masking of other contacts particularly those between the
plutonic units and plutonic and metasedimentary units. These contacts were mapped by studying the colluvial lithology and noting where the lithologic variations occurred (i.e., weathered material does not roll uphill).

Structure

Mesozoic and Cenozoic tectonics associated with the Nevadan Orogeny have produced the major structural character of the study area. Mesozoic tectonics produced the intense folding in the metasediments and the elongated alignment of the pendants. Cenozoic faulting developed the current topographic character and caused erosion of the overlying units by uplifting the area above its old base level.

Faults

Several faults are found in the study area, and many are tectonically related to the Sierra Nevada Fault which is located in the eastern portion of the study area. The Sierra Nevada Fault is a series of range front step faults of the Basin and Range character and has several hundred feet of vertical offset within the study area. Zbur's (1963) geophysical studies of Indian Wells Valley estimated that the total combined vertical offset of the Sierra Nevada Fault is in excess of 8000 feet in the valley. This offset occurs in steps created by a series of parallel faults stepping towards the center part of the valley. Offset along each step is generally several hundred feet to a few thousand feet. The current range front fault, which is located within the study
The trace of the Sierra Nevada Fault is masked by alluvium and colluvium in the study area except for the southeast corner of section 15. The fault trace in this area is marked by a 20 foot scarp, other smaller scarps, and groundwater seeps which follow the trace in a south-southwest trend. The location of the fault can be interpreted from the slope change which occurs at the base of the range shown in Figure 12 and Plate I. In most of the study area, vertical offset along the current range front fault probably exceeds several hundred feet. Neither a core hole drilled at the Tungsten Peak Mine (DDH-4) nor the Tungsten Peak Mine water well, east of the mine, reached bedrock in this area. The core hole, DDH-4, drilled in section 10, approximately 400 feet northeast of the HiPeak Mine headframe and stepped out 200 feet from a limestone outcrop, bottomed out at 342 feet without encountering bedrock. The water well, drilled at the base of the slope near State Highway 14, had a total depth of approximately 450 feet and did not encounter bedrock. This data along with the current elevation difference between the alluvial fan material and the topographic highs in the area, gravity data from Zbur (1963), and other water wells north of the study area indicate that the vertical offset in the area is probably a minimum of 700 to 800 feet.

Zbur's (1963) geophysical study also identifies one of several northwest trending right lateral strike-slip faults in the Cenozoic basement intersecting the Sierra Nevada Fault near the boundary of sections 10 and 15, as shown in Figure 8.
In the area of this intersection are several interesting structural features. The trend of the Sierra Nevada Fault rotates from a north-northeast direction to a north-northwest direction. At this deflection are several radiating faults which enter the uplifted block of the Sierras. This cluster of faults appears to be related to the directional change of the Sierra Nevada Fault and are the only faults mapped along the trend of the Sierra Nevada Fault. The close spatial relationship indicates a probable common origin.

Several other faults are found in the uplifted Sierra Nevada block and are probably related to the release of tectonic stress during the uplifting of the Sierran block. Offset pegmatites and veins identify this faulting as post intrusive and it is probably Cenozoic in age.

Indian Wells Canyon is partially fault controlled as evidenced by a normal fault along its southern edge. The trace of this fault extending into the study area can be seen in the southwest corner of section 16. Another small fault offsets the drainage of Indian Wells Canyon Creek. The fault trace in the young alluvium of Indian Wells Canyon can be seen just north of the normal fault trace in section 16. The northern edge of Indian Wells Canyon also appears to be fault controlled because of the linearity of the alluvial and colluvial contact and slope change. No fault scarp or trace has been found in this area, but the dramatic change in lithology of the roof pendant trend across the east end of Indian Wells Canyon and the exposures of roof pendant material on the north wall of the current drainage channel indicate
that the north wall of the canyon is probably fault controlled.

Similar conditions exist along the north side of Short Canyon in the northwest corner of the study area. Besides the linearity of the north side of the canyon, a small left-lateral offset of the west edge of the hornfelsic pendant-intrusive contact is observed if this contact is extrapolated across the canyon. These two fault zones are highly interpretative, but sufficient evidence appears to support their existence.

Zbur (1963) interpreted that the pendant trend in the study area has been vertically offset by the Sierra Nevada Fault and that it continues in the basement material of Indian Wells Valley for a few miles. He supports this interpretation with gravity data showing a small nose or ridge in the basement material having a similar trend as the pendant material. Since the metasediments are denser than the intrusives, they would appear as an area of higher gravitational attraction, i.e., a gravity high, compared to the intrusives or Cenozoic fill. The existence of this trend is only speculative because no wells have been drilled deep enough to intersect it.

Folds

Most of the small roof pendants and inclusions of metasedimentary units show some tectonic deformation. This deformation primarily occurs as folds although several units have pre-intrusive faults offsetting the units. Such faults
are generally too small to be shown at the scale mapped. The folds, however, are very dramatic. Folds found in the pendants and inclusions of sections 10 and 15 are very tight upright parabolic folds. They affect both the limestones and hornfels and have steeply dipping to near vertical axes. These steeply dipping axes suggest that the pre-intrusive units were extensively deformed and rotated prior to the late Mesozoic intrusive episode. Such an occurrence of steeply dipping fold axes is not common in tectonically passive areas.

Fold axes were determined from beds which could be mapped as continuous within the units. Plate I shows many of these beds as sinusoidal lines in the pendants. Although surface mapping was the only tool available in most of the study area to determine fold axis plunges, plunges of fold axes collected in the HiPeak and Tungsten Peak Mines were compared with data collected from other pendants and inclusions. Overall, the fold axes are steeply plunging in a north to northwesterly direction and plunges greater than sixty degrees are common. Plunges to the south occurred in some of the pendants in the central and southern parts of the study area.

The repetitive upright parabolic folding of many of the units, especially the hornfels, produces false thicknesses of these units. As seen in Plate I, several of the small pendants and inclusions have repetitive parabolic folds which double the actual thickness of the units. The limbs of these folds almost always parallel the trend of the pendant indicating an association between the tectonics which developed the folding and the tectonics which developed the
regional character of the pendants.

Some homoclinal folds are found in the units of the large pendants, but these more massive pendants, especially in section 4, are not as intensely folded as the smaller pendants and inclusions. These larger hornfelsic pendants are more calcareous than their smaller counterparts, and are less broken up by faults than the smaller pendants. This seems to indicate that the more tectonically broken up a pendant is, the more intensely folded it has become.
The HiPeak and Tungsten Peak Mines were small mines that operated in the same skarn ore body but at different times. The skarn is part of a small low-silica limestone roof pendant near the center of section 10. Its maximum dimensions are 150 feet wide, 600 feet long, and approximately 250 feet deep. The skarn occupied the majority of the lower one hundred feet before mining and had several fingers and zones extending upward through the remainder of the pendant to the surface. The skarn's composition varies between diopside-garnet to diopside-epidote but is always pyroxene rich. The ore mineral in the skarn is the calcium tungstate scheelite, CaWO$_4$, which also occurs with molybdenum intermixed with the tungsten producing the scheelite (CaWO$_4$) - powellite (Ca(Mo,W)$_4$O$_4$) series.

The HiPeak-Tungsten Peak pendant, as it is now called, is a small, low-silica limestone pendant similar in shape to an elongated oval and extends to a depth of about 250 to 300 feet below the surface. Thin-bedded limestones have been faulted and folded prior to the intrusive sequence producing a complex lithologic unit.

The older HiPeak Mine, located on one of the surface exposures of the skarn, operated in the 1940's to 50's in the upper portions of the pendant. Three levels were developed and connected by a 40° inclined shaft. Figures 17a, 17b, and 17c are the maps of these three levels and the
Figure 17a. Plan View of the HiPeak Mine 5500 Level.
Figure 17b. Plan View of the HiPeak Mine 5450 Level.
Figure 17c. Plan View of the HiPeak Mine 5400 Level.
connecting shaft is on the western edge of the workings.

The Tungsten Peak Mine, operating in the lower skarn-rich portions of the pendant during the late 1970's, produced more ore in its short term of operation than the HiPeak Mine in its decade of operation. This difference was the result of the Tungsten Peak Mine being located in the lower portions of the pendant which was mostly ore-bearing skarn. The older HiPeak Mine had operated in the upper portions of the pendant which was dominated by limestone. The Tungsten Peak Mine developed a 600 foot long 15° incline which intersected the pendant near its root. Working upward, five main working levels were developed, shown in Figures 18a through 18e, and the ore between these levels was removed producing a single large stope and several smaller stopes.

Figure 19 is a schematic cross section on an east-west plane through the HiPeak and Tungsten Peak Mines and outlines the pendant-intrusive contact. Figure 20 is a plan view of the workings of both mines. Approximately 200,000 short tons of tungsten ore was extracted from the Tungsten Peak Mine (Tungsten Peak Mine Company records), and it has been estimated that 50,000 to 100,000 short tons of ore were removed from the HiPeak Mine. Production calculations by the author for the HiPeak Mine were closer to the lower figure.

Ore grades in the skarn varied from 0.5% WO$_3$, the cut-off grade, to as high as 5% to 10%, WO$_3$, but were generally less than 1%. Notes in Troxel and Morton (1962) on the HiPeak Mine indicate that ore grades were as high as 3%. This grade is
Figure 18. Plan View of the Tungsten Peak Mine 5380, 5360, and 5330 Levels.
Figure 18. Plan View of the Tungsten Peak Mine 5310 and 5300 Levels.
Figure 19. Schematic East-West Cross Section of the HiPeak and Tungsten Peak Mines Showing Approximate Pendant Boundaries.
Figure 20. Plan View of the HiPeak and Tungsten Peak Mines Working Levels.
questionable without first cobbing the shipment since the ore bearing skarns remaining in the mine and ore bearing skarns in the Tungsten Peak Mine rarely were this rich. Shipping data from the Tungsten Peak Mine records show that the average grade of ore shipped from the Tungsten Peak Mine was 0.75% WO$_3$. Geologically the HiPeak-Tungsten Peak pendant is a low-silica crystalline limestone pendant with beds dipping 40° either side of vertical. Bedding within the pendant generally trends north-northwest, but a sharp right angle to parabolic fold along the southern edge of the pendant changes some of the bedding to an east-west trend. The fold axis is nearly vertical with a axial dip to the south. Limbs of the fold are generally at right angles to or slightly parallel to each other in the Tungsten Peak Mine levels. In the HiPeak Mine levels the fold axis is south of the workings, but from core data it appears that the limbs are about 90° apart. Skarn zones occur throughout the pendant but are concentrated around the apex of this fold in the lower portions of the pendant. Ore-grade skarns, those having greater than 0.5% WO$_3$, are in most cases located away from the intrusive contact and grade upward into the limestone units which have not been skarnified by metasomatism. A thin layer, generally 2 to 5 feet of barren or below-grade skarn is found along the skarn-intrusive contact. The rounded bottom of the skarn which extends approximately 40 feet below the lowest production level, the 5310 level, is barren except for a few small zones of ore-grade skarns.
Figures 21 through 23 are the level maps of the two mines including geologic data and will be referred to in the following sections.

Lithology

Two major lithologic formations are found in the area of the HiPeak and Tungsten Peak Mines, the metasedimentary metasomatic units in the pendant and the quartz diorite and granodiorite intrusive units. The metasedimentary-metasomatic units consist of steeply dipping crystalline limestone with compositions ranging from relatively pure limestones to siliceous or high silica limestones, and pyroxene skarns including diopside-garnet and diopside-epidote zones. A few zones of siliceous and calcareous hornfels and schists are found in and adjacent to the pendant. The pendant is surrounded by hornblende-biotite quartz diorite and hornblende granodiorite of the intrusive series. A few small fingers of quartz monzonite are found in underground core holes drilled in the Tungsten Peak Mine, but these are minor.

Metasedimentary and Metasomatic Units

Thin-bedded low-silica to high-silica crystalline limestones are the dominant metasediments in the HiPeak-Tungsten Peak pendant. Minor zones of siliceous and calcareous hornfels, biotite schists, and the skarn zones make up the remainder of the pendant. All of these units are thin-bedded and have various beds and thin laminae of more
Low-Silica and High-Silica Limestones.

Calcareous and Siliceous Hornfels.

Biotite Schist.

Below-Grade and Barren Skarn.

Ore-Grade Skarn.

Aplite Dike.

Granitic Intrusives.

Rubble Zone.

Fault, dashed where inferred.

Probable Pendant Boundary.

Grid system on level maps is 100 x 100 ft. survey grid used as reference grid in mapping underground workings.

Grid system and level maps are referenced in the geologic cross sections and Plate II.

Figure 21. Index to Symbols Used in Figures 22, 23, 30, and 31.
Figure 22a. Geologic Map of the HiPeak Mine 5500 Level.
Figure 22b. Geologic Map of the HiPeak Mine 5450 Level.
Figure 22c. Geologic Map of the HiPeak Mine 5400 Level.
Figure 23. Geologic Maps of the Tungsten Peak Mine 5380, 5360, and 5330 Levels.
Figure 23. Geologic Maps of the Tungsten Peak Mine 5310 and 5300 Levels.
siliceous or more calcareous composition indicating an episodic transgressive and regressive depositional environment.

**Crystalline Limestone Units.** Thin-bedded, low-silica to high-silica limestones are the major component of the HiPeak Tungsten Peak pendant. These steeply dipping units have been metamorphically transformed into crystalline limestones with minor amounts of actinolite, wollastonite, and idocrase. Grain size and texture are highly variable and range from saccharoidal textures of not more than \( \frac{1}{4} \) inch down to aphanitic crystalline textures. Many of the beds show banding which when viewed under a hand lens are seen to result from laminae of quartz and feldspar with alternating with calcite laminae. This banding may represent a metamorphic differentiation since very little intermixing is found even in thin section, as is seen in Figure 16a.

The more siliceous a limestone bed, the deeper into the pendant it extends without being metasomatically altered. Some very siliceous limestones are found in the haulage drift, the 5300 level, of the Tungsten Peak Mine illustrated in Figure 23e. Another siliceous limestone found on the back of the 5310 level occurs with the skarn and could be followed upward into the 5380 level where it blended in with other limestone units, see Figures 23a through 23d.

The composition of the limestone is not the only control over skarnification of limestone. Some rather siliceous
limestones have been skarnified in the lower portions of the pendant. These skarnified siliceous limestones are found in the tightly folded apex of the major fold and had been extensively fractured (i.e., permeable) allowing more fluids to migrate into the limestone units and react with the carbonates. The resulting skarns are always more siliceous and generally ore barren.

Anhedral to subhedral grains of calcite and quartz are found in most of the petrologic samples of the limestones. Composition does not modify grain texture although definite growth relationships do vary with composition. Calcite is the major carbonate mineral although minor dolomite was found in some beds. Distorted calcite grains are found in the beds adjacent to the intrusives contacts and near small siliceous veins indicating some tectonic stress during the intrusion of these units. The amount of recrystallization of the calcite and siliceous minerals corresponds to the amount of solution activity within the unit and the distance from a thermal source (i.e., contact with the skarn or intrusive). Although the limestone units studied have varying degrees of recrystallization, no relict textures have been found. Further recrystallization and grain growth occurs in units closer to the intrusive or skarn contact. The calcite grains show about twice as much regrowth as the siliceous minerals in the same area, (see Figure 16a) which can be explained by calcite's more reactive nature than most siliceous minerals.

The contact zones are predominantly less than a foot wide between the limestones and the intrusives or the skarn. An
increase in the siliceous minerals such as quartz and some feldspars along with extensive regrowth of the calcite occurs within the limestones a few inches from the contact and increase in the intrusive. The intrusives also show a bleached zone adjacent to the limestones. The bleached zone is enriched in quartz, feldspar, and calcite and is depleted of mafics such as hornblende and biotite. This zone extends into the intrusive a maximum of a couple of feet from the contact but usually is no more than six inches wide. This bleached zone along with the siliceous zone in the limestones provide evidence of a definite exchange of components during the intrusive episode.

Lateral contacts between the skarn and limestone are usually less than one inch across. A decrease in grain size of the skarn components and the calcite grains of the limestone is found along almost all these contacts. Adjacent to the reduced calcite grains is a zone of regrowth of calcite which extends a short distance, only an inch or two, into the limestone bed. More siliceous limestones do not show this regrowth zone but do have the reduced grain contact zone. This reduced contact zone is enriched in quartz in several areas, and with the reduced calcite grains, produces a thin white band visible to the eye along many contact. The longitudinal and latitudinal contacts which have this reduction in grain size suggests that the limestones were cooler than the skarn forming fluids and caused a chilling at the contact. The regrowths described above are probably the
result of reheating the contact zone by some method.

Contacts between the skarn and the limestone found at the top of the skarnified zone are much more transitional than the lateral contacts. These transitional contacts are very gradual with a gradual decrease in skarn components and a gradual increase in calcite. All of these transitional contacts show that the majority of the skarn components grow at the expense of the calcite and occasionally the quartz. An example is shown in Figure 24. Some of these contacts are gradual over a maximum of several inches and then abruptly end. This abrupt end to the transition zone could be explained by the sudden cut off of metasomatic fluids or a build up of CO$_2$ pressure. Both possibilities will be discussed in the skarn development section.

Some unique clusters of actinolite and/or wollastonite are found on the 5400 level of the HiPeak Mine near the eastern end of the workings. Large sprays and radiating arrays, some measuring eighteen inches in diameter, are found cross-cutting several thin beds of limestone. Attempts to remove these clusters and arrays were unsuccessful because the arrays are more fragile and friable than the limestone in which they occur. These clusters are not found at distances greater than 15 feet from the skarn zones indicating an association with the skarns (i.e., the skarn's thermal effect). A possible explanation for this occurrence was found in another limestone sample which was studied petrographically, Figure 25. In this sample, a small microrfracture filled with quartz, calcite, and fibrous mineral similar to actinolite or wollastonite, (composition could not
Figure 24. Color Photomicrograph of Skarn Minerals, Diopside (d) and Grossular (g), in a Calcite (c) and Quartz (q) Matrix. (Crossed nicols).
a. Microfracture with fiberous minerals, wollastonite (w) (?). (Crossed nicols).

b. Microfracture ending in fiberous mineral spray. (Fiberous mineral is wollastonite (w) (?), mineral in extinction is plagiocalse (p). Crossed nicols).

Figure 25. Color Photomicrographs of Microfractures with Fiberous Minerals and Sprays.
be determined due to small grain size) terminated in a series of calcite grains. A small radiating spray of this fibrous mineral was developing at the end of the microfracture and a small branch fracture near the end of the main fracture. This growth of the fibrous mineral shown in the figure probably represents similar processes which developed the larger arrays mentioned above. The occurrence of these fiberous minerals near or adjacent to the skarn zones is similar to occurrences that Wright (1973) noted in the Pine Creek Mine near Bishop, California. He suggests that these minerals are associated with a thermal zone which develops around the skarn during the formation of the skarn.

**Argillaceous Units.** Only a few argillaceous units are found in or adjacent to the HiPeak-Tungsten Peak pendant and most of these are small xenoliths in the intrusive units. These units include siliceous and calcareous hornfels and a few lenses of biotite schist. They generally parallel the trend of the limestone units except the smaller units appear to have been slightly rotated during the intrusive sequence. The hornfels are dark green to reddish brown and highly weathered when they occur above the 5380 level and are dark green to green-black in color below this level. This is attributed to the water table level which existed at about the 5300 level prior to opening the Tungsten Peak Mine. The hornfels units above this level have been oxidized and weathered while those below this level have not been exposed.
to the air long enough to be oxidized.

Hornfels in or near the pendant are generally of calc-silicate composition. The more calcareous hornfels have been metasomatically altered producing diopside, epidote, and wollastonite along with the original minerals such as quartz, feldspar, calcite, and biotite. The more siliceous units such as those found in the upper portions of the pendant and adjacent to it show a lesser percentage of metasomatic alteration as would be expected. Anhedral to subhedral grains are common and very few euhedral grains occur in zones of recrystallization. Textures are all aphanitic, but the alignment of biotite and the thin-bedded character of the hornfels produces a schistose texture in most of the hornfels. This alignment can also be seen in the thin section shown in Figure 14b.

Bedding in the hornfels is nearly vertical and has a similar trend to the limestone units. Beds vary in thickness from less than ¼ inch to a maximum of four inches with the majority of the beds being approximately one to two inches in thickness. Width of the hornfelsic units rarely exceeds ten feet, but lengths of xenoliths and lentils can be nearly 40 feet or more.

Small calcite and quartz veinlets are found in all the hornfels. These veinlets have no particular trend and are generally only about ¼ inch wide. The density of the veinlets is much greater in the hornfels than in the adjacent limestones. These occurrences follow the hypothesis put forth
by Turner and Verhoogen (1960) that the calcite-quartz veinlets are formed during the metamorphism of schistose type rocks as a metamorphic differentiation product.

The hornfelsic units seem to be more easily assimilated by the intrusives than the limestones. Small hornfelsic xenoliths and inclusions are found in almost all core samples which extended into the intrusives, and the composition of the intrusive around these small xenoliths include a higher mafic content than the normal intrusive. This compositional change along with the fact that most of the hornfelsic pendants do not extend into the intrusives as deep as the limestones, leads to the conclusion that hornfelsic units in comparison to the limestones were assimilated to a greater extent by the intrusives. This assimilation is similar to that observed by Wright (1973) at the Pine Creek Mine near Bishop, California. At Pine Creek, the limestone rich pendants and septa acted as partitions to the rising intrusives while the more hornfelsic units between these limestone units were assimilated by the upwelling intrusives. An example of this assimilation can be seen along the west edge of the HiPeak-Tungsten Peak pendant. At the surface, a hornfelsic unit is in contact with the limestones of the pendant, but at depths along this contact the intrusives are found with only fragments of the schistose hornfels, and in some zones, a biotite schist remains. This phenomena is illustrated by comparing Plate II and Figures 22a through 22c.

A second major argillaceous unit which is found in the
upper regions of the pendant is a large intrabed of biotite schist. This schist is found in the 5500 and 5450 levels, Figures 22a and 22b respectively, near the center of the pendant. Similar in composition to the other hornfels in the pendant, this schist is more foliated and finer grained. The unit thickens with depth to a maximum thickness of about 20 feet at the 5450 level. Below this level, the schist is no longer visible in the workings except for a small remnant found in a highly fractured zone in the 5400 level, Figure 22c. The disappearance of the schist and the existence of the small remnant which is not continuous with the schist found in the 5500 and 5450 levels is not totally understood.

Associated with this biotite schist is a scheelite bearing skarn which is in contact with the schist along its east edge. This skarn is only a few feet thick but was one of the major producing units of the HiPeak Mine. The contact between the schist and the skarn at the 5450 level is a fault contact. This fault may have been the permeable conduit for the rising metasomatic fluids.

A few other small biotite schist units are found adjacent to the pendant, but most of these seem to be small xenoliths of hornfels which have been metamorphosed to a greater degree.

**Skarn Units.** The majority of the skarn units found in the HiPeak-Tungsten Peak pendant are rooted to a massive skarn found in the lower portions and base of the pendant. This massive skarn is found in the lower hundred feet of the
pendant with nearly all the lower 50 feet of the pendant being composed of skarn, Figures 23b through 23d. From this massive skarn, several fingers and limbs of skarn extend upward into the upper portions of the pendant. Some skarn bodies extend to the surface or near the surface, as shown in Figure 22a and Plate II. A few small isolated skarns are found along the intrusive-pendant contact in the upper portions of the pendant and apparently are not directly connected to the massive skarn, but similarities in composition indicate a probable contemporaneous origin.

The massive skarn is a complex mixture of several different types of skarns formed by Fe-Mg-Si metasomatic reactions occurring in the carbonate environment of the pendant. The metasomatic fluids, which were enriched with Fe, Mg, Al, and Si, and contained minor ions such as Cl, F, WO3, Mo, S, entered the carbonate environment at the contact with the intrusive. The fluids migrated upward through the contact reacting with the host environment producing a complex calc-silicate mineral assemblage called a skarn.

Several different types of calc-silicate skarns are found in the massive skarn and include diopside-garnet, diopside, and diopside-epidote skarns. The general mineral assemblage in these skarns are diopside, calcic garnets, epidote, actinolite, wollastonite, and quartz. Accessory minerals include pyrite, pyrrhotite, magnetite, fluorite, apatite, chalcopyrite, bornite, idocrase, hematite, and sphene. Not all of these minerals occur in the same skarn but occur in
varying concentrations within the different skarns. Ore minerals found in the skarn include the calcium tungstate scheelite and the calcium molybdenum tungstates called Mo-scheelite and powellite. A few minor occurrences of the molybdenum sulfide, molybdenite, were also found but were never in large enough concentrations to be considered a primary or secondary ore mineral.

The cut-off grade for both mines was 0.5% tungsten tri-oxide (WO$_3$), and was controlled by visual estimates. This cut-off grade was set by the ore buyers. This cut-off grade is used in this study to separate the skarns into two main classifications, ore-grade, and below-grade and barren skarns. Because of the complex nature of the skarns found in the HiPeak-Tungsten Peak pendant, a clear separation between ore-grade and below-grade and barren skarns is difficult to accomplish. Separation of ore-grade, and below-grade and barren skarns was based on visual estimates. If the skarn appeared to have 0.5% or greater WO$_3$, it was considered ore and then mined. If the ore grade is below 0.5% WO$_3$, then the skarn was considered to be below-grade or barren and left as wall rock or removed as waste. Exceptions to this criterion were small skarn zones which were not economically mineable but had ore-grade concentrations of scheelite.

1. Ore-Grade Skarns. Three types of ore-grade skarn are found in the pendant and are generally bordered by the below-grade and barren skarns adjacent to the intrusives. The first
type is a diopside-grossular skarn with quartz and calcite composing an equigranular aggregate of grains up to one half inch in size. Accessory minerals include pyrite, pyrrhotite, fluorite, magnetite, bornite, and chalcopyrite. The pyrite and pyrrhotite are generally the most abundant of the accessory minerals. The tungsten minerals are blue-white fluorescing scheelite and the yellow-white fluorescing Mo-scheelite. Diopside, grossular, quartz, calcite, fluorite and most of the accessory minerals are all anhedral to subhedral whereas the pyrite, pyrrhotite, and scheelite is subhedral to euhedral. Some samples of the diopside-garnet skarn show a subhedral-to-euhedral character in the diopside and grossular. Most of the scheelite has a yellow-white fluorescence and some grains show a zoning of yellow color with the richer yellows in the center grading outward to yellow-white or white. Such a gradation indicates a decrease in the Mo component of the scheelite.

The diopside-grossular skarn is generally found in the lower and upper levels of the skarn. This type of skarn is the most abundant ore-grade skarn found in the HiPeak Mine workings except for the central core.

The second ore-grade skarn is a diopside skarn in which grossular is nearly absent. The diopside occurs as equigranular grains with quartz and calcite composing approximately one fourth to one eighth of the skarn. The amount of sulfides within this skarn varied dramatically but was generally less than in the diopside-grossular and
diopside-epidote skarns. Also in the diopside skarn, pyrrhotite and bornite are generally the major sulfides. Scheelite varies from the purer blue-white fluorescent varieties to the yellow-white fluorescing Mo-scheelites and occurs in greater concentrations in the diopside skarns than the diopside-grossular skarns. The diopside skarns can generally be easily differentiated from the other two ore-grade skarns by its darker green color. The color difference can be seen in Figure 26 which is a working face of typical ore-grade skarn.

The diopside skarns are generally restricted to the massive skarn and are intermixed with the diopside-grossular and diopside-epidote skarns. The barren skarn found at the roots of the pendant is very similar to the diopside skarn except for the increase in the amount of quartz to nearly fifty percent.

The third type of ore-grade skarn is the diopside-epidote skarn which is usually a dark apple to lime green in color. Diopside is approximately twice as abundant as epidote and generally better developed, as shown in Figures 27 and 28. Quartz, calcite, and actinolite along with the accessory minerals pyrite, pyrrhotite, fluorite, magnetite, wollastonite, chalcopyrite, and bornite, generally occurs in lesser amounts than in the diopside-grossular and diopside skarns. Scheelite mineralization is more abundant in the diopside-epidote skarns than the other two ore-grade skarns, and small zones of scheelite concentrations up to 10% WO3 were
1. Small Diameter (1.5") Exploration Core Hole

2. Diopside-Grossular Skarn

3. Quartz Vein

4. High-Silica Limestone

5. Diopside-Epidote Skarn

6. Diopside Skarn

Figure 26. Typical Lithology of Ore-Grade Working Face.
Figure 27. Color Photomicrograph of Typical Diopside-Epidote (d,e respectively) Skarn with Pyrite (py) and Pyrrhotite (pr). (Crossed nicols).
Figure 28. Color Photomicrograph of Typical Diopside-Epidote (d,e respectively) Skarn with Grossular (g).

a. Polarized Light. (Crossed nicols).

b. Plain Light. (Uncrossed nicols).
found in these skarns. Scheelite is predominantly light yellow in color indicating a higher Mo content than the diopside-grossular skarn.

Petrologic studies of the diopside-epidote skarn show both primary and secondary epidote. The primary epidote is found in the calcite, quartz, diopside mineral association and occurs as subhedral to euhedral grains as seen in Figure 27. The secondary epidote is found in grossular grains as a regrowth or retrograde mineral as shown in Figure 29. The retrograde metamorphism of the core of the pendant is evidenced by the increase in epidote and decrease in grossular in the skarn. This is similar to what Morgan (1975) saw in the Mt. Morrison tungsten skarn near Bishop, California.

These diopside-epidote skarns are found in the central portions of the pendant in the middle and upper regions which would be expected according to the retrograde metamorphic theory. A temperature gradient develops within the skarn as the pendant begins to cool causing the inner skarns to cool at a much faster rate than the outer skarns. This internal cooling may have been caused by several different factors. Two of the most likely factors are the intrusive bodies may still be holding latent heat or may have been heated by a younger intrusive body, and/or microfractures above the skarn zone developed and allowed the gaseous volatiles of the skarn reaction to escape out of the system removing heat with them. As a result, the garnets in the inner skarn are converted to epidote while those in the outer skarn are preserved. This is
Figure 29. Color Photomicrograph of a Skarn Showing Epidote (e) Replacing Grossular (g). (Crossed nicols).
seen by a decrease in replacement epidote and an increase in garnet from the center of the skarn outward.

Contacts between the skarn and limestones are generally gradational over a few inches with the quantity of calc-silicate mineral decreasing toward the limestone. Poorly developed garnets and pyroxenes are found several inches into the limestone indicating a partial metasomatic reaction in the limestone adjacent to the skarn. The grain size also decreases both in the limestone and skarn toward the central portion of the contact where grain sizes are of uniform size in both the skarn and limestone. In the HiPeak Mine, the diopside-epidote skarn is generally restricted to low-silica limestone beds. Deeper into the pendant the diopside-epidote skarn is found in both the low-silica and moderate-silica units of the high-silica limestone beds. This difference is probably attributably to the greater permeability and reactiveness of the low-silica limestone beds in comparison to the high-silica limestone beds which allowed a greater upward migration of the skarn forming fluids.

2. Below-Grade and Barren Skarn. The below-grade and barren skarns are defined as those in which there is less than 0.5% WO$_3$ in the skarn. These zones occur around the perimeter of the main skarn varying in width from a few inches to several tens of feet and as intrabeds of barren or below grade skarn within the ore-grade skarns. A major below-grade and barren skarn zone is found at the bottom of the pendant as
Lithologically three types of below-grade and barren skarn have been identified: a grossular rich skarn, a grossular-diopside skarn, and a diopside-quartz skarn. The grossular rich (greater than 50%) skarn is found along the southern edge of the skarn in the lower and middle levels and is primarily large ($\frac{1}{2}$ to 3 inch) euhedral to subhedral, reddish-brown garnets in clusters up to 18 inches across. Diopside, quartz and calcite are interspaced within the clusters and in between clusters and are generally anhedral in shape and less than 1 inch in size. Scheelite occurs as sporadic grains, anhedral in character, and generally less than a quarter inch in size. Occasionally a zone will have enough scheelite to be mined, but the greatest portions of the garnet skarn are below-grade or barren.

Contact with the intrusive is characterized by an increase in the amount of quartz and a decrease in the size of the garnets. The contact is also bleached of mafics and generally consists of albite, white orthoclase, and quartz.

A second type of below-grade and barren skarn is also found along the perimeter of the ore-grade skarn. This skarn is generally an aggregate of grossular garnet, diopside, quartz and calcite and is generally light green to dark green in color with anhedral grains less than one half inch in size. The grossular-diopside skarn has gradational changes in the diopside and quartz ratios. These skarns exist along the southeast and eastern edge of the ore bearing skarn in the
Figure 30. Schematic East-West Geologic Cross Section of the HiPeak-Tungsten Peak Skarn.
Figure 31. Schematic North-South Geologic Cross Section of the HiPeak-Tungsten Peak Skarn.
lower and middle levels.

Contacts with the intrusive are generally enriched in massive quartz. One of these massive quartz zones is approximately 18 inches thick and separates the grossular-diopside skarn from the bleached intrusive boundary.

The third type of below-grade and barren skarn is an equigranular quartz-diopside and diopside-quartz skarn. Small amounts of apatite and epidote are also found in this unit. Occurring in the region below the lowest workings, this skarn comprises most of the root of the pendant and the more siliceous beds of the middle and upper areas of the skarn. This siliceous diopside-quartz skarn includes varying amounts of calcite in the middle and upper layers and can be extrapolated upwards to the more siliceous limestone units found in the pendant.

Core samples taken below the 5300 level in the Tungsten Peak Mine show that the contacts between the skarn and intrusive units in the bottom of the pendant are similar to other contact zones in the lower portion of the pendant. The contact zones are approximately 12 inches in width although some contact zones are up to three feet wide. The abundance of quartz in the contact zone increases toward the intrusive. A similar increase in abundance of feldspars on the intrusive side of the contact zone is also noted. In the central portion of the contact zone the quartz component is usually 60 to 75% of the total. The feldspar enriched zone within the intrusive indicates ionic exchange also occurred from the
skarn to the intrusive. Alkali enriched ionic solutions expelled from the limestone-skarn reactions adjacent to the contact zone, migrated into the intrusive and produced the feldspar enriched zone.

Contacts between the skarn and high-silica limestones in the lower portions of the pendant are much more abrupt than the skarn-intrusive contacts and rarely exceed two or three inches in width. Even though the contact zone is much narrower, a transition zone between the two units does exist. This zone shows a gradual decrease in grain size of the skarn to the limestone and a corresponding decrease in the calc-silicate minerals.

Igneous Units

The igneous units found in contact with the HiPeak-Tungsten Peak pendant are predominantly quartz diorite. A few areas of granodioritic type rocks are found along the western edges of the pendant. The quartz diorite is typically of the more siliceous unit of the diorite-quartz diorite series discussed previously in the study area geology section. Hornblende is the major mafic mineral along with biotite while the intermediate plagioclases comprise most of the feldspar component. Accessory minerals include sphene, apatite, pyrite and magnetite. The granodioritic rocks are more siliceous and have a larger percent of orthoclase and sodic plagioclase. Interfingering of granodiorite and quartz diorite found in core samples taken around the perimeter of the pendant
indicate that the granodiorite is post-quartz diorite because the percent of granodiorite increases with depth. Also, minor amounts of epidote and actinolite are found in the quartz diorite indicating probable metasomatic and metamorphic alteration.

Bleached intrusive zones occur at the skarn-intrusive contact as described previously and at the quartz diorite-granodiorite contacts. The bleached zone at the intrusive-intrusive contact is generally less than a foot in width and consists of a fine grained quartz rich matrix with albite and orthoclase and very few mafics.

Several quartz-calcite veins and veinlets can be found in the quartz diorite and skarn with the majority of these occurring in the skarn. Generally only a fraction of an inch in width, some of these veinlets are associated with a late mineralization pulse as mentioned earlier in the ore grade skarn section. These veinlets show evidence of being conduits for mineralization fluids. Occurrences of regrowths of grain boundaries adjacent to the vein or veinlet, the existence of new mineral growths, such as calc-silicate minerals within and along the vein borders, and the extensive grain growth or quenching in the vein itself all indicate that these veins and veinlets carried various mineralization fluids. The lack of scheelite in these veins found in the intrusives indicates that the intrusives do not have enough calcium available to produce large quantities of scheelite from the ore-bearing fluids which passed through them. The occurrence of random
scheelite grains within the intrusives indicates that tungsten mineralization is a regional occurrence, but that the intrusives are not a favorable host rock (i.e. lack enough calcium to produce large quantities of scheelite).

**Structure**

The HiPeak-Tungsten Peak pendant is a relatively small pendant when compared with other pendants in the study area but is one of the larger thin-bedded low-silica limestone pendants. The pendant is similar in shape to an elliptic paraboloid with the crown of the parabolic fold being near the bottom and along its southern edge. Measuring approximately 600 feet in length, 150 feet in width and 250 feet deep, the pendant is elongated in the direction of bedding and parallels the major structural trends in the study area. Bedding within the pendant is near vertical with several folds and faults distorting the general northerly trend. A major parabolic fold, with a tensional fault along its axial plane is found on the surface, see Plate II, but disappears rather quickly down section. Another right angle fold is found farther downsection, see Figures 19a-19d, and may be a faulted extension of that fold found on the surface although their interrelationship is unclear.

At the surface the majority of the bedding in the pendant follows a northeast to northerly arcuate trend. The eastern limb of the parabolic fold, found along the western edge of the pendant, follows this trend. Down section the arcuate bedding
trend continues to about the 5380 level, Figure 23a. Below this level a right angle fold occurs in the pendant. The relationship between this fold and the parabolic fold at the surface is unclear, but it appears that a very complex fold axis is related to both. Faulting along the axial plane and along the western edge of the pendant may have offset the folds. Faulting along the axial plane of both folds suggests this hypothesis. Additional evidence for this hypothesis was found in core holes drilled south of the 5400 level, Figure 22c. Dramatic changes in bedding directions in the core were separated by a rubble and gouge zone similar to that seen in the axial plane fault on the 5380 to 5330 levels Figures 23a - 23c.

A minor right-lateral strike-slip motion along the axial plane zone in the lower levels appears to have occurred after the skarns were developed. The dip-slip component is indicated by the offset of the skarn-limestone contact between the 5310 and 5330 levels, see Figures 23c and 23d, and the strike component is indicated by the small extension faults which radiate into the intrusives at the southern end of the 5330 level, Figure 23c.

The fault which offsets the western edge of the pendant is found in the lower parts as a wide rubble zone with both pendant and intrusive rubble material. This rubble zone is composed of two northerly trending faults approximately ten to fifteen feet apart with a large rubble and gouge zone between them. This fault zone extends upward to the 5360 level,
Figure 23b, where it is a large rubble zone about 10 feet wide. No major rubble zones are found in the working levels above the 5360 level but fault contact between the limestone pendant and intrusives is seen along the western edge of the pendant in the levels above.

Both of the faults discussed above appear to have been active during both pre and post-skarn development. Trace scheelite mineralization is found in both faults and appears to be in place rather than crushed material of the adjacent units. Gouge material and rubble of post-skarn material are also found within the gouge zone indicating two periods of movement which occurred before and after the development of the skarn.

A large north-northwest trending fault is found about 50 feet east of the pendant in the 5300 and 5310 levels (see fig. 30c). This fault correlates with several parallel fault trends found along the eastern edge of the pendant at the 5500 level and surface. This fault appears to be part of the Sierra Nevada Fault system as the eastern side has been down-dropped with respect to the western side and the fault parallels the trend of the Sierra Nevada Fault. This normal fault character is seen by comparing the intrusive units on either side of the fault zone in the Tungsten Peak Mine haulage decline east of the 5300 level. The intrusive units east of the fault zone are deeply weathered quartz diorites, whereas west of the fault the intrusives are more competent quartz diorite and diorite. Similar weathering of the
intrusives west of the fault occurs between the 5450 and 5500 levels which are over 150 feet higher than the level where the Tungsten Peak Mine decline crosses the fault trace.

Figures 30 and 31 are schematic cross sections through the HiPeak-Tungsten Peak pendant on east-west and north-south lines. These sections were constructed to show the basic geologic character of the pendant and major structural occurrences.
SKARN FORMATION

The HiPeak-Tungsten Peak skarn was developed in thin-bedded low-silica and high-silica limestone units which were thermally metamorphosed into crystalline limestone units. The low-silica units have been metamorphosed into a near marble character (marmorized), and the high-silica units were converted to crystalline siliceous limestones. Tremolite-actionolite and wollastonite are found in several regions of the limestone units and are always close to a skarn unit. These minerals are probably associated with increased temperature gradient created by the skarn forming fluids rather than the thermal metamorphism accompanying the intrusion. This hypothesis is substantiated by the fact that these minerals are only found close to skarn units and not wide spread through the limestones.

The skarns were developed from intrusive derived fluids rich in Fe, Si and Al migrating upward and contacting the carbonate host rocks. Reactions produced calc-silicate minerals such as pyroxenes and garnets while releasing CO$_2$. The volumes of material exchanged are enormous as can be seen by relating the volume of skarn developed to its original limestone character. In most cases the igneous unit shows very little alteration in contrast to the skarn which has resulted from a tremendous input of material converting the limestone to skarn. Calculations by Edwards and others (1956) were developed as theoretical evaluation of what was required to produce a typical tungsten skarn of average grade, 0.5%
WO$_3$, from a million tons of marble. The following values demonstrate the quantity of material needed to produce this skarn.

+ 370,000 tons SiO$_2$
+ 250,000 tons Fe$_2$O$_3$
+ 55,000 tons Al$_2$O$_3$
+ 30,000 tons H$_2$O
+ 10,000 tons MgO
+ 7,500 tons WO$_3$
- 350,000 tons CO$_2$
- 82,500 tons CaO

A net increase of almost 300,000 tons of material is necessary to develop a skarn from one million tons of marble. Adjacent limestone or marble units may remain relatively unaltered except for normal metamorphic reactions such as the formation of wollastonite and/or tremolite-actinolite. The majority of this net increase must be absorbed in the skarn.

The inflow of fluids into the limestone is generally controlled by pressure and thermal gradients across the pendant, the permeability of the carbonate, and the gas or fluid pressure of the fluids. The gradients are controlled by the intrusive temperature and depth of burial (i.e., pressure). The permeability is a function of the host rock's composition and tectonic history. The fluid pressure is controlled by the volatiles present and the driving force behind the fluid.

The gradients across a pendant must be such that fluids will move toward the pendant from the intrusive, and the
gradient must be stabilized for a period of time to allow the migration of fluids at a relatively uniform rate (Bryzgalin, O.V., 1958). This does not mean that the fluids are continually flowing through the material, but probably are flowing intermittently.

Wright's (1973) study of the Pine Creek skarn near Bishop, California established a temperature range of 500° - 700°C with pressures of only a few kilobars determined by the occurrences of wollastonite in the pendant. This low pressure indicates a relatively shallow depth and corresponds to the studies by Evernden and Kistler (1970) which hypothesized that the general depth of emplacement of the Sierra Nevada Batholith was only a few kilometers (1-2 miles). Similarities between the skarns found at the HiPeak-Tungsten Peak Mines and the Pine Creek Mine tend to indicate that their origins were at similar depths.

Permeability of the carbonate host rocks at the HiPeak-Tungsten Peak skarn seems to be controlled by the tectonic history. The majority of the skarns occur in zones which have been broken tectonically, such as along fracture zones, adjacent to small dikes, and along the apex of a major fold in the carbonates. The most massive skarn occurs at the fold apex illustrated in Figures 20a through 20d. Other occurrences of skarn in the HiPeak Mine and Tungsten Peak Mine are also related to tectonic fracturing of the carbonates. This tectonic fracturing developed the supercapillary and capillary conduits as described by Holser (1947) which increased the permeability of the carbonates resulting in a
greater volume of fluids contacting the grain boundary and intra-lattice conduits. The importance of tectonic fracturing of the carbonates can be observed in other areas not as extensively fractured. The skarns in these areas are only a few inches to a few feet wide bordering a small fracture zone. The variations in permeability of the carbonate units produced the variability in upward skarn migration. In general the low-silica units had a greater permeability than those of more siliceous character.

Stratigraphic character of the host rock also controls the development of skarn. A host rock with abundant calcium must be available to develop the calc-silicate mineral assemblage. As seen in the skarns of the HiPeak and Tungsten Peak Mines, the low-silica limestone beds have better developed calc-silicate mineral assemblages in their associated skarns than the high-silica limestones whose associated skarns have a much greater abundance of siliceous minerals rather than calc-silicate mineral assemblages.

The combination of tectonic chewing and favorable calcic host rock are the primary components in skarn development. An example in the Tungsten Peak Mine is seen in the 5310 level. At this level good carbonate host rocks have been tectonically shattered along the apex of a fold. Well developed skarns are found along the apex of the fold. Along the limbs of the fold, which have not been as extensively shattered, the skarns are less developed or non-existent.

The fluid pressure within the pendant appears to have been relatively constant during fluid migration resulting in
relative uniform upward extent of the skarn. The skarn zones that have a greater vertical extent are found in the more permeable (i.e. low-silica) limestone beds. Volatiles and partial pressures of the gaseous phases also play a part in fluid movements. The pressures of the gases drive the fluids into low pressure regions and force the fluids along these paths. These paths are the same channels of fluid flow discussed by Holser (1947). Little work has been done on the partial pressures of gases and fluids in metasomatism and skarn development, but it is accepted that the release and escape of CO\textsubscript{2} from the skarn environment must be accomplished for the necessary reactions to occur. If the CO\textsubscript{2} cannot escape the reaction zone, the reactions cannot proceed due to excess CO\textsubscript{2} pressure.

The skarn forming process occurs along the advancing fluid front (Holser, 1947; Korzhinsky, 1950). As the fluid is depleted by reaction with the carbonates, additional fluid is added to the reaction zone. In order for the reaction zone to advance into the host carbonates, the newly developed skarn must retain a permeability that allows fluids to continue migration. This permeability is retained by the microfractures which allow the movement of fluids into new carbonate units. These microfractures were observed in thin sections of several samples, see Figure 32, as thin veinlets of micro-crystalline quartz which filled the microfractures during post skarn phases. If fluid flow is interrupted, the skarn forming reactions cease for lack of new supply of fluids entering the area.
a. Random microfractures in Diopside-Epidote Skarn filled with quartz (q) and wollastonite (w) (?). (Crossed nicols).

b. Quartz (q) and Calcite (c) in parallel microfractures (in extinction) in Quartz-Diopside (d) Skarn. (Crossed nicols).

Figure 32. Color Photomicrographs of Microfractures in Skarn Units.
Changes in fluid chemistry have been demonstrated by Wright (1973) in geochemical studies of the Pine Creek Mine skarn. Generally these changes in the chemistry of the fluids were identified by zoning in the garnets and pyroxenes although some subtle changes in overall mineralogy were also noted by Wright. Zoned garnets and diopside, as shown in Figure 33, were seen in some units of the HiPeak-Tungsten Peak skarn indicating that fluid chemistry changes also occurred in this area. In Wright's (1973) studies of the Pine Creek skarn, he states that temperature gradients controlled much of the major skarn character and zones. Several variations in skarn composition are found in the HiPeak-Tungsten Peak skarn, but these variations are attributed to the variations in the host limestone composition rather than temperature gradients.

The only zoning in the skarns which appeared to have been controlled by temperature is the thin band of below grade and barren skarn which is found around the perimeter of the major skarn zone between the 5310 level and 5360 level. The zone of below-grade and barren skarn is generally one to three feet in width and has a much higher quartz content than those skarns found in the interior of the pendant. This enrichment in quartz is related to the exchange of siliceous and carbonate components across the contact with the intrusives and the units of the pendant. Holser's (1947) studies indicate that this exchange is created by a thermal gradient across the contact.

Zoning developed during the cooling of the intrusive
a. Zoning in grossular (g). (Crossed nicols).

b. Zoning in diopside (d), in Dioside-Epidote (e) Skarn with calcite (c). (Crossed nicols).

Figure 33. Color Photomicrographs of Zoning in Grossular and Diopside.
bodies and pendants within these intrusives as evidenced by the retrograde metamorphic occurrence of epidote. The grossular garnets have partially retrograded to epidote (see fig. 31) in the central portions of the pendant, while around the outer edges of the pendant only limited retrograde metamorphism has occurred. This indicates that a decreasing thermal gradient existed into the central portion of the pendant after the skarns were developed. An apparent sudden quenching of the region (i.e. tectonic uplift to a cooler environment) created a halt in the retrograde processes. This halt in retrograde metamorphism is similar to what was seen by Morgan (1975) in the skarns of the Mt. Morrison pendant near Bishop, California.

Scheelite formed as a late or post skarn component in the overall skarn development as is indicated by subhedral to anhedral grains in a subhedral to euhedral matrix. The occasional euhedral scheelite grains are always found in a calcite or epidote grain cluster. The presence of scheelite in the skarn is definitely controlled by the calcareous nature of the replaced bed. Those beds high in calcium-rich skarn minerals always have a higher concentration and better developed scheelite than beds with calcium-poor or siliceous minerals. The occurrence of greater concentrations of scheelite in the diopside-epidote skarns in comparison to the diopside and diopside-grossular skarns indicates that the scheelite mineralization occurred late in the skarn forming sequence. This can be explained by the release of calcium from the retrograde reaction of garnet to epidote which
occurred in the latter part of the sequence. This additional calcium was then available to the tungsten bearing fluids to form the additional scheelite seen in the diopside-epidote skarns.

The occurrence of scheelite and the Mo-scheelite or powellite in skarn and vein deposits has been studied by Hsu and Galli (1973) and Khodakovskiy and Mishin (1971). The two groups of authors derive different hypotheses for the association of this mineral group. Khodakovskiy and Mishin relate the occurrence of Mo-scheelites to the similar solubility of the tungsten oxide and molybdenum oxide ions at high temperatures allowing for isomorphous substitution. Hsu and Galli relate the existence of the scheelite-powellite series to the fugacities of oxygen and sulfide gases. As the $f_{s2}$ rises, the formation of molybdenite will result if $f_{o2}$ is low. If $f_{o2}$ is high and $f_{s2}$ is intermediate to low, the molybdenum will usually occur in the scheelite or powellite series.

A late pulse of Mo-poor scheelite mineralization is shown by the occurrence of the quartz-calcite-scheelite veins and veinlets which are found throughout the massive skarn zone in the lower portions of the pendant. The scheelite in these veins and veinlets fluoresces white to bluish-white and appears also as reaction rims around more yellow scheelite grains. The amount of the Mo-poor scheelite adjacent to these veins and veinlets in high calcic beds is much greater than the Mo-scheelites which increases in abundance away from the vein or veinlet.
The late Mo-poor scheelite mineralization is limited in extent because only a few of these veins and veinlets are found above the 5340 level of the Tungsten Peak Mine. This indicates that the pulse was of short duration since an extensive Mo-poor scheelite mineralization would have produced a larger volume of these veins and veinlets. Instead, microfractures and veinlets farther up section are filled with a later microcrystalline quartz-calcite mixture which is also found crosscutting the scheelite bearing veins and veinlets.

In summary, the development of the skarn in the HiPeak-Tungsten Peak pendant occurred in the following sequence:

1. Tectonic deformation and faulting prior to and during batholithic intrusive created an extensive microfracture system in the areas of highest tectonic stress (folds and faults).

2. Thermal metamorphism by the intruding magmas converted the carbonate units into crystalline limestones and produced a few metamorphic minerals such as wollastonite, tremolite-actinolite, and idocrase.

3. Magmatic fluids rich in Si, Al and Fe reacted with highly permeable carbonate units producing the pyroxenes, garnets, quartz and calcite.

4. The skarn zone, forming at the contact between the intrusives and limestone, expanded as more fluids entered the pendant. Some flow of material from the skarn reactions interacted with the igneous contact to produce a bleached zone devoid of mafic minerals.
5. Emplacement of tungsten rich fluids into the skarn produced scheelite. Concurrently, retrograde metamorphism changed garnets into epidote in the central portions of the skarn.

6. The major episode of fluid flow ceased except for a fluid of silica, calcite, and tungsten (molybdenum poor) which produced the veins and veinlets of quartz, calcite and Mo-poor scheelite.

Concurrent with 5 and 6, the Sierran block was uplifted decreasing the thermal gradient of the area which terminated the retrograde metamorphism (Morgan, 1972).
CONCLUSIONS

The occurrence of tungsten mineralization in limited amounts in the Indian Wells Canyon Mining District is the result of complex lithology, tectonics, and mineralization process which took place over a time span of approximately 200 million years. An interpretive discussion of the development of the area follows.

Argillaceous sediments were deposited in a shallow marine basin along with a few carbonate lenses which may have been supratidal reefs (Saleeby and others, 1978). These carbonate lenses were contaminated by some of the argillic sediments intermixing with the reef structures (?). A few isolated zones of reef, however, were left relatively uncontaminated. Burial by later Mesozoic sediments and downwarping of the synclinatorium developed by the subducting oceanic plate may have produced limited thermal metamorphism which partially destroyed evidence of the reef structure in the carbonate lenses. Uplift and tectonic deformation by the Nevadan orogeny created tightly folded and faulted units dipping near vertical. The apexes of the tightly folded units were highly fractured. Fracturing along shear zones also occurred in the more competent units which were generally the carbonates. The argillaceous units show less fracturing along the fold apexes indicating a more plastic deformation. A general rotation of the lithologic units occurred after deformation placing most fold axes in a near vertical mode.

Intrusion of the late Mesozoic plutons into the area was
typical of other emplacements in the batholithic complex. A mafic rich granitic sequence intruded the area first and crystallized as a diorite-quartz diorite group. This unit had assimilated much of the overlying cap rock as seen by the number of xenoliths. This group probably created the basic roof pendant contact with the now metamorphosed early Mesozoic sediments. After the diorite-quartz diorite group had crystallized, a more acidic granodiorite group intruded the area. This intrusive appears to be the major pluton in the study area and along the range front in the area, since massive granodiorite is found throughout the area. The granodiorite group assimilated much of the diorite-quartz diorite group as evidenced by an increase in mafic character of the granodiorite in close proximity to the more mafic diorite-quartz diorite. The coarse grain character of the granodiorite group indicates a much longer cooling period than the finer diorite-quartz diorite group.

Metasomatism of the early Mesozoic units is probably associated with the granodiorite group intrusive sequence. Several other metasomatic skarn occurrences in the Sierras show this association and the lack of extensive metasomatic alteration within the minerals of the granodiorite group excludes the later quartz monzonite as the source of the metasomatic alteration. Metasomatism occurred in most of the pendants of the early Mesozoic metasediments but only the more calcic rich showed extensive metasomatic alteration. A definite relationship between the calcareous nature of the
metasediments and their secondary permeability is observed. The more calcareous and more permeable the unit, the greater the metasomatic alteration. The most extensive metasomatic alteration occurred in the highly fractured, highly calcareous carbonate units of the HiPeak-Tungsten Peak skarn. Other less developed skarns are found in more siliceous and less fractured carbonates and calcareous hornfels producing calc-silicate mineral assemblages.

Tungsten mineralization occurred during late skarn development. This mineralization pulse was widespread throughout the region as traces of scheelite (CaW\(_2\)O\(_4\)) can be found in almost all the early Mesozoic sediments, the diorite-quartz diorite group and granodiorite group. It appears that the calcareous nature and secondary permeability of the unit controlled the amount of mineralization.

The final intrusive unit, the quartz monzonite unit, may actually be a small intrusive arm of a major quartz monzonite intrusion found west of the study area. Although many of the other tungsten prospects are found in this quartz monzonite, small areas of granodiorite are found in contact with the pendants indicating an assimilation of granodiorite by the quartz monzonite. The units of the early Mesozoic metasediments found in the pendants of this area are also less tectonically deformed, i.e., folded and faulted. Emplacement of the quartz and potassium feldspar pegmatites was late to post quartz monzonite as indicated by contact relationships. The limited gold mineralization in minor quartz veins and
fractures is probably related to post quartz monzonite activity since it occurs in the granodiorite and quartz monzonite groups.

Tectonic uplift and erosion of the overlying Mesozoic rocks gradually brought the area to a near surface environment. Circulating groundwater deposited secondary quartz, calcite, and uranium enriched opal in major fracture-controlled watercourses found in both the intrusives and metasediments.

Basin and Range tectonics during the Pliocene and Pleistocene uplifted the units causing erosion to remove the final overlying metasediments and exposing the intrusive sequences. Late Pleistocene and early Holocene block faulting developed the area into its current topographical character.

The occurrence of the HiPeak-Tungsten Peak skarn within the region is not an isolated incident but the combination of both local and regional parameters. Occurrences of trace amounts of scheelite and metasomatic minerals throughout the region indicates that metasomatic alteration and tungsten mineralization occurred over a large area. Why, then, is the HiPeak-Tungsten Peak pendant the only pendant which was extensively skarnified? The answer is found by studying the lithologic and structural character of the HiPeak-Tungsten Peak pendant and its difference from other pendants in the area.

Lithologic and structural characteristics that distinguish the HiPeak-Tungsten Peak pendant from other
Pendants in the area include: a low-silica limestone which has undergone low-grade regional metamorphism into a crystalline limestone; the fine-grained and thin-bedded character of this low-silica limestone which provided good primary permeability; and the tectonic deformation and folding of the low-silica limestone pendant which increased the permeability through microfracturing. This combination was not found in other pendants of the area.

From the data and information collected in this study, an exploration program for small tungsten skarns in the southern Sierra Nevada Mountains can be developed. Parameters which would be included in such a program would be as follows:

1. Does the target area lie within the regional tungsten mineralization belt as defined by Kerr (1946)?

2. Are carbonate metasediments or roof pendants found in the area, and if so do they have a small siliceous component?

3. Is there evidence of regional metasomatic alteration and trace amounts of tungsten mineralization?

4. Do the carbonate units show evidence of tectonic chewing?

5. Are there carbonate pendants which are large enough to support an economic ore body?
6. Are these pendants which meet the previous criteria orientated such as to enhance, rather than restrict fluid migration (i.e. is bedding dipping into the intrusives)?

If the above parameters are identified in a pendant within the target area, then a detailed exploration program of the pendant can begin. Such a program would include detailed mapping of the pendant to identify probable dip and potential folded or fractured zones. This would be followed by an exploration core drilling program whose targets would be the roots and lower portions of the pendant.
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