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Stanford University, Ph.D., 1971
Geology

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THE MINERALOGY AND GEOCHEMISTRY OF THE TUNGSTEN DEPOSITS OF THE BLACK ROCK MINE AREA, MONO COUNTY, CALIFORNIA

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF GEOLOGY

AND THE COMMITTEE ON GRADUATE STUDIES

OF STANFORD UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

By

James Edward Elliott

March 1971

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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(Principal Adviser)

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ABSTRACT

This study was undertaken to determine the origin and character of tungsten mineralization in tactites at the Black Rock mine, Mono County, California. The tactite deposits are replacements of Paleozoic calcareous metasediments, localized in an asymmetric north-plunging anticline in interbedded marble, calc-hornfels, and siliceous hornfelses. A Mesozoic quartz monzonite stock exposed on the surface and in underground workings of the mine has intruded the metasediments and may be genetically related to the tungsten mineralization and tactites.

Types of metasomatism represented by tactites at the Black Rock mine are iron-magnesia-silicate and hydrothermal ore metasomatism. Chemical analyses of marble and tactite indicate that the principal constituents added were SiO_2, Fe, Al_2O_3, and MnO and principal losses were of CO_2 and CaO.

Mineralogic and petrographic studies and chemical analyses indicate that the common tactite minerals, amphibole, garnet, and pyroxene, contain unusual amounts of iron and manganese and the concentrations of these metals are higher in these minerals from ore grade tactites than in the same minerals from low grade and barren tactites. Three types of garnets are distinguished: andradite, grossular, and almandine-spessartine.

Field observations and spectrographic analyses indicate that the tungsten-bearing tactites developed by replacement of relatively pure marble whereas many of the more abundant barren tactites developed from impure marble and calc-hornfels. Greater amounts of Ti, Cr, Ni, Sc, V, Y, and Zr found in barren tactites relative to tungsten-bearing tactites reflect the original detrital content of the impure calcareous rocks.

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Spectrographic analyses of tactites and tactite minerals and statistical treatment of these data indicate that in the process of tungsten mineralization tungsten was accompanied by a suite of elements consisting of Fe, Be, Cu, Mo, Nb, Sn, and Mn, resulting in a higher concentration of these elements in the tungsten-bearing tactites relative to barren tactites.

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INTRODUCTION

The contact metasomatic or pyrometasomatic mineral deposits are a distinctive group of deposits which are important for the production of iron, copper, zinc, lead, tin, tungsten, and other metals. Most commonly this type of deposit is localized where intrusive granitic masses came in contact with carbonate sedimentary rocks. In the western U.S. such contact zones are especially important as sites for tungsten deposits.

The western belt of tungsten deposits, extending northerly from southern California thru western Nevada, Idaho, eastern Oregon, and Washington, is economically the most important tungsten producing area in the U.S. (Kerr, 1946, p. 9). Within this belt the more productive tungsten deposits have been in Nevada and California, where many of the deposits are of the contact metasomatic type and the predominant ore mineral is scheelite. The deposits are found either within or near areas of Mesozoic intrusives (Kerr, 1946, p. 9). There is general agreement as to a connection between the emplacement of these granitic masses and the mineralized zones of metasomatism in the adjacent country rocks. Within the Sierra Nevada batholith the association of tungsten deposits in the Bishop district with certain intrusive granitic rocks has been shown by Bateman (1965, p. 146).

The Black Rock tungsten mine, in southern Mono County, California, is similar in many aspects to other tungsten deposits in Nevada and California. The mineralization consists of local dissemination of scheelite in tactite formed by selective metasomatic replacement of a calcareous zone in metasediments of Paleozoic age. The deposits may be

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genetically related to a quartz monzonite stock exposed adjacent to the mine workings. Structural control is important, with the ore bodies localized near the crest of an asymmetric anticline, a structural setting rather unusual for tungsten deposits. A large volume of calcareous metasediments has been converted to tactite which locally contains economic concentration of scheelite. In most of the tactite, however, scheelite is absent or present in quantities too low to be economic. This is in contrast to some other well-known tungsten deposits such as the Pine Creek mine in the nearby Bishop district where the proportion of barren tactite to scheelite-bearing tactite is much lower.

Gross mineralogy of the Black Rock tactites is similar to that of productive deposits in the nearby Bishop district but there are some notable differences. For example, the Black Rock deposits have abundant dark green amphibole throughout the tactites and this mineral is not common in the Bishop district (Bateman, 1965, p. 127). The Black Rock tactites have very little wollastonite or feldspars which are abundant elsewhere. In the Bishop district the common sulfides are molybdenite and chalcopyrite, but these are rare in the Black Rock sulfide zone where the predominant sulfide is pyrrhotite. In the Bishop district, scheelite-bearing ore shoots are of two generals kinds; those in ordinary tactites which are poor in quartz and those in siliceous zones abnormally rich in quartz. The quartz-rich type of scheelite deposit is present only sparingly at the Black Rock mine and is quantitatively unimportant.

The Black Rock mine is of particular interest because of the apparent structural and stratigraphic control of the tungsten-bearing tactites. Presumably the migration of fluids responsible for the metasomatism was controlled by the favorable zones of more reactive rocks (calcareous

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versus siliceous metasediments) and the anticlinal structure. A third factor in the localization of tactite and tungsten ore seems to be the proximity to the quartz monzonite stock. Most of the ore bodies are in the west dipping limb of the anticline, near surface and underground exposures of the stock, and the intensity of metasomatism fades both to the east and south where tactite ends and considerable thicknesses of unreplaced marble are encountered.

The Black Rock mine area was judged to be an excellent area in which to study trace element variation in tactite minerals. Garnet and pyroxene were selected as prime subjects. These two minerals are widely distributed as essential minerals in both barren and tungsten bearing tactite. Thin section study suggests they formed during the most intense stage of metasomatism and at about the same time and from the same solutions as scheelite in tungsten-bearing tactites. Trace element abundances and variations in these minerals might reflect differences in the original country rocks, the character of the metasomatizing solutions, or zonation related to igneous contacts.

Separates of actinolite and scheelite were also prepared from many of the same samples selected for separation of garnet and pyroxene. These were relatively easy to separate and were expected to provide valuable additional information.

Because of the great volume of tactite exposed both at the surface and in underground, the small-scale complexity of the geology (especially in mixed zones of tactite, marble, and calc-hornfels), and the difficulty of preparing clean separates of garnet and pyroxene, it was realized early in the study that only a relatively small number of samples could be studied in detail. The sampling was too sparse to provide answers to questions conceived at

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the beginning of the study and only problems of a more general nature could be attacked. The distributions of Be, Ti, V, Ni, Sn, Cu, Y, Sc, Co, and Mn in coexisting skarn minerals were examined to determine if any association existed between the abundance of these elements and the tungsten content of the enclosing tactite. In addition, a suspected increase of Mo in scheelite corresponding to increasing distance from the igneous contact was checked by determining the Mo content of scheelite.

Later in the study it was decided that determination of trace elements in whole rock samples of tactite would provide data helpful in interpreting 1) the origins of barren and tungsten-bearing tactites and 2) the compositional character of the tungsten-bearing solutions. Supplemental studies of the petrography and mineralogy of the tactites provided data on the sequence of metasomatism. A petrographic study of the quartz monzonite stock and other igneous rocks in the mine area was undertaken to determine if the igneous rocks and the tungsten deposits were genetically related.

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GENERAL GEOLOGY OF THE BLACK ROCK MINE AND SURROUNDING AREA

Geographic Setting, History, and Production

The Black Rock mine is located in the northeast corner of the Casa Diablo Mountain quadrangle in southern Mono County, east-central California (Fig. 1). Nearby towns are Benton, 3 miles north of the quadrangle boundary, and Bishop, 20 miles south of the southern limit of the quadrangle. The mine is accessible by gravel road from Benton or by asphalt road which connects with U.S. Highway 6 approximately 25 miles north of Bishop. The mine is located near the crest and on the east-facing slope of the Benton Range, in an area of moderate relief. The workings are 6,500 to 7,000 ft. in altitude.

Scheelite was discovered in the mine area in 1917 by A. E. Beauregard, but no development was undertaken at that time. In 1928, Beauregard relocated the property and worked the mine until 1936 when it was sold to the Tungsten Corporation of California. A 150-ton mill was completed in 1937 and operated until the company failed in 1941. The property reverted to Beauregard, who shipped a small tonnage of ore during the period 1942 to 1948. The property was purchased by the Tungsten Corporation in 1949 and then leased in 1950 to the Black Rock Mining Corporation, which operated the mine through 1954 (Rinehart and Ross, 1956, p. 11). In 1952, a 250-ton mill was constructed and an exploration program initiated (U.S. Bureau of Mines, 1952, v. I, p. 1069-1070). The name of the organization, Black Rock Mining Corporation, was changed in 1954 to Wah Chang Mining Corporation (Rinehart and Ross, 1956) which operated

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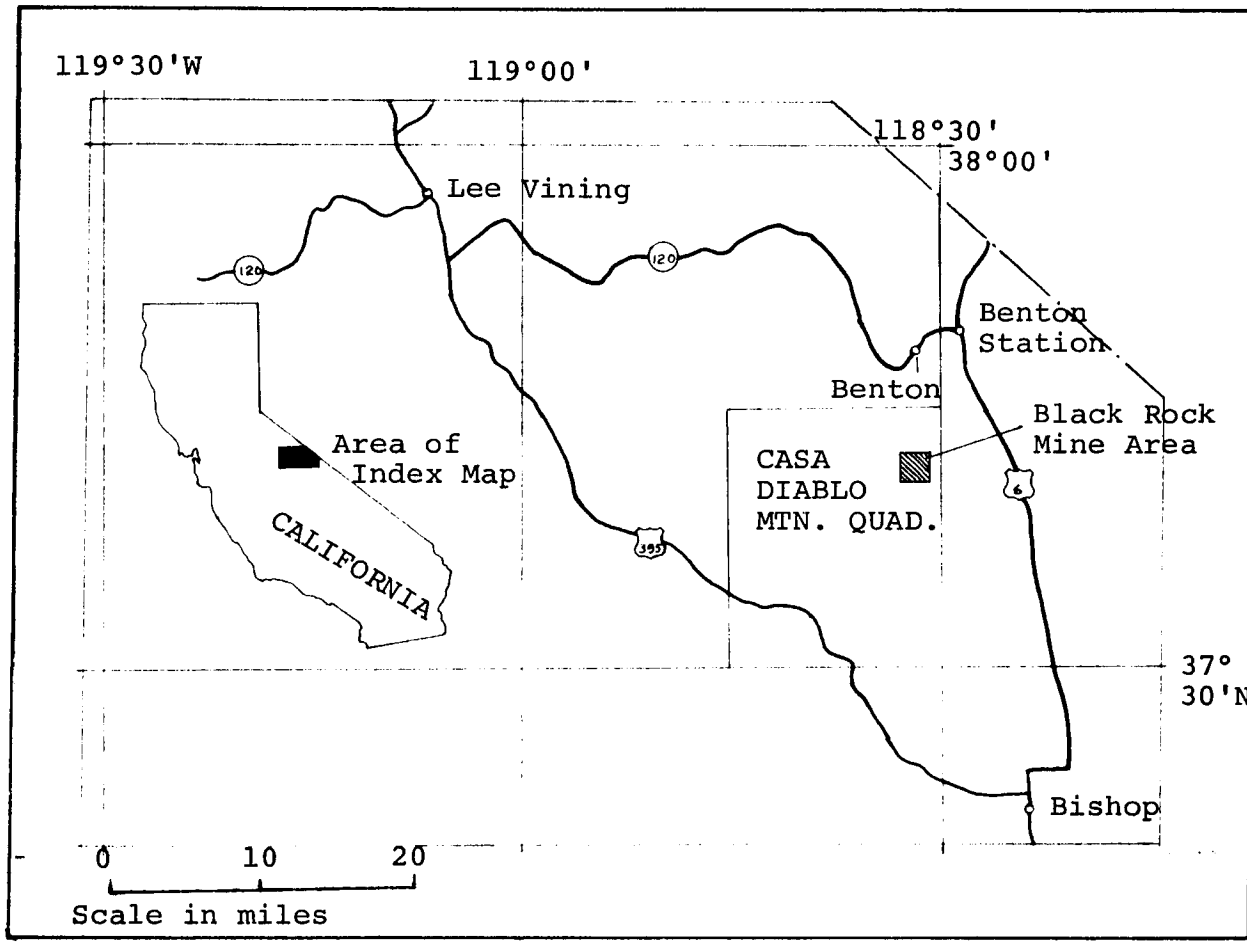

FIGURE 1. Index map showing location of the Black Rock mine area.

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the property until August 31, 1957, when operations ceased completely (U.S. Bureau of Mines, 1957, v. III, p. 227). The property was idle until 1963 when claims were located by Union Carbide Nuclear Corporation. Assessment work by Union Carbide has continued to the time of this study but mining has not been resumed.

The mine was most productive during the years 1950 to 1956. Through 1949 the total production was about 85,000 tons of ore (Rinehart and Ross, 1956). During the next 7 years approximately 515,000 tons were mined (U.S. Bureau of Mines, 1950-57), giving a grand total of about 600,000 tons of ore having an overall average grade of approximately 0.5 percent WO_3. In 1953, the Black Rock Mine was the second largest producer of tungsten in California and the sixth largest in the United States, and by 1955 it ranked as the second largest producer in both California and the nation (U.S. Bureau of Mines, 1954-57).

Workings

The mine is developed in several large open cuts, more than 3 miles of underground level workings, and probably several thousand feet of raises, stopes, and winzes (see pl. 2, 3). Nearly all of the workings were accessible during this study. There are five major levels with 2,000 to 4,000 feet of level workings each. Four of the five levels are accessible by adit and the fifth (6600 level) is accessible by winze from the 6700 level. The largest of the surface workings are the Glory Hole (450 x 300 feet in plan) and the Senior pit (600 x 200 feet in plan).

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General Geology

Previous work. The earliest reference to tungsten deposits in the area is that of Hess and Larsen (1921). They discuss briefly the geologic setting of the Black Rock mine, which was merely a prospect at that time. A brief description of this mine and other mines of the area is given by Sampson and Tucker (1940). The earliest discussion of the general geology of the region is by Gilbert (1941), who emphasized the late-Tertiary volcanism and Basin-and-Range faulting that produced the present topography. The earliest comprehensive report on the general geology and ore deposits of the Black Rock mine area was in 1941 (Lemmon, 1941). The most up-to-date and comprehensive reference to the geology and ore deposits of the mine appears in a report on the economic geology of the Casa Diablo Mountain quadrangle (Rinehart and Ross, 1956). The geologic map and description of the geology of the Casa Diablo Mountain quadrangle appear in a later report by Rinehart and Ross (1957). The following summary of the geology of the area (pl. 1) is based on the published reports of Rinehart and Ross.

Rock types. Most of the area of plate 1 is underlain by metasedimentary rocks of early Paleozoic or older age which, on a regional scale, comprise a body underlying about 15 square miles of the Benton Range in the Casa Diablo quadrangle. These rocks have been intruded by plutons of diorite-gabbro and quartz monzonite and dikes of porphyritic rhyolite and hornblende gabbro. Quaternary rhyolitic ignimbrite and alluvium cover the remainder of the area.

Within the metamorphic body of rocks in the Benton Range the most abundant rock types are micaceous and siliceous rocks, including quartz-sericite hornfels, quartz-mica phyllite, graphite and andalusite hornfels, siliceous

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hornfels, and biotite-quartz hornfels. Calcareous rocks including calc-hornfels, marble, and tactite are less abundant, being restricted to a few narrow bands. The metamorphic rocks were probably originally a sequence of shales, siltstones, and argillaceous sandstones, locally carbonaceous and locally interstratified with limestone. The total stratigraphic thickness of the metasedimentary sequence is probably more than 10,000 feet. The regional dip is northerly to easterly.

No formational names have been applied to units in the area, as it is doubtful whether positive correlation of these rocks is feasible. The age of the metamorphic rocks is unknown. No diagnostic fossils were found during this study or earlier work, although part of a rugose coral was found in marble but was too poorly preserved for identification. Rinehart and Ross consider the sequence to be of early Paleozoic age, or possibly older.

Regionally, the metamorphic rocks of the Benton Range are one fragment of a disrupted Late Precambrian to Mesozoic sequence that occurs as scattered roof pendants and septa in the eastern Sierra Nevada and the northern White Mountains. Fairly continuous sequences of late Precambrian to early Paleozoic rocks occur in the west slope of the White Mountains east and southeast of Bishop (Bateman, 1956, p. 9). Rocks of Early Ordovician to Permian(?) age are present in the Sierra Nevada in the Mt. Morrison quadrangle immediately west of the Casa Diablo quadrangle (Rinehart and Ross, 1964, p. 1). A younger Mesozoic sequence in which metavolcanic rocks predominate also occurs in the Sierra Nevada (Bateman, 1965, p. 21). The absence of metavolcanic rocks and the gross lithological similarity of the metamorphic rocks of the Benton Range with the Paleozoic metasedimentary rocks of the Sierra Nevada and the sedimentary rocks of the White Mountains indicate a probable Paleozoic or older age for these rocks.

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Plutonic rocks occurring in the area of plate 1 include light-colored granitic rocks and dark-colored diorite and gabbro. The largest body is a small stock of quartz monzonite west of the Black Rock mine. Because of a possible genetic connection between this body and the tungsten deposits, the petrography and modal composition of this pluton were examined in the present study. Rinehart and Ross mapped this body as granodiorite and correlated it with a much larger pluton of granodiorite which is exposed just outside the map area to the northwest. Modal analyses, however, show that the Black Rock pluton is predominantly quartz monzonite.

The plutonic rocks of the area were thought to be Cretaceous in age by Rinehart and Ross, an assumption based on a supposed correlation with the quartz monzonite of Wheeler Crest in the Sierra Nevada (Bateman, 1965, p. 72). This quartz monzonite occurs near the north edge of the Mount Tom quadrangle and extends into the Mount Morrison and Casa Diablo Mountain quadrangles.

More recent work suggests a much wider range of Mesozoic ages for the granitic rocks of the Bishop district and the Benton Range. Evernden and Kistler (1970) have subdivided the plutonic rocks of batholithic complexes in California and western Nevada into five intrusive epochs ranging from Middle and Late Triassic (Lee Vining epoch) to Late Cretaceous (Cathedral Range epoch) in age. Plutonic rocks of the Benton Range have been assigned to the Inyo Mountains (160-180 m.y.) and Lee Vining (195-210 m.y.) intrusive epochs (Evernden and Kistler, 1970, plate 1). Because of lack of age data on the plutonic rocks of the Black Rock mine area and in light of the above mentioned work only a very general age of early to middle Mesozoic can be assigned to these rocks.

Dikes of porphyritic rhyolite, hornblende gabbro, and quartz monzonite occur in the Black Rock mine area. A quartz monzonite dike which is exposed in the mine workings

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is probably a satellitic body of the stock exposed immediately west of the mine, as judged from its similar texture and modal composition. The porphyritic rhyolite, occurring as steeply dipping, north-trending dikes and sills, is very abundant in the part of the Benton Range mapped by Rinehart and Ross and is considered to be related in age and origin to the plutonic granitic rocks in this area. Dikes of hornblende gabbro are exposed in the mine workings and, although mostly altered, where fresh are similar to the diorite-gabbro occurring as a pluton northwest of the mine (pl. 1). No definite ages can be assigned to these dike rocks. They were considered to be Cretaceous in age by Rinehart and Ross, but as previously mentioned, the intrusive epochs of this area have been assigned an earlier age and a tentative early to middle Mesozoic assignment seems more likely. Relative ages of the various rock types in the mine area were established by crosscutting relationships. Plutonic rocks are intruded by porphyritic rhyolite which are in turn cut by dikes of hornblende gabbro.

Structure. Structures in the Black Rock mine area can be conveniently divided into two distinct patterns: 1) structures in the metamorphic rocks which predate the intrusive epochs and 2) Basin-and-Range normal faulting.

The older structures predate mineralization and probably were important for localizing the ore deposits. Folding in the area of the Black Rock mine has resulted in a large, asymmetric north-plunging anticline (see pl. 1 and 2). In general the east limb dips more steeply (45-70°) than the west limb (25-35°). Similar north-trending, north-plunging folds in the metamorphic rocks are clearly visible north and west of the mine area. The folding predates the intrusives, as evidenced by the truncation of the folded rocks by the intrusive rocks.

Examples of faults that predate the igneous activity are found west and northwest of the mine (pl. 1). These

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faults displace the metamorphic rocks but do not have the surface expression of the much younger Basin-and-Range faults. Premineralization faults and breccia zones associated with mafic dikes in underground working of the Black Rock mine also are probably representative of this period of faulting. Locally these premineral faults may have controlled the circulation of hydrothermal ore-bearing solutions and therefore may be a control of the form, size, and distribution of ore bodies.

The older set of structures probably coincides with the period of weak regional metamorphism which is evident in megascopic and microscopic structures of the metasedimentary rocks. Small scale folds and boudins are common in the calcareous metasedimentary rocks. In the siliceous hornfels weak but distinct schistosity, foliation, or slaty cleavage is locally discernible.

The younger Basin-and-Range structures have determined the present topography. The Benton Range is a faulted block in the central part of a large and complexly faulted graben between the Sierra Nevada and the White Mountains. The faulting of this system probably commenced in the late Tertiary and has been more or less recurrent to the present.

Metamorphism. Structures, metasomatism, and mineral assemblages in the metamorphic rocks of the Black Rock mine area suggest that metamorphism took place in at least two stages. First was a period of weak regional metamorphism which probably coincided with the preintrusive folding and faulting. The second stage was chiefly thermal and was the result of intrusive activity during emplacement of small and large plutons of the Sierra Nevada batholith. Evidence of the earlier stage remains in the form of weak to well-developed foliation, schistosity, or cleavage, all of which are most evident in the micaceous hornfels. Boudins in marbles as well as small and larger scale fold-

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ing also give evidence of regional metamorphism. Local banding in calc-hornfels and in interstratified siliceous and calc-hornfels may be the result of metamorphic differentiation during regional metamorphism. The later period of thermal metamorphism resulted in the development of assemblages characteristic of the hornblende-hornfels facies, although local variations in temperature resulted in slightly lower or higher grade assemblages. The thermal metamorphism was chiefly isochemical except where calcareous rocks were intruded by plutons and additive metasomatism resulted in the formation of tactites.

Three successive episodes of metamorphism have been documented in the Sierra Nevada by Bateman et al. (1963, D9), characterized by three conditions: The first episode was kinematic; the second, overlapping kinematic and thermal; and the third, thermal. The effects of the first and third are readily distinguished but effects of the second episode are difficult to distinguish from those of the third. In the Black Rock area the second or middle episode has not been recognized, and only two episodes are distinguished. A more complex history of metamorphism has been described from studies of metamorphic rocks in the Mono Craters quadrangle (Kistler, 1966). Three distinct regional deformations as well as thermal metamorphism have been identified based on metamorphic structures. The ages of these deformations are Permian(?), Early or Middle Triassic, and Late Jurassic. In the Black Rock mine area evidence for more than one period of regional deformation was not distinguished.

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Geology of the Black Rock Mine

Metasedimentary rocks. Micaceous and siliceous hornfelses and calcareous rocks make up the metasedimentary sequence in the Black Rock mine area. Dominant types in the micaceous and siliceous hornfelses are quartz-sericite hornfels, graphite-andalusite hornfels, siliceous hornfels, and biotite-quartz hornfels. Calcareous rocks include marble, calc-hornfels, and tactite. At the Black Rock mine the calcareous rocks predominate in surface and underground workings (pl. 2). Here, a band of calcareous rocks has been tightly folded into an asymmetric north-plunging anticline and largely converted to tactite by metasomatism. The calcareous rocks are surrounded by and locally interbedded with siliceous and micaceous hornfelses.

Perhaps the most abundant rock type in the metasedimentary sequence is quartz-sericite hornfels, and it is also the most common type of metasedimentary rock in the area of the Black Rock mine outside the zone of calcareous rocks. Most commonly it is light to medium gray, less commonly reddish-brown or grayish-green. It is very fine-grained and generally bedding is not apparent, although there is a crude layering defined by reddish-brown iron oxide staining. The rock grades from a phyllite to a schist and may have a poor to well-developed foliation or cleavage. Jointing locally is well developed. Small folds with wave lengths of 1 to 2 feet and amplitudes of 2 to 3 inches were noted in outcrop. Characteristically, in this area the rock has a spotted appearance due to dark spots, 1 to 5 mm in diameter and composed of fine-grained sericite and biotite. Dominant minerals are sericite, quartz, biotite, andalusite, and plagioclase.

Graphite-andalusite hornfels is abundant west and northwest of the mine area. It is dark-gray, brown, or black and has prominent, euhedral, gray to green, acicular

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andalusite porphyroblasts up to 2 inches long. Contacts with quartz-sericite hornfels are gradational (Rinehart and Ross, 1957).

Siliceous hornfels is interstratified with quartz-sericite hornfels north and northwest of the mine area. It is light to dark gray, fine to medium-grained and thinly-bedded (2-20 mm) to massive. It is commonly a granoblastic aggregate of quartz and plagioclase with minor amounts of sericite, biotite and chlorite (Rinehart and Ross, 1957).

Biotite quartz hornfels is common in the surface and underground workings of the Black Rock mine as a fine-grained granoblastic aggregate of quartz and biotite containing variable quantities of sericite. In underground exposures it may be intermixed and interlayered with calc-hornfels down to a scale of bands 2 cm or less in thickness. It is medium to dark-gray, fine-grained, and thinly-bedded or banded to massive. At many localities it has a spotted character, with spots 1-3 mm in size, grading into a vermicular texture. The dark spots are clots of fine-grained biotite and the vermicular texture is defined by intergrowth of quartz-rich and biotite-rich clots. These textures are best developed near or at contacts with porphyritic rhyolite dikes.

Calc-hornfels occurs interstratified with impure and pure marbles and grades into siliceous hornfels. It is light gray to pale green, but may be white, light brown, or greenish gray. This rock may be thinly laminated to massive and fine to coarse-grained (locally vuggy) and is commonly mottled. Pyroxene, epidote, clinozoisite, amphibole, and quartz are essential minerals; common accessories are garnet, calcite, wollastonite, sphene, and vesuvianite.

White to light gray marble is commonly fine-to medium-grained (locally coarse-grained adjacent to tactites) and is thinly bedded to massive. The normal color is light to

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medium gray but bleaching in the vicinity of tactite gives rise to white zones of marble in the mine area. Elsewhere white calcite appears as coarse-grained veinlets and boudins crosscutting the light-gray thinly-bedded marbles. In the mine area, evidence of plastic deformation is common in the form of small-scale folds and pods of marble in hornfels which are crosscutting to original bedding. Pods, layers, and lenses of siliceous hornfels (which may have originally been chert nodules and lenses), tactite, and calc-hornfels occur in the marble.

Tactite is important because it is the host for the tungsten ore deposits. The occurrence of scheelite, $CaWO_4$, is restricted nearly exclusively to tactite, but not all tactites contain scheelite. Most of the tactite is restricted to the mine area. Characteristically it is dark-brown to dark-green, fine-to medium-grained, dense and massive and may be mottled in various shades of green and brown. Locally it is coarse-grained and vuggy and may show banding. Garnet, of the grossularite-andradite series, commonly is the dominant mineral. Other principal minerals are pyroxene, amphibole, epidote, quartz, calcite, vesuvianite, and biotite. Locally pyrrhotite is a major constituent. Minor constituents are sphene, apatite, scheelite, chlorite, zircon, plagioclase, magnetite, pyrite, chalcopyrite, marcasite and molybdenite. The petrography, mineralogy, and genesis of the tactites will be dealt with in more detail in a later section.

Igneous rocks. Three distinct varieties of igneous rocks occur in and adjacent to the mine workings. These are quartz monzonite, altered hornblende gabbro, and porphyritic rhyolite. The quartz monzonite occurs as a small stock exposed west and northwest of the mine area and the altered hornblende gabbro and porphyritic rhyolite occur as north-trending steeply-dipping dikes in the surface and underground workings of the mine.

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The main mass of quartz monzonite outcrops as a small irregular stock adjacent to the mine workings, with an outcrop measuring approximately 3,000 feet (east-west) by 4,200 feet (north-south). In the approximate center of the stock is a small inclusion (or roof pendant) of quartz-sericite hornfels. Contacts of the pluton with the meta-sedimentary rocks dip, in general, away from the outcrop of the stock, indicating that the size of the stock increases with depth. The main mass of quartz monzonite is penetrated in mine workings only on the 6,500 level, the lowermost drift. Fine-grained quartz monzonite also occurs as dikes in surface and underground workings. The dikes are probably connected at depth with the main mass of quartz monzonite.

The mineralogic composition of the Black Rock stock was determined by counting modes of stained slabs of 19 specimens, collected at the locations shown in plate 1. The methods used are described in the appendix. The results are tabulated in table 1 and plotted on figure 2, after recalculating plagioclase + quartz + potassium feldspar = 100%. The figure shows a general grouping in the quartz monzonite-alaskite field with a few samples falling in the granodiorite field.

The stock is actually composite, made up of two distinct rock types which are distinguished on the basis of texture, mineralogy, degree of alteration, and chemistry. The two types are grouped separately on table 1 and plotted separately on figure 2. Type II is a normal quartz monzonite or granodiorite which plots near the quartz monsonite-granodiorite boundary of figure 2. Type I, an altered quartz monzonite or alaskite (as shown by lack of mafics in table 1) occurs in the southern half of the stock and is most abundant in the southeastern lobate part of the stock. The normal quartz monzonite phase (type II) is more abundant in the stock and also occurs underground on the 6500 level and as dikes in surface and underground workings.

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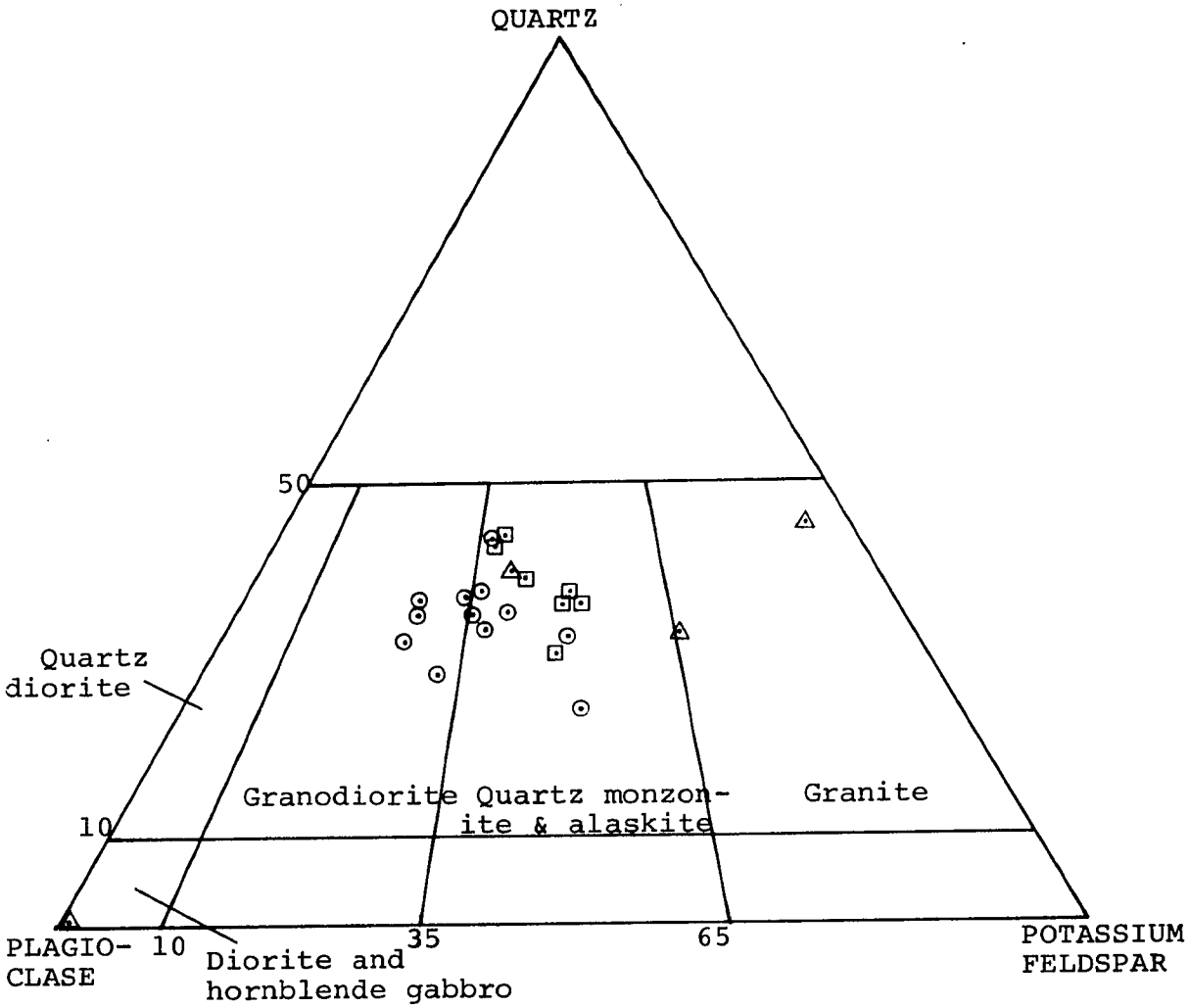

Figure 2. Plot of modes of samples from the Black Rock stock and dikes. ⊡ type I quartz monzonite, ⊙ type II quartz monzonite and granodiorite, ◬ dike rocks. Classification after Bateman (1965, p. 48).

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Sample Number	Quartz	Potassium feldspar	Plagio-clase	Biotite	Accessory or Secondary	Total Mafic
S-1	41.0	21.4	33.8	<.1	3.4	0.5
S-3	39.6	19.8	30.0	<.1	10.6	<.1
S-4	29.9	32.6	35.4	<.1	16.2	<.1
S-6	32.7	29.7	27.5	<.1	9.2	<.1
S-8	38.3	25.2	33.1	0.1	3.2	0.1
J40	35.5	30.3	31.2	<.1	2.7	0.4
J41	36.3	30.3	29.3	<.1	3.3	0.7
S-2	33.0	24.3	40.2	2.0	0.4	2.4
S-5	32.1	20.5	37.7	9.3	0.5	9.8
S-7	26.1	22.5	45.3	5.0	1.1	5.4
S-9	29.4	16.2	45.4	8.5	0.5	9.0
S-21A	32.8	15.3	41.7	9.7	0.5	10.2
J34	35.9	21.7	37.5	4.4	0.5	4.9
J35	37.6	19.6	31.4	11.0	0.3	11.3
J36	31.8	15.8	43.5	1.5	6.9	2.0
J37	31.1	32.3	32.3	3.3	0.9	3.8
J38	34.6	20.3	38.2	6.5	0.4	6.9
J39	32.0	24.0	34.0	8.5	1.5	9.0
J43	23.1	37.0	34.7	5.1	0.1	5.2
S-18	37.0	23.0	32.0	5.0	3.0	5.0
J29	31.2	41.8	21.8	3.0	2.4	3.6
67-2	<1.0	<1.0	33.8	11.2	17.8	56.2
BR-5	41.0	47.0	4.0	2.0	4.0	2.0
Coeff. of variation	11.5%	13.3%	7.8%	22.1%	54.9%	

Table 1. Modal analyses of igneous rocks. Methods and apparatus similar to that described by Smithson (1963). Precision expressed as coefficient of variation shown in lowermost row.

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Accessory or Secondary	Total Mafic	
3.4	0.5	Type I quartz monzonite
10.6	<.1	"
16.2	<.1	"
9.2	<.1	"
3.2	0.1	"
2.7	0.4	"
3.3	0.7	"
0.4	2.4	Type II quartz monzonite
0.5	9.8	"
1.1	5.4	"
0.5	9.0	"
0.5	10.2	"
0.5	4.9	"
0.3	11.3	"
6.9	2.0	"
0.9	3.8	"
0.4	6.9	"
1.5	9.0	"
0.1	5.2	"
3.0	5.0	Quartz monzonite dike fine-grained
2.4	3.6	Same--probably contaminated
17.8	56.2	Altered hornblende gabbro contains 34.4% hornblende
4.0	2.0	Porphyritic rhyolite from dike
54.9%		Obtained by 10 replicate analyses of J38

nd apparatus
). Precision
in lowermost

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The field relations between these two rock types could not be ascertained because of poor exposures but they may be gradational. Modal compositions of quartz and feldspar show some overlap in figure 2.

Type II, the normal quartz monzonite phase, is a medium-grained, porphyritic hypidiomorphic granular rock. Large megacrysts of microcline up to 3 cm in length and smaller megacrysts of plagioclase and quartz are abundant. The microcline is generally perthitic. The groundmass is a fine-grained intergrowth of quartz and microcline exhibiting a mosaic or sutured texture. Synneusis texture of biotite and locally of plagioclase is common. Fractured and strained quartz gives evidence of cataclasis.

The essential minerals are plagioclase, quartz, microcline, and biotite; accessory minerals are muscovite, zircon, apatite, epidote, and minor opaques. Secondary minerals include sericite (and muscovite), epidote, chlorite, sphene, and kaolinite(?). The content of biotite (equivalent to the mafic content and the color index) varies from 1.5 to 11 percent. The lower mafic content in some rocks is partially the result of alteration of biotite. The plagioclase, determined by measuring extinction angles in sections normal to x, is oligoclase with cores of approximately An_{30} and rims of An_5 to An_{10} and shows normal nonoscillatory zoning. Both plagioclase and biotite show the effects of slight to moderate alteration; plagioclase is altered to sericite and biotite to chlorite and muscovite.

Major and minor element contents of the intrusive rocks are shown in table 2. All elements except Hg were determined by a 6-step semiquantitative spectrographic procedure. Mercury was determined by an atomic absorption technique. The results show type II and type I rocks to be distinctly different in chemistry. Type II rocks are higher relative to type I in iron, magnesium, calcium, titanium, manganese, barium, lanthanum, strontium, vanadium and zirconium.

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	Qtz. monz. stock		Dike rocks			
	1	2	3	4	5	6
Fe pct.	0.7	1.6	10.0	0.7	1.5	0.05
Mg "	0.1	0.4	2.0	0.07	0.3	0.02
Ca "	0.065	0.62	3.0	0.5	0.5	0.05
Ti "	0.05	0.13	0.5	0.05	0.1	0.002
Mn ppm	110	483	1500	200	1000	10
B "	16	<10	<10	15	10	10
Ba "	161	859	1000	100	200	20
Be "	2.1	1.5	1	2	5	1
Cu "	5.7	5.3	70	5	<5	5
La "	N	29	30	N	20	20
Nb "	23	14	<10	20	50	10
Ni "	5.0	5.0	20	5	5	5
Pb "	30	17	50	30	30	10
Sc "	<5	<5	20	<5	5	5
Sr "	N	242	700	N	N	100
V "	15	29	300	10	30	10
Y "	23	13	30	10	15	10
Zr "	48	74	100	50	50	10
Hg "	0.05	0.03	0.06	0.04	0.04	0.01

Table 2. Semiquantitative spectrographic analyses of igneous rocks. Column 1 is geometric mean of 4 samples of type I quartz monzonite. Column 2 is geometric mean of 7 samples of type II quartz monzonite. Columns 3, 4 and 5 are of 1 sample each of hornblende gabbro, porphyritic rhyolite, and quartz monzonite dikes respectively. Listed in column 6 are the lower limits of determination for the spectrographic method. N = not detected at limit of detection, <X = detected, but below limit of determination. Elements looked for but not found or mostly below detection limits and their limits of detection are: Ag(0.5), As(200), Au(10), Bi(10), Cd(20), Co(5), Cr(5), Mo(5), Sb(100), Sn(10), W(20), Zn(200). Analyses by E. L. Mosier, U.S. Geol. Survey.

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Type I rocks are characterized by a fine- to medium-grained allotriomorphic granular texture with quartz megacrysts 2 to 5 mm in diameter giving a weakly porphyritic texture. The essential minerals, quartz, microcline, plagioclase, and muscovite, are generally fine-grained and show a mosaic or sutured texture. Accessory minerals are zircon, biotite, garnet, sphene, and apatite. Secondary products are muscovite, reddish-brown iron oxides, epidote, and kaolinite(?). The plagioclase is extensively altered and replaced by felty masses of muscovite. Biotite is nearly lacking but may have been present originally, having been replaced by muscovite. Muscovite commonly occurs in synneusis-like clots associated with reddish-brown oxides, opaques, and sphene which suggests it is a secondary product after biotite. The plagioclase was probably sodic oligoclase or albite, as indicated by the low calcium content in the chemical analysis. In outcrop, type I rocks are commonly cut by pegmatitic quartz-muscovite veins up to 6 inches in width. This phase also exhibits veining and staining by reddish-brown iron oxides suggestive of minor sulfide mineralization. Spectrographic analyses suggest type I rocks may be higher than type II rocks in yttrium, beryllium, and niobium. More data, however, would be needed to fully evaluate possible differences in these and other elements.

The structure of most of the granitic rocks of the stock is massive, lacking foliation or flow structure. Schlieren and xenoliths are rarely seen and are small (measurable in terms of a few feet or inches) if present. Contacts with metamorphic rocks are generally sharp where seen but most of the contacts are obscured by talus and slope wash. Thermal effects such as recrystallization are evident at contacts with hornfels.

Fine-grained quartz monzonite dikes, essentially fine-grained equivalents of type II rocks, occur in surface and

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underground mine workings. Two samples, S-18 and J29, are plotted in figure 2 based on point counts from thin sections shown in table 1. The high content of potassium feldspar in J29 suggests that it is probably a contaminated phase and not a reliable representative of the bulk composition. The spectrographic analysis of S-18, included in table 2, shows it to be closely related chemically to type II quartz monzonite.

Altered hornblende gabbro occurs as steeply-dipping, north-trending dikes in surface exposures and underground workings of the Black Rock mine. Most of the dikes were extensively sheared and affected by saussuritization and propylitic alteration. The shearing may have been largely the result of pre-mineral faulting. Only one sample of relatively unsheared and unaltered material was obtained; the petrographic description of this rock unit is based on the study of the one fresh specimen and of altered samples.

The gabbro is porphyritic with a fine-grained groundmass. Conspicuous phenocrysts of hornblende 2 to 5 mm in length predominate but phenocrysts of plagioclase are also common. The groundmass is composed of hornblende, 0.2 to 1 mm in size, intergrown with biotite and plagioclase laths. The plagioclase is calcic, ranging from approximately An_{65} to An_{70} for cores, An_{40} to An_{30} for intermediate zones, and a low of An_{15} for rims. These figures are based on a relatively few measurements by the x-normal method. Both hornblende and biotite are light brownish green. Some of the biotite is secondary after hornblende. Essential minerals are plagioclase, hornblende, and biotite, and accessories are opaques, sphene, apatite, and quartz. Secondary alteration products are epidote-group minerals, muscovite, chlorite, and calcite.

The mode for hornblende gabbro based on the point count of a thin section is shown in table 1. The spectro-

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graphic analysis of an altered sample of hornblende gabbro, S-16, is shown in table 2. The mafic character of this rock is evident in the relatively high content of iron, magnesium, and calcium.

The hornblende gabbro dikes intrude rhyolite dikes as well as the metamorphic rocks, establishing a younger age for the mafic dikes, but age relations between quartz monzonite and hornblende gabbro have not been observed. The mafic dikes are probably related to bodies mapped as diorite-gabbro northwest and west of the mine area (pl. 1).

Porphyritic rhyolite occurs in the mine area as north-trending, steeply dipping dikes. Subhedral to euhedral phenocrysts, generally 0.2 to 1.0 mm in diameter, of quartz, microcline, and plagioclase are conspicuous in a light gray aphanitic groundmass. Essential minerals are quartz, microcline, and plagioclase, and accessories are biotite and muscovite. The groundmass, consisting of an intergrowth of quartz, microcline, biotite, and muscovite, has a grain size generally less than 0.05 mm. Plagioclase is altered to sericite, quartz, and epidote and the biotite is moderately altered to chlorite. Microscopically there is little evidence of late or post-crystallization fracturing. The mode for a sample of porphyritic rhyolite is listed in table 1 and plotted in figure 2. The semiquantitative spectrographic analysis for S-17 is listed in table 2. Chemically, texturally, and modally this rhyolite is distinct from the quartz monzonite facies.

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TACTITES AND TUNGSTEN MINERALIZATION

The Process of Metasomatism

Contact metamorphism may be an additive or nonadditive process; when additive it is termed metasomatism. As used here the term "contact (or thermal) metamorphism" is restricted to recrystallization under high temperature without the addition of substances. Many ore deposits are found at or near igneous contacts, and a genetic association of these deposits with the intrusives has been shown or assumed. Because of the considerable compositional difference between these resultant contact deposits and the original country rock metasomatism must have taken place. These deposits have been called contact metasomatic, igneous metamorphic, or pyrometasomatic.

Metasomatism has been defined by Lindgren (1933, p. 91) as "the process of practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly differing chemical composition may grow in the body of an old mineral or mineral aggregate." Goldschmidt (1922, p. 106) defined metasomatism as "...a process of alteration which involves enrichment of the rock by new substances brought in from the outside. Such enrichment takes place by definite chemical reactions between the original minerals and the enriching substances." The latter definition is concerned primarily with those aspects of metasomatism involving introduction and removal of certain substances resulting in changes in the bulk composition of the host rock as well as changes in mineralogy. This definition of metasomatism, somewhat more limited than Lindgren's, is used here.

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The classiciation of metasomatism has been based on: 1) character of the parent rock, 2) character of the added substances and resultant product, and 3) on the stage of magmatic or post-magmatic processes. Goldschmidt (1922, p. 108) recognized four main types of metasomatism based on character of the rock involved: 1) metasomatism of silicate and silica rocks, 2) metasomatism of carbonate rocks, 3) metasomatism of salt deposits, and 4) metasomatism of sulfide deposits. Further subdivision of metasomatism according to the metal or "metalloid" introduced was made by Goldschmidt into alkali-, magnesia-, lime-metasomatism and others. A simplified version of this subdivision was adopted by Eskola (1939, p. 375-392), who proposed five major headings: 1) alkali metasomatism, 2) lime metasomatism, 3) iron-magnesia-silicate metasomatism, 4) metasomatism with introduction of Si, Sn, B, Li, F, Cl, S, and 5) carbon dioxide metasomatism. A more recent version of this type of subdivision is by Mehnert (1969, p. 284-286), who gives the seven most frequent types of metasomatism as: 1) alkali metasomatism, 2) calc-silicate metasomatism, 3) iron-magnesia-silicate metasomatism, 4) hydrothermal ore metasomatism, 5) boron metasomatism, 6) fluorine metasomatism, and 7) carbon dioxide metasomatism. The third type of classification has been proposed by Korzhinskii (1964, p. 1926) who subdivides metasomatism into: 1) magmatic metasomatism, 2) early alkaline post-magmatic metasomatism, and 3) acid and late alkaline post-metasomatic processes. The determining factors in this type of classification are temperature and depth (lithostatic pressure).

In the process of metasomatism the PTX-conditions prevailing during replacement are certainly the most important controlling factors. Other fundamental factors are: 1) mobility of components, 2) penetrability of parent rock, and 3) reactivity of the parent rock (Mehnert, 1969, p. 282-283).

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During metasomatism, the completeness of chemical change in composition may be variable and depends on the replacing substances and on the character of the host rock. Certain geochemicaly "immobile" elements may remain behind while other "mobile" ones are exchanged. The question of mobility of substances has been thoroughly investigated by Korzhinskii who proposed the following mobility series. The oxides and elements are listed in order of decreasing mobility (Korzhinskii, 1947, p. 130).

H_2O, CO_2, S, SO_3, Cl, K_2O, Na_2O, F, CaO, O_2, Fe, P_2O_5, BaO, MgO, SiO_2, Al_2O_3, TiO_2

This sequence is valid only as a general principle, as many deviations may occur (Mehnert, 1969, p. 283).

The extent and effectiveness of metasomatism is controlled by the penetrability of the parent rock. In porous rocks liquids and gases may migrate easily but in metamorphic rocks pore spaces are mostly closed so that diffusion must be confined to intergranular spaces. Migration is facilitated by deformation which provides preferred channels of migration through broken rocks and minerals in zones of deformation (Mehnert, 1969, p. 283). In carbonate rocks thermal effects may also be important in increasing penetrability. Experimental work on calcite-bearing rocks indicates marked increases in permeability when the rocks are heated to 100° to 200°C or more with confining pressures of up to 10,000 lb/in^2 (Maxwell and Verrall, 1953, p. 105). Edwards et al. (1956) state that "this behavior of limestones and marbles results from the fact that the thermal expansion of calcite is strongly anisotropic, so that heating sets up intergrain stresses, loosening grain boundaries and opening up cleavages."

A third factor controlling metasomatism is the reactivity of the parent rock relative to the introduced substances. For instance, the reaction proceeds quickly if the parent rock is of a basic character, i.e., if it is

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rich in Ca, Mg, and Fe, and is invaded by a fluid of acid character rich in HCl, HF, etc. Considerable local enrichment of the reaction products may result, producing in some cases metasomatic ore deposits. If the chemical differences are small the reaction products often are widely distributed with little local enrichment (Mehnert, 1969, p. 283).

The mechanism of metasomatism has also been investigated by Korzhinskii (1964) who recognizes two types; diffusive and infiltration. Diffusive metasomatism occurs by diffusion of components through pore solutions and is very slow and limited to distances which never exceed a few tens of meters. Metasomatic alteration of large bodies of rock can take place only by infiltration metasomatism where the rock body is saturated by mineralizing solutions (Korzhinskii, 1964, p. 1718-1719). Distinction is also made in replacement bodies formed by these two different mechanisms. Diffusive metasomatism between adjacent rock bodies of different composition such that they enter into chemical reactions gives rise to bimetasomatic replacement (Korzhinskii, 1964, p. 1729). An example of this type of replacement would be the contact zone of marble and granitic intrusive where both show metasomatic effects of reaction and exchange of substances. Contact-infiltration zones develop in bodies of rock affected by infiltration metasomatism. The majority of contact metasomatic deposits develop by bimetasomatic processes, but the most valuable ore deposits belong to the contact-infiltration class (Korzhinskii, 1964, p. 1948). Many skarn deposits have developed by infiltration metasomatism where large volumes of marble or limestone have been replaced at considerable distances away from contacts with rocks with which reactions might take place. Most contact metasomatic zones are probably of a dual nature showing evidence of both diffusive and infiltration metasomatism.

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Since Lindgren's study of the Clifton-Morenci district (Lindgren, 1905) it is customary to assume volume for volume replacement in metasomatic processes. Considering volume changes, Lindgren (1918, p. 542-545) concluded that "while there may be in certain cases diminution of actual volume expressed in porosity and drusy textures, the opposite, i.e. an increase of volume will not take place by replacement in rigid rocks and that metasomatism does not normally involve changes of volume. Because of the dual transfer of material into and out of the system volume changes are usually difficult to document. The frequent preservation of textures and structures of the parent rock are often cited at the best evidence of no volume change (Lindgren, 1918, p. 548). Rarely, good stratigraphic control has shown that no change in volume has occurred during replacement. For example, Edwards et al. (1956, p. 92) demonstrated that thin marker beds bounding both marble and nearby tactite were not displaced or distorted as would be expected had there been some change in volume. Some studies have shown that sediments of a mixed calcareous nature can lose considerable volume if thermally metamorphosed without addition of material (Barrell, 1902 and 1907; Cooper, 1957). This takes place where there is silica present as quartz or impurities that may react with the carbonates (calcite and dolomite) to produce a stepwise series of decarbonation reactions with increasing temperatures (Bowen, 1940). Carbon dioxide is released in these reactions and removed from the system, resulting in a loss of volume.

Chemical Additions and Losses

The formation of tactite from marble results in a rock which has a wholly different mineralogy and composition and increased specific gravity. In order to account for these

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changes a considerable mass of substances must have been added and a somewhat smaller amount removed. Gains and losses of substances can be calculated if the chemical compositions and specific gravities of tactite and marble are known and possible changes in volume are considered.

To check the gains and losses in substances for tactite formation in the Black Rock mine area, partial chemical analyses and specific gravity measurements were obtained for two samples of marble and two of tactite. The results are shown in table 3. Carbon dioxide was not determined chemically but was obtained by calculation. In the marbles it was assumed that all of the MgO and CaO was contained in carbonates and the necessary amount of CO_2 needed to combine with these oxides to form calcite and dolomite was calculated and taken as the approximate amount present. In the tactites, the volume percent of calcite was obtained by counting 1000 points in thin section and CO_2 was then calculated assuming that it only occurred combined with CaO as calcite and taken as the approximate amount present. Both powder densities and bulk densities were obtained by a method described in the appendix. Porosities were then calculated from these results.

One of the marble samples (6-19-1) was obtained from a marble band continuous with and adjacent to tactite immediately south of the mine workings. The other sample (6-19-2) of marble is from a calcareous band approximately 1 mile southwest of the mine which is probably stratigraphically equivalent to the calcareous rocks in the mine area. These sample locations are shown on plate 1. Results from chemical analyses are shown in table 3 and indicate that both are quite pure calcite marbles.

Both tactite samples are of ore-grade scheelite-bearing tactite from exposures on the 6700 level. Sample no. 67-4 is from the west-dipping limb, 220 ft. horizontally from the quartz monzonite contact projected to this level,

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Oxides	Marble		Tactite	
	6-19-2	6-19-1	7-14-1	67-4
SiO_2	3.6 %	4.8 %	37.5 %	34.0 %
Al_2O_3	1.2	0.9	8.2	6.0
Total Fe calc. as Fe_2O_3	0.71	0.13	14.3	21.5
MgO	0.65	0.78	0.55	0.65
CaO	50.4	50.4	25.0	26.2
Na_2O	0.11	0.11	0.10	0.08
K_2O	0.21	0.05	<0.04	<0.04
MnO	0.07	0.01	5.16	4.90
CO_2	40.3	40.5	4.6	1.8
Totals	97.25	97.68	95.41	95.13
Specific Gravity Measurements				
Bulk Density	2.69	2.66	3.18	3.54
Powder Density	2.72	2.70	3.41	3.64
Porosity (calc.)	1.2%	1.5%	6.8%	2.8%

Table 3. Partial chemical analyses, densities, and porosities for samples of marble and tactite. SiO_2 and Al_2O_3 determined colorimetrically; total Fe, MgO, CaO and MnO by atomic absorption; Na_2O and K_2O determined by flame photometer; by G. T. Burrow and John Gardner; both of the U.S. Geological Survey. Average precision estimated at ±3% of the amount of the element present. No estimate of accuracy available. CO_2 by calculation; see text for explanation.

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and 7-14-1 is from the east portion of the crest of the anticline approximately 880 ft. horizontally from the projected igneous contact.

Using the chemical analyses and the bulk density, the mg. per cc. of each oxide can be calculated. This is shown in table 4 for one of the marble and both tactite samples in columns 1-3. Because of the chemical similarity of the other marble sample and its occurrence outside the immediate mine area, calculations were not made for that sample. The gains and losses are then obtained by subtraction resulting in the values shown in columns 4(col. 3 minus col. 1) and 5(col. 2 minus col. 1). The higher porosity for one of the tactites relative to marble suggest that some volume decrease has taken place in this case. The results shown in column 6 are based on a 5 percent volume decrease (obtained by subtracting col. 1 from 0.95 col. 2) in the replacement of marble by tactite and is probably a more realistic estimate of the actual gains and losses. Column 7 is the average of columns 4 and 6.

Results of these calculations show that the principal gains in converting marble to tactite were in SiO_2, Fe, Al_2O_3, and MnO in that order. The total gain, obtained by summing the mg. per cc. for the four oxides amounted to 2187.5 mg. per cc. for 67-4(col. 4) and 1844.1 mg. per cc. for 7-14-1(col. 6). This is equivalent to a 62% increase by weight of the tactite in the former and a 58% increase in the latter case.

The principal losses were in CO_2 and CaO. Total losses average 1436 mg. per cc. or 55% by weight of marble. MgO shows a small loss in one case and a small gain in the other.

These results are comparable to those obtained by other workers in studies of tactite tungsten deposits. Bateman (1965, p. 132) calculated gains and losses for the conversion of marble to tactite at the Pine Creek mine in the Bishop district and also found that the chief losses were of CO_2 and CaO with smaller losses of K_2O and H_2O. By

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Oxides	mg per cc			gains and losses in mg per cc				
	6-19-1	7-14-1	67-4	no vol. change		5%decr.	average	Pine Creek Mine
	1	2	3	4	5	6	7	8
SiO_2	127.7	1192.5	1203.6	+1075.9	+1064.8	+1036.1	+1056.0	+971.1
Al_2O_3	23.9	260.8	212.4	+188.5	+236.9	+223.9	+206.2	+294.2
Tot.Fe asFe_2O_3	3.5	454.7	761.1	+757.6	+451.2	+428.5	+591.1	+787.0
MgO	20.7	17.5	23.0	+2.3	-3.2	-4.1	-0.9	+53.8
CaO	1340.6	795.0	927.5	-413.1	-545.6	-585.4	-499.3	-192.7
Na_2O	2.9	3.2	2.8	-0.1	+0.3	+0.1	0.0	-0.2
K_2O	1.3	<1.3	<1.4	--	--	--	--	-18.8
MnO	0.3	164.1	173.5	+173.2	+163.8	+155.6	+164.4	+99.5
CO_2	1077.3	146.2	65.6	-931.1	-1011.7	-938.3	-974.5	-800.4

Table 4. Calculation of chemical gains and losses in the formation of tactite from marble. Values in column 8 from Bateman (1965, p. 131). Columns 4, 5, and 6 are results of subtracting col. 1 from col. 3, col. 1 from col. 2, and col. 1 from 0.95 col. 2 respectively. Column 7 is the average of columns 4 and 6.

percentage weight of marble the losses totaled 37%, somewhat less than in the Black Rock case. Principal gains for the Pine Creek tactite were of SiO_2, FeO, Fe_2O_3, Al_2O_3, MnO, and MgO with a smaller gain of TiO_2. Total gains amounted to 55% by weight of tactite. Although, in general, the results of this study are the same as obtained for the Black Rock tactites, on an oxide-by-oxide comparison there are some notable differences. Inspection of column 8 of table 4 shows that the gains at Black Rock are somewhat less for Al_2O_3, Fe (as Fe_2O_3), MgO, and more for SiO_2 and MnO. Principal losses for Black Rock are notably more for CaO and more for CO_2. Loss in K_2O was not evident in the Black Rock samples because of the low contents of K_2O in both marbles and tactites.

Chemical changes involved in mineralization have been calculated by Edwards et al. (1956, p. 93) in a study of the Kind Island scheelite mine in Australia. The findings were also similar to results of the Black Rock calculations. Principal losses were of CO_2 and CaO, totaling 43% by weight of marble. Principal gains were of SiO_2, Fe_2O_3, and Al_2O_3 with smaller gains of FeO, MgO, H_2O, and WO_3. Total gains amounted to 55% by weight of tactite.

Form and Distribution of Ore Bodies

The only ore mineral at the Black Rock mine is scheelite, $CaWO_4$, and the ore consists of local concentrations of this mineral in garnet tactite. The amount of scheelite in tactite ranges from slightly over 2 percent to nil; most of the tactite is barren or has concentrations of scheelite too low to be considered economic. The ore bodies, therefore, are defined by cut-off limits determined by assay and economics.

The ore bodies vary in shape from highly irregular masses to stratiform lenses parallel to bedding in the adjacent rocks. Thicknesses of individual ore bodies vary from a few feet to approximately 30 feet with most in the range of 5 to 20 feet. Ore bodies generally have strike lengths

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of 50 to 100 feet, and stratigraphically favorable zones along which ore bodies occur can be followed for several hundred feet. Examples of the larger ore bodies are the ones exposed in the Glory Hole and Senior Pit open cuts (pl. 2), both of which are along the upper portion of the tactite near the tactite-hornfels contact.

Most of the ore bodies are confined to tactite zones along the west-dipping limb or crest of the anticline. Examples are the ore bodies exposed in the Senior Pit and Glory Hole open cuts (pls. 2 and 4) and their underground extensions. Ore bodies also occur rarely in the steep, eastward-dipping limb.

The major ore bodies exploited in the past occur above the 6600 level. The 6500 level has had limited production and was used mainly as a haulage level. There has been little exploration at depths below the 6500 level.

The localization of ore bodies is controlled principally by stratification and structure. Lithology is important since the scheelite mineralization is restricted to dark colored garnet tactites developed by replacement of marble. Structural control is evidenced by the localization of ore bodies in the crest and west-dipping limb of the anticline (pl. 2, 4). Plate 2 shows that ore bodies such as those in the Glory Hole, Junior, and Senior open cuts occur in tactite that locally encloses masses and blocks of unreplaced marble and is continuous with marble bands to the south. Figure 4 shows a view of the pit wall in the Glory Hole open cut where blocks of unreplaced marble are enclosed in tactite, some of which is scheelite-bearing.

Sedimentary stratification and depositional contacts between siliceous and calcareous rocks also may be factors controlling the replacement of marble by tactite and the localization of scheelite mineralization. In an area immediately north of the Black Rock mine the marble has been little affected by contact metasomatism and only minor amounts of tactite have been developed. Where tactite

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Figure 3. Outcrop of silicated marble showing incipient formation of tactite (T) in marble (M). Selective replacement is controlled by bedding in marble.

Figure 4. View of pit wall in Glory Hole open cut showing blocks of unreplaced marble (M) in tactite (T).

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is present, as in the outcrop shown in figure 3, selective replacement of marble by tactite was evidently influenced by bedding in the marble. Primary stratification for example between limestone and shale or siltstone or between relatively pure and impure calcareous units, may have been important in controlling the distribution of tactite and scheelite mineralization. One of the most persistent ore zones in the Black Rock mine occurs near the base of a tactite bed adjacent to calc-hornfels. This bed is shown in plate 4 as the upper continuous tactite along which several scheelite-bearing zones are located. Scheelite-bearing tactite, locally of ore grade, is also found near the top of the thick tactite bed underlying the calc-hornfels bed mentioned above. Details of these relationships are illustrated in figure 5, which is a section showing workings and geology along 255ON. In this figure, three zones of scheelite-bearing tactite are shown, two of which (A and C) have been extensively mined. Of these, A is the most continuous and formed by replacement of marble adjacent to the calc-hornfels. Scheelite-bearing tactite at B is adjacent to the lower contact of the calc-hornfels and grades downdip into unreplaced marble. The ore zone at C is separated from the overlying calc-hornfels by approximately 25 feet of barren or low grade tactite but still is within the upper part of the lower tactite-marble bed shown in plate 4.

These primary sedimentary contacts may have controlled the localization of ore bodies in one or more ways. During folding, zones of secondary permeability due to deformation may have developed because of the different structural characteristics of the two contrasting rock types. Thereby, preferred channels of migration were created, along which later tungsten-bearing solutions moved along a thermal gradient. Evidence of this type of deformation was found in thin sections of marble adjacent to tactite on the 6500 level. At this locality the sequence of units from southeast to northwest is (1) mixed calc-hornfels and siliceous hornfels,

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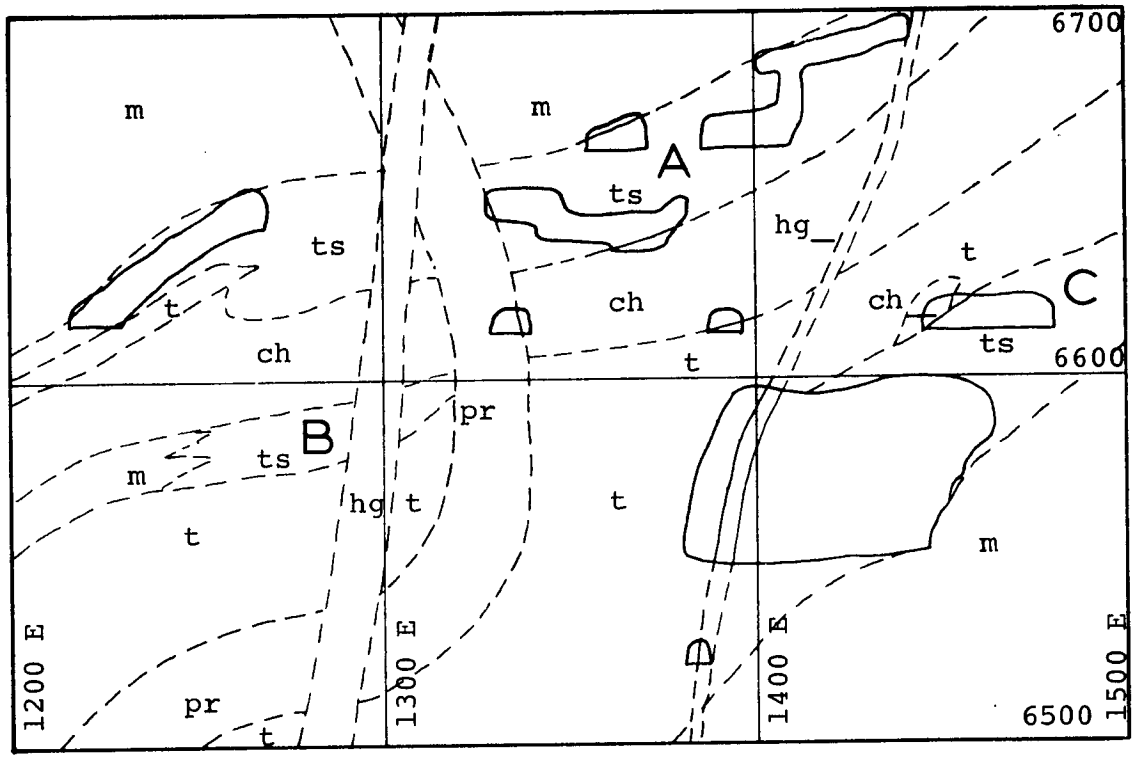

Figure 5. Section along 2550 N showing workings and geology. Scheelite-bearing tactite zones are present at A, B, and C. Symbols are the same as in plates 2 and 4. Scale 1 in. = 50 ft. Mapping by Wah Chang Corporation.

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(2) low grade and barren epidote garnet tactite (3 to 4 ft. wide), (3) ore grade garnet and pyroxene tactite (3 to 4 ft. wide), and (4) marble. Thin sections were prepared from samples selected at one-foot intervals across this tactite zone and into the bordering hornfels and marble. In the marble, increasing deformation in the direction of the tactite is shown by changes in the texture and structures of the calcite of the marble. These changes, towards the tactite, are (1) an increase in the amount of granulation along grain boundaries and in recrystallization, (2) an increase in secondary twinning and internal deformation such as bent twin lamellae, and (3) a change from mosaic to sutured texture. At this locality there is no megascopic or microscopic evidence of post-tactite deformation. Therefore, the deformation must have been prior to or contemporaneous with the formation of the scheelite-bearing tactite and may have created a favorable zone along which tungsten-bearing solutions may have migrated and reacted with the calcite of the marble to produce scheelite along with accompanying tactite minerals.

The primary contacts between calcareous and siliceous sediments are contacts between units of differing chemical character. This factor may have been important in the localization of scheelite-bearing tactite. The minerals of the tactites are principally calcium silicates and in these contact zones reaction, accompanied by hydrothermal fluids, would produce a bimetasomatic zone of tactite. Because of the greater reactivity of the carbonates, the resulting tactite would be largely a replacement of the marble, but constituents such as silica, alumina, and some of the iron could have come principally from the adjacent hornfels.

Mineralogy of Tactites

The mineralogy of the tactites was studied in thin sections, polished sections, and as mineral separates. Non-opaque minerals were identified optically, and opaque

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minerals were determined by physical and etch tests and by X-ray powder photographs. Since a major part of this study is concerned with the trace element contents of garnet, pyroxene, amphibole, and scheelite, major effort was devoted to determining the optical and chemical properties of these four minerals. Specific gravities, refractive indices, and unit cells were measured for garnets; partial chemical analyses were obtained for samples of garnet, amphibole, and pyroxene; and the molybdenum contents of scheelites were measured. A few refractive index measurements were made on amphibole, pyroxene, and other minerals. For convenience minerals have been grouped as non-opaque and opaque in the list in table 5.

In general, tactites of the Black Rock mine can be grouped into high grade scheelite-bearing tactites and low grade or barren tactites. By far the largest proportion of tactite is barren or low grade. Many minerals are common to both types of tactite but some are relatively more common or restricted to one type or the other. For example, fluorite was found only in high grade tactites. Epidote, vesuvianite, wollastonite, and sulfides are common only in barren or low grade tactites. Minerals which occur in major amounts, either locally or commonly, are pyroxene, amphibole, epidote, pyrrhotite, biotite, and quartz. The high grade tactites are generally dominated by garnet, pyroxene, and/or amphibole while the barren tactites have a more diverse mineralogy.

Most tactites are shades of brown and green, and are commonly mottled as a result of variations in abundances of brown garnet and the green minerals; pyroxene, amphibole, and epidote (fig. 11). Because of the higher content of iron-rich garnet, the high grade tactites are generally dark brown in color while the low grade or barren tactites are light green to light brown.

The tactites are fine to medium grained, massive or banded, and inequigranular. Characteristically they are internally heterogeneous with clots or local accumulations of epidote, pyroxene, amphibole, or other minerals. The

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high grade scheelite-bearing tactites are generally finer grained than the barren or low grade tactites, some of which are coarse grained and display vugs which contain large euhedral crystals. The grain size varies with the minerals. Garnet, for example, is generally medium to coarse grained, epidote is medium to very coarse grained (up to several cm.), and scheelite is predominantly fine grained.

Opaque minerals are locally very abundant, occurring as disseminations and veins in tactite and hornfels. The principal opaques are pyrrhotite and magnetite and of these the sulfide, pyrrhotite, is more common and is always accompanied by minor amounts of other sulfide minerals; mostly chalcopyrite but small amounts of pyrite, marcasite, or sphalerite may be present. The sulfide minerals are more abundant on the lower levels of the mine, in close proximity to the intrusive contact, than on the upper levels and in surface exposures. On the 6500 and 6600 levels, there are large volumes of pyrrhotite tactite containing more than 50 percent hexagonal pyrrhotite. On the upper levels and in surface exposures opaques are minor, occurring as disseminations and in small veinlets (fig. 10).

Amphibole.--The tactites contain as much as 20 percent amphibole, including tremolite, actinolite, and green hornblende. The iron-poor, light-colored amphiboles of the tremolite-actinolite series are found in calc-hornfels and barren tactite, whereas the more iron-rich actinolite and hornblende are common in the more iron-rich and scheelite-bearing tactites. The amphiboles are generally fine to medium grained, fibrous to prismatic, commonly occurring as replacements of pyroxene. Dark green actinolite commonly occurs intergrown with sulfides, especially pyrrhotite and chalcopyrite (figs. 14, 16). Actinolite and sulfides commonly occur as thin veinlets filling fractures in other silicate minerals (fig. 16) as well as in disseminated spots and masses. Actinolite also occurs intergrown with late

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Non-opaque	Opaque
amphibole	chalcopyrite
apatite	magnetite
biotite	marcasite
calcite	molybdenite
chlorite	pyrite
epidote	pyrrhotite
fluorite	spalerite
garnet	
plagioclase	
pyroxene	
quartz	
scheelite	
sphene	
vesuvianite	
wollastonite	
zircon	

Table 5. Mineralogy of tactites

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quartz and calcite and as replacements of pyroxene. These modes of occurrence suggest late origin for the actinolite.

Amphiboles of the tremolite-actinolite series are the result of both progressive and retrograde contact metamorphism. During progressive metamorphism of impure limestones containing dolomite and silica, tremolite may form. Since the Ca:Mg ratio is greater in dolomite than tremolite, calcite is also formed in the reaction (Bowen, 1940, p. 239).

$$5CaMg(CO_3)_2 + 8SiO_2 + H_2O \rightarrow$$

dolomite quartz

$$Ca_2Mg_5Si_8O_{22}(OH)_2 + 3CaCO_3 + 7\ CO_2$$

tremolite calcite

At a higher grade of metamorphism tremolite is unstable in the presence of excess silica and may react with calcite and silica to form diopside (Bowen, 1940, p. 243; Deer, et al., 1963, p. 258):

$$Ca_2Mg_5Si_8O_{22}(OH)_2 + 3CaCO_3 + 2SiO_2 \rightarrow$$

tremolite calcite quartz

$$5\ CaMgSi_2O_6 + 3CO_2 + H_2O$$

diopside

Many of the calc-hornfels and tactites, especially barren tactites, show evidence that these two reactions took place resulting in the common assemblage calcite-quartz-diopside. In the presence of high iron concentration actinolite and more iron-rich pyroxenes of the diopside-hedenbergite series form.

A stage of incipient retrograde metamorphism is evidenced by textures suggesting that anhydrous silicates have been replaced by OH-bearing silicates, such as actinolite as a replacement of pyroxene, and epidote as a replacement of garnet. Much of the dark-green actinolite common to many of the scheelite bearing and some barren tactites probably formed during this stage by the breakdown of pyroxene:

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$$5Ca(Fe,Mg)Si_2O_6 + 3CO_2 + H_2O \rightarrow$$
pyroxene

$$3CaCO_3 + SiO_2 + Ca(Fe,Mg)_5Si_8O_{22}(OH)_2$$
calcite quartz actinolite

This reaction would also account for at least part of the late stage quartz and calcite which commonly occur with the actinolite.

A few tactite samples have minor amounts of green hornblende occurring with actinolite. Hornblende is distinguished from actinolite by nonfibrous character, well-defined amphibole cleavage, lower birefringence, and pleochroism, but otherwise properties are transitional with actinolite and the two minerals presumably have a similar composition. The hornblende may be derived from actinolite by an increase in the content of alumina and local increases in the grade of metamorphism.

Nine samples of actinolite, prepared as mineral separates using heavy liquids and magnetic separation, were analyzed using a semiquantitative spectrographic procedure for ten elements occurring in trace or minor quantities. The results will be discussed in a later section.

Four of the actinolite separates were also analyzed for total Fe, MgO, CaO, and MnO (Table 6). Although these partial chemical analyses cannot be used to calculate accurate chemical formulas, they are of use in calculating an approximate mol. percent tremolite end-member composition in each sample (shown in Table 6). This is obtained simply by dividing weight percents by molecular weights, giving molecular proportions of the oxides, and then calculating according to the equation: % $Ca_2Mg_5Si_8O_{22}(OH)_2$ = 100 Mg/(MgO + FeO + MnO).

Values obtained for the four samples of actinolite range from 27.0 to 61.5 mol. percent $Ca_2Mg_5Si_8O_{22}(OH)_2$. These are maximum values since the presence of some iron as Fe^{3+} would give a lower mol. percent value. Most actinolites from the Black Rock tactites probably are in the range of 25 to 50 mol.

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Field No.	Mineral	Total Fe, calculated as FeO percent	MgO%	CaO%	MnO%	Percent*
66-1	Actinolite	13.9	3.60	11.0	3.36	27.0
66-4	Actinolite	12.4	6.10	11.2	2.00	42.9
7-14-1	Actinolite	11.4	7.20	10.6	3.49	46.2
65-1	Actinolite	9.3	9.21	11.9	1.42	61.4

*$Ca_2Mg_5Si_8O_{22}(OH)_2$

Table 6. Partial chemical analyses of actinolites. Total Fe, MgO, CaO, and Mn determined by atomic absorption by W. Mountjoy, U.S. Geological Survey. The usual accuracy of the method is about ±3 percent of the amount of the element present. Precision expressed as the coefficient of variation is estimated to be 2 percent or less based on duplicate analyses.

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percent tremolite. Optical data for sample no. 65-1 are:

$\alpha = 1.638 \pm .003$, $\beta = 1.657 \pm .003$, $\gamma = 1.664 \pm .003$, and $\delta = 0.026$.

These actinolites are more iron-rich than most analyzed actinolites. "In the tremolite-ferroactinolite series, minerals in which the replacements of Mg by Fe^{+2} range from 0 to 50 percent are common. More iron-rich members have only rarely been described" (Deer, et al., 1963, p. 250). The most notable feature of these actinolites, however, is the rather high content of MnO. Normally actinolites have less than 1 percent MnO, but in these samples MnO values range from 1.4 to 3.5 percent. The pyroxenes and some of the garnets are also MnO-rich. The high iron and manganese contents of these minerals probably reflect the character of the metasomatizing fluids rather than original compositions of the metasediments.

Apatite.--Apatite is a rare accessory in tactites except in certain pyrrhotite-rich or magnetite-rich tactites. In these, apatite occurs as anhedral to subhedral grains up to 0.5 mm. in size and many constitute up to 2 percent by volume of the rock. Other minerals with which it is associated are magnetite or pyrrhotite, garnet, biotite, and quartz. Paragenetically apatite is an early-formed mineral, contemporaneous with garnet and magnetite. From one sample (7-6-24) the refractive index of apatite was $N_o = 1.629 \pm .005$. No other optical or compositional data were obtained.

Biotite.--Biotite is a common constituent only in pyrrhotite tactites and tactites with much magnetite (in which it may occur in quantitites of up to 30 percent by volume of the rock). It commonly occurs with garnet, magnetite or pyrrhotite, apatite, and quartz. Biotite is late in origin, occurring as anhedral aggregates and felty decussate masses filling interstices. Individual plates may be up to 2.5 mm. in diameter, but much of the biotite is fine grained. Most of the biotite is a bright grass green

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in color. The refractive index of green biotite from 7-6-24 is N_β 1.655 ± .005. The tactites containing biotite are all from the lowest workings and near the intrusive contact.

Calcite.--Calcite is a minor or major component in most of the tactites, occurring in quantities of from 1 to greater than 10 percent by volume. Commonly it is fine to medium grained, rarely coarse grained, occurring mostly as anhedral masses with mosaic texture filling interstices between garnet and other silicates, and also as fine-grained veinlets and fracture fillings. These occurrences are probably late in origin. Minor amounts of calcite also occur as inclusions in garnet and as small pods of anhedral grains residual from marble. These residual patches show evidence of penetrative deformation in the form of crushed grain boundaries and secondary twinning of calcite.

Chlorite.--Chlorite is rare in tactites, occurring as a late-stage alteration product of biotite and, in one case, as late-stage vein filling with calcite.

Epidote.--Intermediate members of the clinozoisite-epidote series are common in many of the tactites. Epidote is especially abundant in tactites in which scheelite is minor or absent, occurring in amounts of up to 35 percent by volume. It is less common in scheelite-bearing tactites. Epidote is light green to colorless in thin section and occurs as anhedral to subhedral grains up to 1 mm. in diameter interstitial to garnet and pyroxene. Coarse grained euhedral epidote, especially in vugs, is also common. Much of the coarser grained epidote is poikiloblastic. Epidote is commonly contemporaneous with late-stage quartz and calcite, less commonly with actinolite. Much of the epidote has developed by replacements of garnet, pyroxene, and vesuvianite. In sample no. J19 a paired replacement relationship was noted in thin section: garnet and pyroxene, an early stage stable assemblage, are partially replaced by epidote and actinolite, a later assemblage, and pyroxene is more completely destroyed

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than garnet. Epidote with quartz has also been noted in late-stage cross-cutting veinlets in tactite. These textures and mineral associations suggest that epidote is a late mineral and may be the result of late-stage incipient retrograde metamorphism. Compositionally, the epidote minerals are probably intermediate members of the clinozoisite - $Ca_2Al_3(OH)Si_3O_{12}$ to epidote - $Ca_2(Al,Fe)_3(OH)Si_3O_{12}$ series. All are monoclinic and have 2V's varying from (-) 80° to (+) 85°.

Fluorite.--Fluorite is a rare constituent occurring in minor or trace amounts in some scheelite-bearing tactites. In thin section it is colorless, fine to medium grained, and anhedral. Fluorite is early in origin. In sample no. J7 textural relations suggest that the early-formed stable assemblage is pyroxene-fluorite-garnet-scheelite.

Garnet.--Garnet, the most abundant and ubiquitous mineral in the tactites, constitutes normally 25 to 50 percent by volume of the rock, in some specimens up to 70 percent. In general the scheelite-bearing tactites show a higher proportion of garnet than the barren tactites. Garnet is mostly in the size range of 0.1 to 2 mm., but some crystals range up to 10 mm. or larger. Garnet is generally idioblastic to subidioblastic granular but may be massive. Porphyroblasts are poikiloblastic with inclusions of nearly all other minerals. The most common inclusions are pyroxene and calcite; scheelite, epidote, calcite, vesuvianite, and quartz are less common.

Garnet is generally one of the earliest minerals to form, along with pyroxene, scheelite, fluorite, and vesuvianite. Pyroxene, the most common accompanying mineral, is contemporaneous or slightly earlier. Much of the garnet has replaced calcite, present originally in marble (fig. 9), and intergrowth textures with calcite are seen in some specimens. Garnet also commonly forms skeletal crystals ("atoll" texture) which have cores of calcite. Much garnet shows effects of fracturing with fracture fillings and cross-cutting veinlets

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of quartz and calcite or, in some cases, sulfides. Where epidote is abundant, replacement of garnet by epidote is evident. Garnet shows pronounced zoning and is commonly anisotropic.

In many samples, thin section studies show evidence of two distinct garnets of different appearance which are sequential in formation. The early phase is colorless in thin section and light brown in hand specimen, commonly isotropic or nearly so, not zoned, and contemporaneous with diopside. The later phase is light brown in thin section and dark brown in hand specimen, anisotropic, zoned, and forms contemporaneously with scheelite, which is common as inclusions in late garnet (fig. 6). These two types of garnet commonly take the form of grains with colorless isotropic cores and anisotropic brown rims (fig. 7).

Because garnet is the most ubiquitous mineral in all types of tactites, it was selected as the main mineral on which to study optical, physical, and chemical properties. Mineral separates of 23 samples of garnet were prepared using heavy liquids and magnetic separation. The methods of mineral separation are described in the appendix. The garnets were from a variety of tactites, representing all types, both barren and scheelite-bearing. Plate 3 shows the location of these samples. After purification, the trace elements Be, Ti, V, Ni, Sn, Cu, Y, Sc, Co, and MnO content were determined by a semiquantitative emission spectrograph technique. Specific gravities were measured using Clerici solution. Refractive index determinations were made using index oils and unit cell measurements were made by X-ray diffraction methods. These methods are described in the appendix. Partial chemical analyses were obtained on eight garnet samples for which Fe, MgO, CaO, and Mn were determined by atomic absorption. Whole rock samples from which these garnets were separated were submitted to a 30-element semiquantitative analysis and separate chemical determinations of Hg and W.

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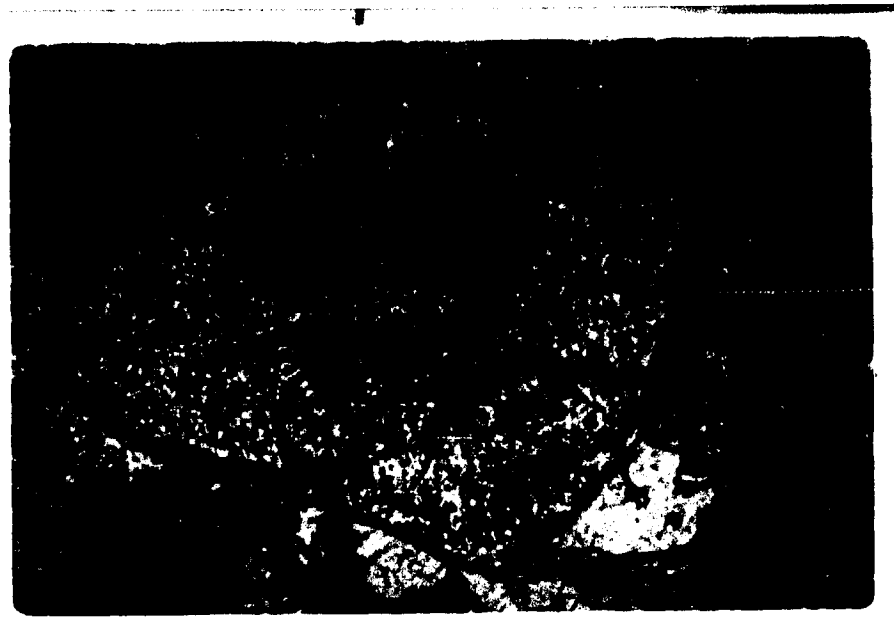

Figure 6. Photomicrograph of no. 66-1, a scheelite-bearing tactite, showing euhedral scheelite enclosed by garnet. Magnification 160X, polarized light.

Figure 7. Two stages of garnet are shown in this photomicrograph of 7-6-22, a sample of high grade scheelite-bearing tactite. The early garnet (E) is colorless and nearly isotropic whereas the later garnet (L) is light brown and anisotropic. Magnification 15X, polarized light.

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Nearly all the garnets showed a range in refractive indices indicating a range in composition. The extreme range was 1.771 to 1.861 for sample number 7-6-11, but as was shown by X-ray diffraction this represents a composite of two distinct garnet compositions and not a continuous range in composition.

More than half of the X-ray diffraction patterns showed two sets of peaks indicating garnets of two different unit cells and therefore two distinct compositions. In 10 of the 23 samples two sets of measurements were obtained giving two unit cells. The larger of the two unit cells is, in all cases, indicative of a higher content of $Ca_3(Fe^{+3},Ti)_2Si_3O_{12}$ (andradite) relative to the ferrous iron (almandine), manganese (spessartine), and calcium (grossular) end members. In the remaining 13 there was either only one garnet present, the second garnet was not present in sufficient quantity to give a measureable peak, or the peaks were broad indicating a range in composition in the garnet present. These results are shown in table 7. In most cases where two sets of peaks were present, the peaks were sharp indicating little variation in composition for each garnet and for the most part no intermediate compositions. The garnet with the larger unit cell edge (higher ferric iron content) was nearly always dominant over the second garnet, with relative intensity ratios for the {420} peak varying from 50:50 to 90:10 in the cases where the second garnet could be distinguished and measured.

Refractive indices, specific gravities, and unit cells are listed in table 7 for 23 garnet separates. In figure 8 these garnets are plotted in relation to the end members of the garnet group; andradite, uvarovite, almandine, spessartine, grossular, and pyrope on the determinative chart by Winchell (1958, p. 598). Also outlined on figure 8 are compositional fields of garnet which are from high grade scheelite-bearing tactites, low grade or barren sulfide-rich tactites, and other low grade or barren tactites. All the garnet separates having

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Reference No. for figure 8	Sample No.	Refractive Indices	Specific Gravity	Unit Cell measurements in Å
1	65-1	1.760-1.765	3.625	11.880
2	65-3	1.765-1.781	---	11.804, 11.887
3	6-24-4	1.743-1.755	3.66	11.871
4	6-24-7	1.755-1.769	3.66	11.883
5	7-6-25	1.786-1.805	---	11.624
6	7-6-27	1.801-1.811	4.11	11.627
7	67-1	1.780-1.833	---	11.794, 11.929
8	67-3	1.791-1.831	---	11.783, 11.934
9	6-24-12	1.751-1.759	---	11.871
10	66-1	1.782-1.857	3.95	11.772, 11.933
11	66-2	1.788-1.859	3.78	11.794, 11.962
12	66-3	1.781-1.792	3.90	11.615, 11.723
13	66-4	1.776-1.807	3.86	11.808
14	66-5	1.799-1.858	3.88	11.795, 11.966
15	67-6	1.800-1.801	3.95	11.782
16	67-7	1.781-1.801	---	11.755
17	67-9	1.771-1.803	---	11.898
18	67-10	1.792-1.819	---	11.899
19	7-6-11	1.771-1.861	3.82	11.790, 11.953
20	7-6-22	1.788-1.805	3.95	11.713, 11.795
21	7-14-1	1.780-1.824	3.84	11.912
22	7-14-2	1.776-1.805	3.81	11.798, 11.901
23	7-6-24	1.811-1.812	4.13	11.613

Table 7. Refractive indices, specific gravities, and unit cell edge measurements for garnets. The precision of the measurements for refractive indices, ±003; specific gravities, ±0.1; and unit cells, ±.004 Å.

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Figure 8. Plot of refractive indices, n, and unit cell, a, in relation to end members of the garnet group. Symbols are AND. = andradite, UV. = uvarovite, ALM. = almandine, SP. = spessartine, GRO. = grossular, and PYR. = pyrope; (┃) is used for garnets showing range (length of vertical line proportional to range) of n but with single unit cell, a; (●—●) is used for garnets showing two unit cells and a range in refractive indices. Numbers refer to reference numbers in table.

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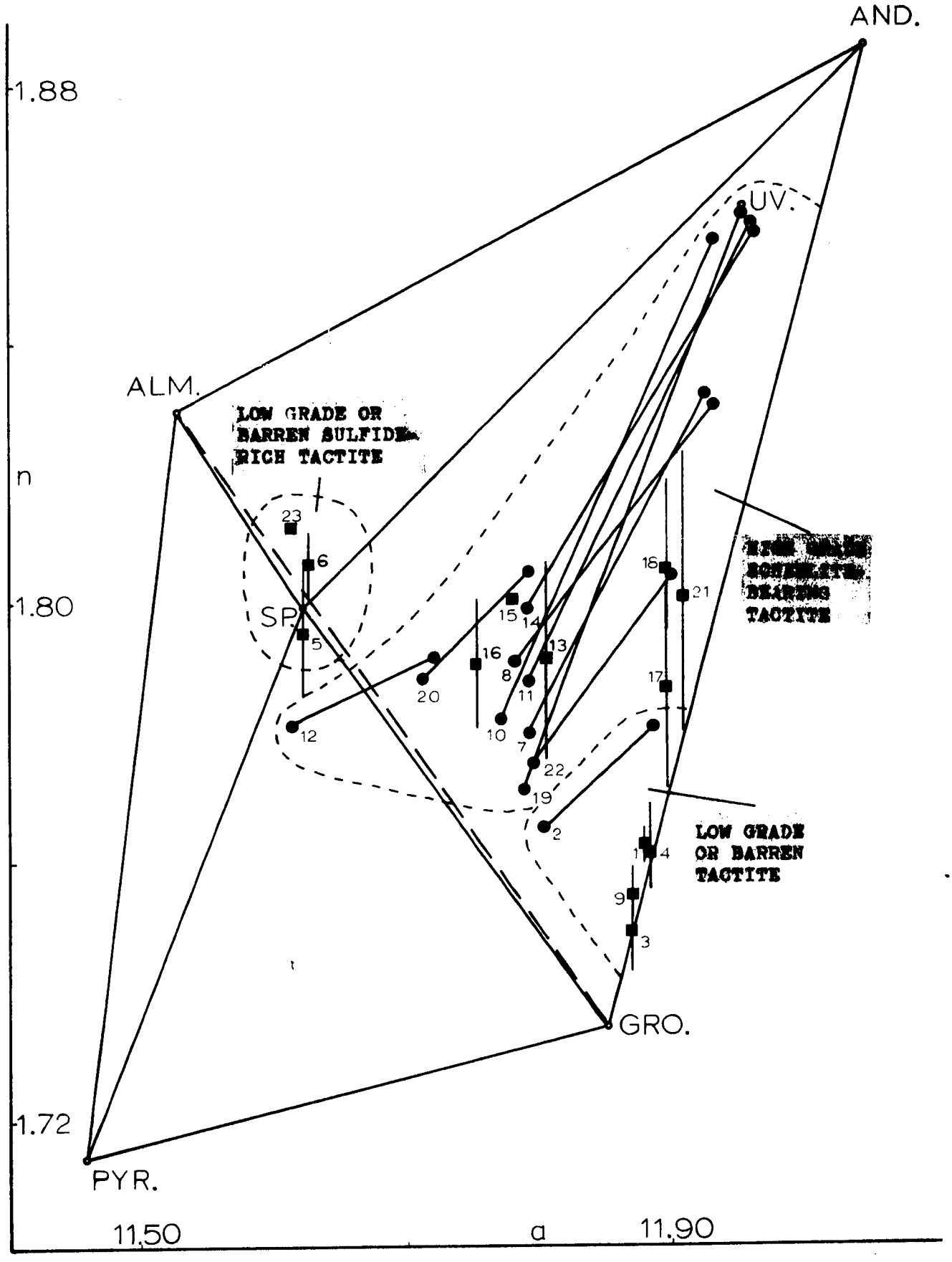

Figure 8.

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two unit cells and therefore consisting of two garnets of different compositions are from scheelite-bearing tactites. In these cases, in thin section it was noted that scheelite is associated with the more iron-rich late garnet (having the larger unit cell).

Partial chemical analyses were obtained for eight of the separated garnets. The results are shown in table 8. The eight which were selected were from a variety of tactites ranging in tungsten content from nil to greater than 1 percent and were chosen by their physical and optical properties so as to show the complete range in composition to be expected in this group of garnets. Four of the garnets (7-14-2, 67-10, 66-2, 66-4) were from high grade tactites containing 0.1 percent or more tungsten; one (6-24-12) was from a low grade tactite containing 50 ppm tungsten; three (65-1, 6-24-4, 7-6-27) were from essentially barren tactites containing less than 20 ppm tungsten. One of the barren tactites, 7-6-27, contained a major amount of pyrrhotite.

MgO is low in all of the garnet separates and chromium, as determined in spectrographic analyses, is low in these tactites, indicating that the proportion of $Mg_3Al_2Si_3O_{12}$ (pyrope) and $Ca_3Cr_2Si_3O_{12}$ (uvarovite) is low or negligible. The garnets consist of various proportions of the four components, $Fe_3^{2+}Al_2Si_3O_{12}$ (almandine), $Mn_3Al_2Si_3O_{12}$ (spessartine), $Ca_3Al_2Si_3O_{12}$ (grossular), and $Ca_3(Fe^{3+},Ti)_2Si_3O_{12}$ (andradite). Most of the garnets are calcium- and iron-rich indicating compositions in the grossular-andradite series. However, some of the iron may be present as ferrous iron indicating presence of the $Fe_3^{2+}Al_2Si_3O_{12}$ component and the high contents of MnO in some of the garnets indicate a large proportion of the $Mn_3Al_2Si_3O_{12}$ component. These data confirm the compositions which were indicated by plotting the physical and optical properties shown in table 7 on the determinative chart (figure 8).

The eight analyses shown in table 8 may be subdivided into three groups based on chemical composition; (1) a low iron, low

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Field No.	Total Fe as Fe_2O_3%	MgO%	CaO%	MnO%
65-1	6.68	0.14	33.2	0.57
6-24-4	5.04	0.45	34.4	0.52
7-14-2	13.2	0.085	27.3	6.33
67-10	14.7	0.14	25.7	7.75
6-24-12	5.77	0.31	34.9	0.48
do.	5.68	0.31	34.3	0.47
7-6-27	17.2	0.81	3.98	21.80
66-2	20.4	0.062	27.4	5.55
66-4	13.9	0.095	22.9	8.39

Table 8. Partial chemical analyses of eight garnet separates. Total Fe, MgO, CaO, and Mn determined by atomic absorption by W. Mountjoy, U.S. Geological Survey. The usual accuracy of atomic absorption analysis is about ±3 percent of the amount of the element present. Precision expressed as the coefficient of variation is estimated to be 2 percent or less based on duplicate analyses.

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manganese, and high calcium group including 65-1, 6-24-4, and 6-24-12, (2) a high iron, intermediate manganese, and high calcium group consisting of 7-14-2, 67-10, 66-2, 66-4, and (3) a high iron, high manganese, and low calcium group represented by 7-6-27. These three groups correspond to the groups outlined on figure 4 based on physical properties.

Garnets with appreciable contents of manganese and ferrous iron are somewhat unusual for skarn deposits of this type since garnets occurring in this environment are generally of the grossular-andradite series. In a study of the relations between garnet and rock types, Tröger (1962) found that garnets formed from sedimentary carbonate rocks through metamorphism or metasomatism were made up principally of the $Ca_3(Fe^{3+},Ti)_2Si_3O_{12}$ and $Ca_3Al_2Si_3O_{12}$ components. Five groups of analyses representing 108 garnets showed average end member compositions of grossular (10-90 percent) and andradite (4-82 percent) while the highest average spessartine and almandine contents were 3.5 and 11.5 percent respectively. Skarn garnets with high manganese (e.g., spessartine) occur but are quantitatively unimportant (Tröger, 1962, p. 673). Skarn garnets from iron deposits were studied by Karpenko, et al. (1961) and found to be of the grossular-andradite series. The content of pyrope-almandine end members was less than 10 percent and MnO was 0.77 percent or less indicating a low spessartine content. Garnets associated with manganiferous pyroxenes in a skarn-polymetallic deposit (Tarasov, 1966, p. 628) have a maximum pyrope + spessartite + almandine content of less than 10 percent.

The compositions of the garnets from the Black Rock tactites vary in accordance with variations in the enclosing tactite. Three types of garnets are distinguished based on composition, refractive index, specific gravity, and unit cell. These three types and their parent tactites are; (1) high ferrous iron, high manganese (almandine-spessartine) garnets typical of low grade or barren sulfide-rich tactites, (2) high ferric iron, high calcium (andradite) garnets of high

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grade scheelite-bearing tactites, and (3) high calcium, low iron (grossular) garnets of low grade or barren sulfide-poor tactites. Most of the high grade scheelite-bearing tactites have two generations of garnets of different composition. The later garnet is more iron-rich (ferric iron) and closer to andradite in composition than the original garnet. This garnet encloses and replaces the earlier garnet. Scheelite is intergrown with and enclosed by the later but not the earlier garnet. The composition of garnets could be used as a guide in the search for undiscovered scheelite-bearing tactite in the Black Rock area.

Plagioclase.--Plagioclase is a rare and relatively unimportant mineral in tactites and was noted at only one locality. Here, it occurred as late xenoblastic grains in association with garnet, epidote, vesuvianite, calcite, and diopside; it shows patchy extinction and sodic (approx. An_{20}) composition.

Pyroxene.--Next to garnet, pyroxene group minerals are the most common and abundant constituents of the Black Rock tactites. Compositionally the pyroxenes are mainly of the series diopside, $CaMgSi_2O_6$, to hedenbergite, $CaFe^{+2}Si_2O_6$, but Mn occurs in significant amounts in many of the pyroxenes meaning that a third component $CaMnSi_2O_6$ (johannsenite) must be considered. The Fe-poor members are common in the tactites containing little or no scheelite and the Fe-rich hedenbergite is characteristic of many of the scheelite-bearing tactites.

The pyroxenes are colorless to light green in thin section and light green to green in hand specimen. The darker colored pyroxenes are faintly pleochroic with positive 2V's near 60° and $Z \wedge C$ is 41°-49°, increasing with the darker green varieties. Grains are mostly subhedral and in the size range of 0.1 to 1.0 mm, but may be euhedral where they occur in a matrix of quartz or calcite and may be anhedral when they exist as clots showing sutured texture or as inclusions in other minerals, especially garnet. The proportion of pyroxene

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is quite variable, ranging from trace amount to 50 percent by volume but commonly in the range 10 to 30 percent.

Pyroxene is the earliest or one of the earliest formed minerals in all tactites in which it occurs. It is either earlier than or accompanied by garnet and other early minerals such as scheelite, vesuvianite, and fluorite. Very rarely does pyroxene have inclusions of other minerals but commonly it occurs as inclusions in other minerals, especially garnet. Evidence of its contemporaneous growth with garnet is seen in one sample (no. 65DC7) where pyroxene inclusions in garnet are from 0.1 to 0.5 mm in size, whereas pyroxenes not enclosed in garnet are up to 5 mm in size. The pyroxene as inclusions had its growth arrested by engulfment in rapidly growing garnet, while other pyroxene crystals continued to grow unrestricted. Pyroxene also occurs as inclusions in vesuvianite. Pyroxene, like garnet, may be the result of two growth stages, an early light green Fe-poor diopside and a late darker green Fe-rich hedenbergite, but evidence is lacking in any one sample to verify this. However, in samples containing two generations of garnets darker green pyroxene occurs with late brown garnet and scheelite. This pyroxene is poikiloblastic and contains inclusions of scheelite.

Much of the pyroxene is altered and replaced, most commonly by dark green fibrous actinolite. Less common is replacement by epidote, garnet, or vesuvianite. In general, pyroxene is more altered and replaced than is garnet.

Mineral separates of pyroxene were prepared from six of the samples from which garnet was also separated. Five samples were ore-grade scheelite-bearing tactites and one (6-24-12) was a low-grade tactite with minor scheelite. Pyroxene was selected for more detailed chemical and mineralogical work since it is ubiquitous, occurs with garnet, and formed in equilibrium or near-equilibrium with garnet. The concentration and distribution of trace elements in garnet and pyroxene were of particular interest. The pyroxene mineral separates were prepared in the same way as the garnet

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separates, using heavy liquids and magnetic separation. Results of a spectrographic analysis for Be, Ti, V, Ni, Sn, Cu, Y, Sc, Co, and MnO will be discussed in a later section. The six samples were analyzed by X-ray diffraction to determine composition. Partial chemical analyses were also obtained for total Fe, MgO, CaO, and Mn on three samples of pyroxene (table 9).

The results of atomic absorption analysis for total Fe, MgO, CaO, and Mn (as MnO) are shown for pyroxene samples 6-24-12, 67-10, and 7-6-22 in table 9. The composition is shown in terms of the three end members $CaMgSi_2O_6$ (diopside), $CaFeSi_2O_6$ (hedenbergite), and $CaMnSi_2O_6$ (johannsenite). This is found by dividing each of the oxides FeO, MgO, and MnO by their respective formula weights and calculating according to the relationships; % diopside = 100 x MgO/MgO + FeO + MnO, % hedenbergite = 100 x FeO/MgO + FeO + MnO, and % johannsenite = 100 x MnO/MgO + FeO + MnO. These three samples probably represent the approximate range in composition to be found in the pyroxenes from Black Rock tactites. 7-6-22 and 67-10 are from ore grade scheelite-bearing tactites whereas 6-24-12 is from low grade tactite with minor scheelite (50 ppm tungsten). Other data obtained from 7-6-22 are S.G. ca. 3.630, $\alpha = 1.722 \pm .001$, $\beta = 1.730 \pm .001$, and $\delta = 1.753$. The density (measured in Clerici solution) is extremely high and the reason for this is not known. Normally, hedenbergite has a maximum density of 3.56 and johannsenite, 3.55.

The six pyroxene separates were analyzed by an X-ray diffraction method described by Zwaan (1954), by which compositions can be determined from measurements of the angles or distances between reflections on an X-ray chart of film. The results obtained were spurious and did not agree with chemical data for 6-24-12, 67-10, and 7-6-22. Mol. percents of diopside for these three samples, for example, were 58 (6-24-12), 43 (67-10), and 25 (7-6-22). The discrepancy arises probably because Zwaan's study did not include pyroxenes containing manganese, so the effect of variable amounts of the

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Field No.	Total Fe as FeO %	MgO%	CaO%	MnO%	Composition mol. percent $CaMgSi_2O_6$	$CaFeSi_2O_6$	$CaMnSi_2O_6$
6-24-12	4.95	11.2	23.6	0.90	77.3	19.2	3.5
67-10	6.93	6.69	21.6	4.52	50.8	29.6	19.6
do.	6.93	6.60	21.4	4.52			
7-6-22	11.34	0.78	20.3	6.46	7.2	58.9	33.9

Table 9. Partial chemical analyses of pyroxene separates. Total Fe, MgO, CaO, and Mn determined by atomic absorption by W. Mountjoy, U.S. Geological Survey. The usual accuracy of atomic absorption analysis is about ±3 percent of the amount of the element present. Precision expressed as the coefficient of variation is estimated to be 2 percent or less based on duplicate analyses.

johannsenite molecule were not determined. In the Black Rock pyroxenes, however, MnO is an essential component (up to 12.5 percent in 7-6-11 by spectrographic analyses) and its effect on physical, optical and structural properties must be considered. In fact, these pyroxenes are somewhat unusual in their high content of Mn. Generally, the manganese content of the magnesium-rich members of the diopside-hedenbergite series is low but may increase in the more iron-rich minerals. Deer, et al. (1963, p. 45) give average MnO values for 37 analyses as: diopside, 0.09 percent; salite, 0.26 percent; ferrosalite, 0.29 percent; and hedenbergite, 2.25 percent. Some manganese-rich diopsides and salites have been described by Zharikov and Vlasova (1955, p. 814) and it is probable that diopside, hedenbergite, and johannsenite form a complete isomorphous group (Deer, et al., 1963, p. 45). The Black Rock pyroxenes are similar to manganhedenbergites studied by Tarasov (1966). Nine analyzed pyroxenes from a skarn zone at a contact between felsic igneous rock and carbonate rocks had the following compositions: johannsenite (20-32%), diopside (20-28%), and hedenbergite (40-57%), (Tarasov, 1966, p. 628).

In pyroxenes of the Black Rock tactites, as the amount of iron increases so does the manganese content so that in the magnesium-poor pyroxenes (e.g., 7-6-22) the molecular percent $CaMnSi_2O_6$ reaches 34 percent. Even higher contents of MnO have been indicated by spectrographic analyses.

Like the garnets, the pyroxenes have compositions which reflect the character of the enclosing tactite. Iron-poor, magnesium-rich pyroxenes are characteristic of low grade or barren tactites. As the amount of scheelite increases the pyroxenes as well as the garnets are found to be higher in iron and manganese.

Quartz.--This mineral is a common constituent of all the Black Rock tactites, generally occurring in quantities of 1 to 10 percent by volume. In sulfide-rich tactites

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quartz is more abundant, in some constituting as much as 40 percent. Quartz is generally anhedral, up to 1 mm in size, interstitial to other earlier formed minerals, and is of late origin commonly occurring with calcite as fracture-fillings and cross-cutting veinlets. Late deformation is evidenced by straining and fracturing in quartz and the development of undulatory extinction in a few samples.

Scheelite.--Calcium tungstate as scheelite, $CaWO_4$, is the only ore mineral of economic importance in the Black Rock deposits. Scheelite occurs as fine-grained disseminated grains in tactite (fig. 12). Ore-grade tactites generally average 1 percent or less of scheelite and the highest concentration in any one hand specimen was 2.5 percent. Scheelite occurs as subhedral to euhedral grains that are remarkably uniform in size, mostly 0.1 to 0.5 mm, rarely as small as 0.05 or as large as 1.5. Coarser grained scheelite was noted at only one locality (65J16) where scheelite up to 5 mm occurs.

Where two garnets are present, scheelite is post-early garnet and pre-late garnet or overlapping with late garnet. Much of the scheelite occurs as inclusions in garnet (fig. 6), and in some specimens in pyroxene. Contemporaneous growth of scheelite and garnet is suggested in some samples, where there is a disparity in grain size of scheelite occurring as inclusions in garnet and scheelite external to garnet. The finer-grained included scheelite had its growth arrested and was engulfed by rapidly growing garnet while other scheelite grains continued to grow unrestricted. (These textural relationships suggest scheelite is early, having formed before or contemporaneously with garnet and pyroxene.)

Fourteen mineral separates of scheelite were prepared from samples from which garnet was also separated and analyzed spectrographically. The results for Be, Ti, V, Ni, Sn, Cu, Y, Sc, Co, Mo, and Mn will be discussed in a later section.

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The Mo content varies from 0.13 to 6.60 weight percent. This corresponds to a variation in mol. percent of powellite, $CaMoO_4$, of 0.27 to 13.8 percent in solid solution with scheelite, $CaWO_4$.

Sphene.--Occurring as a common accessory mineral, sphene takes the form of subhedral to euhedral grains generally 0.1 to 0.3 mm. Sphene is generally associated with mafic minerals such as pyroxene, epidote, and biotite. Wedge-shaped euhedra are common. Much of the sphene has clouds of submicroscopic inclusions imparting a dusty appearance in thin section.

Vesuvianite.--Vesuvianite (idocrase), which has a structure closely related to that of grossular garnet (Warren and Modell, 1931, p. 422), is a common constituent of barren tactites but rare in scheelite-bearing tactites. In tactite bodies showing a gradation from ore-grade scheelite-bearing tactite through barren tactite to marble, vesuvianite invariably occurs in the barren tactite, especially adjacent to marble. Pods consisting of garnet, vesuvianite, and epidote commonly occur in the marble near the tactite contact (fig. 9).

Vesuvianite may occur in amounts up to 15 percent by volume in subhedral to euhedral columnar grains 0.5 to 3 mm in size. It is colorless to light brown in thin section (brown in hand specimen) and exhibits patchy anomalous brown interference colors. In thin section it may be poikiloblastic with abundant inclusions of diopside and occasional garnet.

Vesuvianite is nearly always associated with and probably contemporaneous with colorless, isotropic grossular garnet. These two minerals are earliest to form during the replacement of marble and development of tactite. Nearly all vesuvianite exhibits some evidence of replacement by epidote.

Wollastonite.--Wollastonite occurs in minor amounts at the contacts between marble and tactite and in silicated

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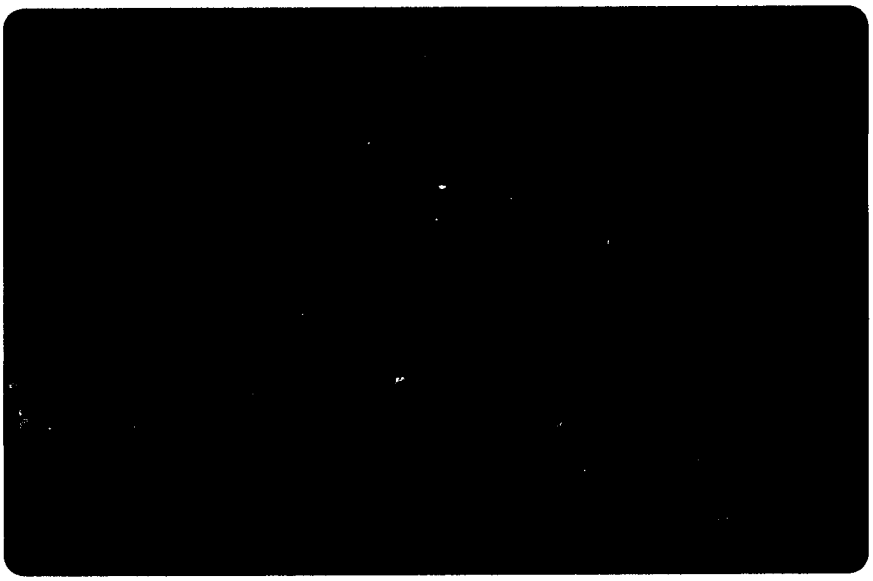

Figure 9. Specimen of silicated marble showing replacement of gray calcite (C) by garnet (G), epidote (E), and wollastonite (W). Minor amounts of vesuvianite are also present.

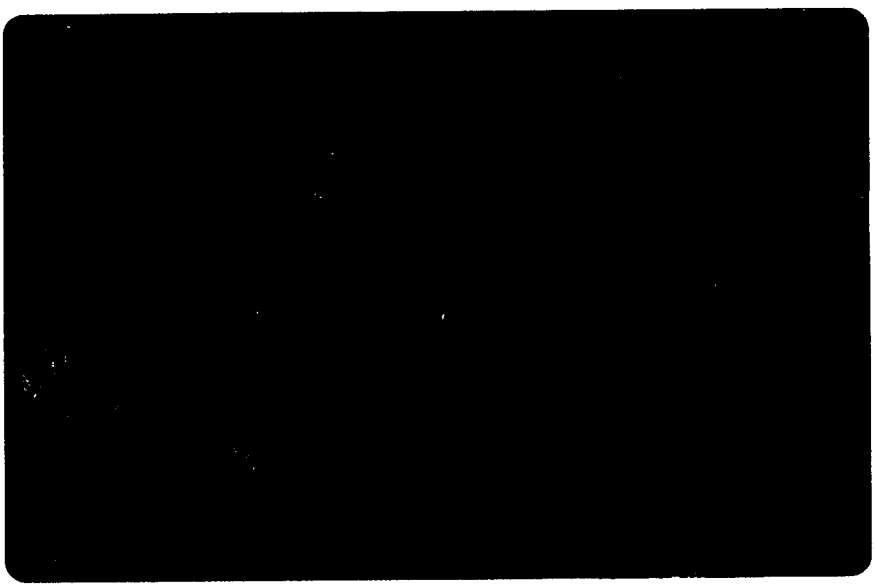

Figure 10. Specimen of banded calc-hornfels from underground exposure on 6500 level cut by vein. Vein is composed of green pyroxene, quartz, and sulfides (mainly pyrrhotite).

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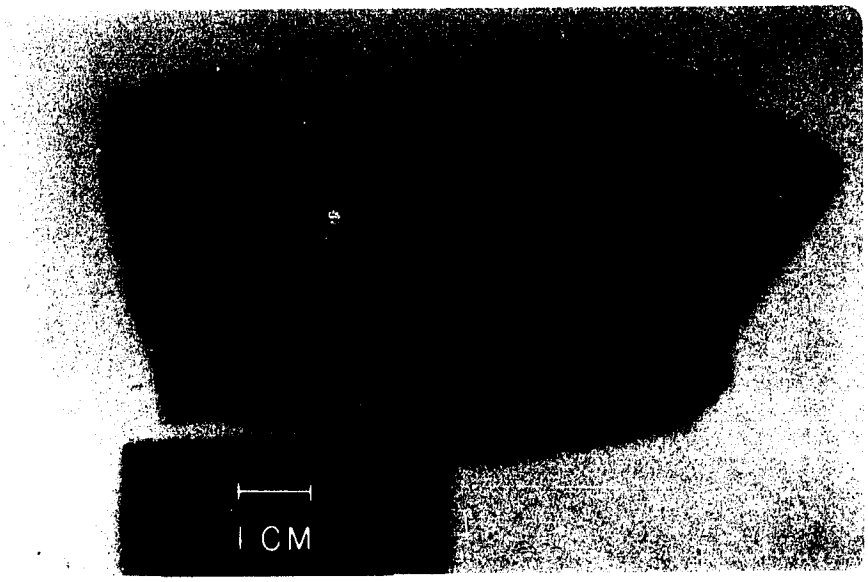

Figure 11. Specimen of high grade scheelite-bearing tactite, no. J27, from underground exposure on the 6900 level. Brown areas are garnet-rich and green areas are rich in pyroxene (lighter green) and actinolite (darker green).

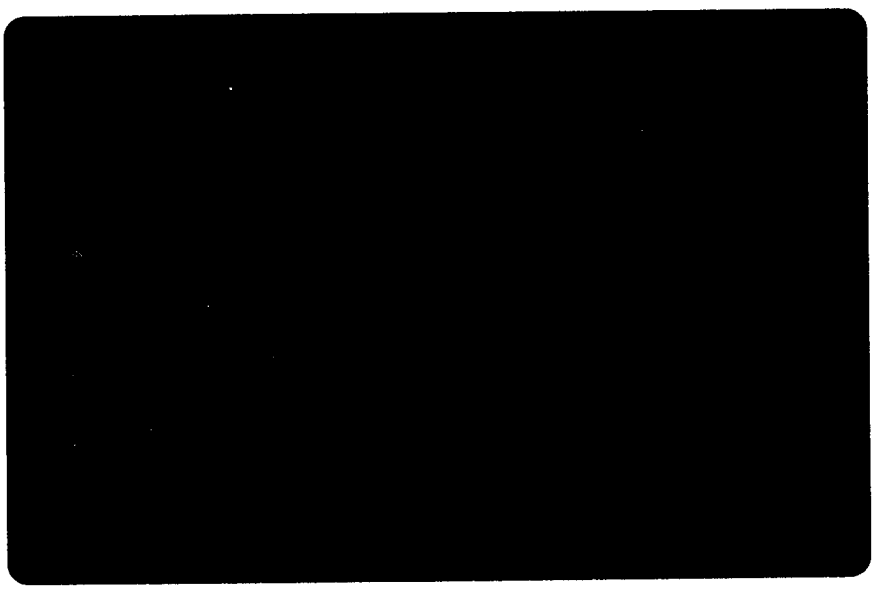

Figure 12. Same as 11 in ultra-violet light showing the distribution of scheelite (white). Comparison with 11 shows that scheelite occurring with garnet is finer-grained than that occurring with pyroxene and actinolite.

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marble as elongated fibrous grains intergrown with calcite (fig. 9). Wollastonite, a rare constituent of the Black Rock tactites, is commonly the result of the reaction $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$.

Zircon.--A few grains of zircon, less than 0.1 mm, were noted in only two samples of tactite. These are rounded and partially metamict and are presumably detrital in origin, having been originally deposited in an impure limestone or calcareous siltstone.

Chalcopyrite.--Chalcopyrite is a minor but ubiquitous constituent, invariably associated with pyrrhotite. It occurs as anhedral blebs and irregular masses ranging in size from 0.01 to 0.5 mm in quantities of 1 percent by volume or less. With pyrrhotite, chalcopyrite occurs near outer margins of the pyrrhotite masses and as thin veinlets and disseminations in the surrounding gangue of silicates and carbonates. Chalcopyrite occurs along grain boundaries of marcasite, intergrown with pyrite or magnetite in veinlets, and along fractures in pyrite as reticulate texture. Where chalcopyrite occurs as a fracture-filling it is commonly intergrown with dark green fibrous actinolite indicating simultaneous growth (fig. 14). In one sample chalcopyrite occurs as rounded to irregular shaped blebs from less than 1 to 25 microns in hosts of magnetite forming emulsion-like textures. The magnetite in this sample characteristically is very "spongy" and contains many inclusions of silicates as well as sulfides. The chalcopyrite in magnetite may be either the result of replacement of magnetite or the selective replacement of silicate inclusions in the magnetite.

Magnetite.--Magnetite occurs as anhedral to subhedral equant grains, ranging from 0.01 to 0.5 mm in size. Generally it is a minor constituent, but appears in major proportions in at least one locality where it occurs with garnet and green biotite. Magnetite is found associated

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with sulfides and with non-sulfides such as garnet, amphibole, biotite, quartz and calcite. With non-sulfides it generally occurs as disseminated grains having inclusions of quartz, actinolite, and calcite. The "spongy" or poikiloblastic texture of magnetite in many samples suggests replacement of earlier formed silicates. With sulfides magnetite generally occurs as rounded to irregular shaped grains with corroded outlines and is the host in emulsion-like textures with pyrrhotite and chalcopyrite. Magnetite also is cut by fractures which have later been filled by sulfides (fig. 15). These textures suggest that most of the magnetite is earlier in origin than the sulfide minerals.

Marcasite.--Marcasite is abundant in only one sample and occurs sparingly in three others. Positive identification of this mineral was made in 7-6-11 by X-ray powder methods. It occurs as porous aggregates of microcrystalline grains as a replacement of pyrrhotites. Marcasite occurs in and around margins of pyrrhotite as microgranular aggregates 0.1-1.0 mm which are pseudomorphous after pyrrhotite. The aggregates are nearly isotropic and exhibit colloform-like and banded textures. Some have circular or oval concentric structures (fig. 13) such as "birds-eye" structures (Ramdohr, 1960, p. 555).

Molybdenite.--Molybdenite was noted at one locality 1/3 mile south of the main Black Rock mine workings. It occurs as radially arranged coarse-grained plates forming rosettes up to 1/2 inch in diameter. The molybdenite rosettes are coated and replaced by powellite, $CaMoO_4$, a secondary alteration product. The host rock is medium to coarse-grained tactite consisting of garnet, epidote, and quartz.

Pyrite.--As a minor constituent in many sulfide-bearing tactites, pyrite occurs as anhedral to subhedral grains, 0.05 to 0.5 mm in diameter, commonly with ragged outlines or

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"caries" texture. Evidence of fracturing is seen in several specimens, the fractures being filled with late calcite and quartz. Pyrite commonly occurs as inclusions in other sulfides, especially pyrrhotite, and may be rimmed and penetrated by chalcopyrite. Textural relationships suggest pyrite has formed prior to the main stage sulfides such as pyrrhotite, chalcopyrite, and sphalerite and has been partially replaced by these sulfides. Evidence of post-magnetite formation of pyrite, however, is seen in sample 7-6-24, a magnetite-rich tactite, where a pyrite veinlet cuts magnetite (fig. 15). The veinlet is obviously a post-magnetite fracture-filling with no evidence of replacement of magnetite by pyrite.

Pyrrhotite.--Pyrrhotite is by far the most abundant sulfide in the Black Rock tactites, locally making up more than 90 percent of the opaque minerals. It occurs in an allotriomorphic granular, mosaic to sutured texture of equant grains ranging 0.5 to 5 mm in size. Commonly pyrrhotite is fractured and may exhibit "exploding bomb" texture. It forms emulsion-like textures in magnetite. Pyrrhotite is later than many of the silicate minerals; commonly occurring as fillings in fractures of garnet and other silicates (fig. 16). Contemporaneous growth with actinolite (fig. 14) is shown in many samples by intergrown crystals with no evidence of replacement.

Sphalerite.--Sphalerite occurs in minute amounts as small blebs and irregular grains, 0.01 to 0.5 mm, associated with pyrrhotite and chalcopyrite. Like chalcopyrite, it is found most commonly around borders of pyrrhotite masses and disseminated in the surrounding silicates and carbonates.

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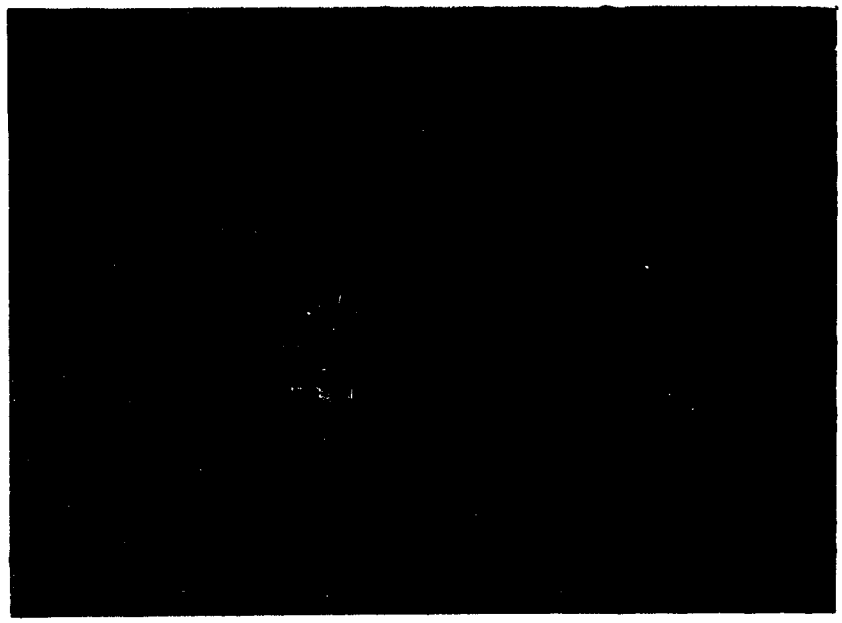

Figure 13. A concentric structure ("bird's-eye" structure) in marcasite (M) in sample no. 7-6-11. A small residual of pyrite (P) is also shown. 175X, reflected light.

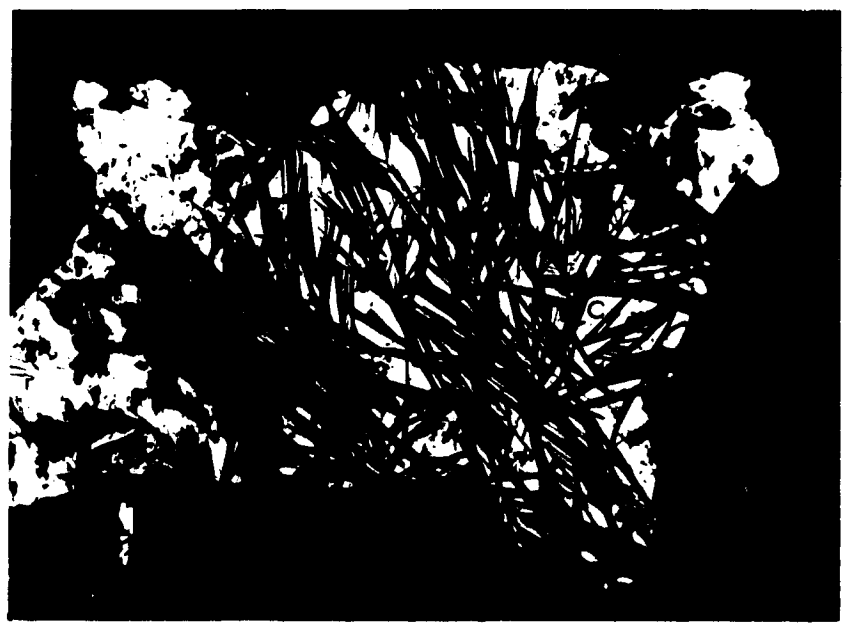

Figure 14. Intergrowth of chalcopyrite (C) with fibrous actinolite (A) in garnet (G) in sample 67-5. 175X, reflected light.

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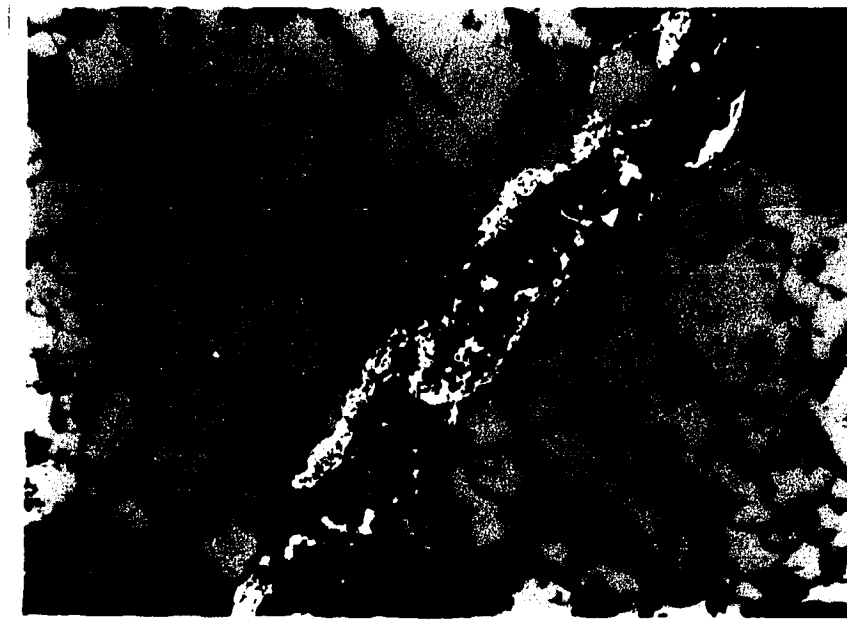

Figure 15. A pyrite (P)- quartz (Q) filled fracture cuts magnetite (M) in sample no. 7-6-24. Magnetite is intergrown with garnet (G). Magnification 175X, reflected light.

Figure 16. Pyrrhotite (P) fills fractures in gangue, mainly garnet (G), in sample 7-6-23. Intergrowth of actinolite (A) with pyrrhotite is shown in right side of photo. 175X, reflected light.

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GEOCHEMISTRY

Geochemical studies of the Black Rock tactites consisted of the determination of 1) major, minor, and trace elements in whole-rock samples of tactite, hornfels, and marble by 30-element spectrographic analysis and 2) certain elements in skarn minerals by spectrographic analysis. Whole-rock spectrographic analyses were obtained for tactites representative of barren, low grade, and high grade scheelite-bearing varieties. In addition, possible parent rocks of tactite, hornfels, and marble were also analyzed. Mineral separates of garnet, pyroxene, actinolite, and scheelite were made from a variety of tactites that ranged in tungsten content from barren to ore grade. Two of these minerals, garnet and pyroxene, are the commonest essential minerals in scheelite-bearing tactites and are thought to have formed contemporaneously with scheelite. Actinolite, although probably formed somewhat later than the main-stage minerals coexisting with scheelite, is a common mineral in both barren and scheelite-bearing tactites.

Theoretically the tungsten deposits of the Black Rock mine are the result of reaction of hydrothermal fluids with calcareous sediments. In addition to the tungsten mineral, scheelite, the reactions resulted in assemblages of oxide, sulfide, and silicate minerals which are generally indicative of high temperature origin. The reactions resulted in an overall change in bulk composition involving inward and outward migration of constituents and requiring the addition of large quantities of constituents such as silicon, iron, aluminum, and manganese. No doubt the composition and physical conditions of the fluids varied as the result of local conditions and degree of reaction, giving rise to different amounts and kinds of minerals. The most obvious variation of this type is the variation of scheelite content

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in the tactites. The solutions which deposited scheelite to form tungsten-bearing tactite must have differed in some way or ways from those that resulted in the formation of barren tactites. In addition to the major elements (silicon, iron, aluminum, and manganese), there probably was a suite of minor and trace elements which accompanied the tungsten mineralization and which were preserved in the resulting tactite.

To study the possible suite of indicator elements accompanying tungsten mineralization, 30-element spectrographic analyses were obtained for barren, low grade, and high grade tactites. Statistical evaluation of the data helps to identify these added elements and to distinguish them from elements that were present in the original sediments. Additional analyses of hornfels and marble, together with tactite analyses, provide evidence useful in determining if the parent rocks of tactites were pure marbles, impure marbles, or hornfels. Certain elements are higher in hornfels and impure marbles relative to pure marbles and reflect higher contents of detrital minerals in these rocks. The relative amounts of these elements in tactites aid in deciding the parent rocks of barren and scheelite-bearing tactites.

Ideally the skarn minerals formed from the metasomatic fluids should be a record of the composition of these fluids. The suite of indicator elements accompanying tungsten should be preserved in the minerals which formed contemporaneously with scheelite and these elements should be absent or in lower quantities in the same minerals in barren tactites. One of the main reasons for studying the trace elements in minerals was to trace the behavior of certain indicator (as well as other elements) elements in the common skarn minerals; garnet, pyroxene, and actinolite. Garnet and pyroxene are ubiquitous in all tactites and formed contemporaneously with scheelite in tungsten-bearing tactites. Actinolite is thought to have formed during the

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waning stages of metasomatism probably after most of the tungsten and associated elements were depleted. These three minerals, as well as scheelite, were analyzed for Be, Ti, V, Ni, Sn, Cu, Y, Sc, and Co. In addition, MnO was determined in the silicate minerals and Mo and Mn were determined in scheelite.

A second reason for determining trace elements in skarn minerals was to examine possible zonations defined by variations in trace elements. Because of the great quantities of metals required to transform calcareous sediments to tactite a source outside of the metasediments themselves is probably required. A likely source for these fluids is the quartz monzonite immediately west of the Black Rock mine. A genetic link between this stock and the tactites is suggested by its proximity to the mine area, the distribution of tactite and tungsten ore bodies, and the petrography and chemistry of samples from the stock. During the ore-forming process, fluids moving outward and upward from the igneous source would change continually in composition because of changes in temperature and pressure and reaction with wall rocks. Ideally some of these changes would be preserved in the trace element contents of minerals thus formed and would present a spatial pattern related to the original source. Such a zonation was sought in the analysis of trace elements in the skarn mineral separates.

Semiquantitative Spectrographic Analyses of Tactites

To determine the suite of elements accompanying tungsten mineralization and to study background levels of these and other elements in possible parent rocks, 79 samples of tactites and 11 samples of hornfelses and silicated marbles were analyzed for 30 elements by a 6-step semiquantitative spectrographic method. The tactite samples included 34 of barren tactites (less than 50 ppm tungsten), 10 of low grade tactites (50 to 1000 ppm tungsten), and 35 of high grade

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tactites (1000 ppm or more of tungsten). These analyses are listed in tables 18 to 21 in the appendix. In addition to the spectrographic analyses, mercury was determined by an atomic absorption method.

The results of the analyses were then treated statistically, using statistical computer programs in current use by the U.S. Geological Survey. A statistical summary was obtained by transforming the data to logarithms and calculating geometric means and geometric deviations (table 10) using a program called GEOSUM. This program is designed principally for summarizing and tabulating results of semiquantitative spectrographic analyses by the U.S. Geological Survey. In addition, analyses of variance and correlation analysis programs were run on log-transformed data on tactites.

Preparation of histograms indicated that the data are distributed approximately lognormally rather than normally. This being the case then the geometric mean of the data is a more consistent (Fisher, 1950, p. 11) measure of central tendency than the arithmetric mean, and the geometric mean and geometric deviation are more efficient measures than the arithmetric mean and standard deviation, respectively (Fisher, 1950, p. 11-12). A consistent measure of central tendency is one that tends toward the true mode of the population from which the sample is drawn; an efficient statistic is the one that is the most stable (least subject to change with the addition of new data) (Miesch, 1963, p. 20). The geometric mean is the antilogarithm of the arithmetric mean of the logs of the data and the geometric deviation is the antilogarithm of the standard deviation of of the logs of the data. The geometric deviation is used in the same way as the standard deviation except that the geometric mean is divided or multiplied by the geometric deviation to obtain population estimates. For example, approximately two-thirds of the concentrations of iron in all tactites should lie within the range of the geometric

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	All Tactites			Barren Tactites		
	Geom. Mean	Geom. Dev.	No. of Values	Geom. Mean	Geom. Dev.	No. of Values
Fe	9.70%	1.52	73	7.54%	1.41	28
Mg	1.33%	1.64	76	1.43%	1.44	31
Ca	15.54%	1.57	76	11.76%	1.72	31
Ti	0.10%	3.14	76	0.22%	2.33	31
Be	5.0 ppm	3.4	69	2.2 ppm	3.6	24
Co	9.5 "	2.5	63	14.0 "	2.0	30
Cr	21.2 "	4.8	65	49.2 "	3.3	30
Cu	23.9 "	16.3	60	39.3 "	13.6	17
La	8.2 "	3.4	20	13.2 "	2.9	12
Mo	8.5 "	12.6	44	1.1 "	3.3	5
Nb	22.3 "	2.6	67	12.6 "	2.2	24
Ni	15.0 "	2.4	73	27.8 "	1.6	31
Sc	5.4 "	2.5	46	10.1 "	1.7	27
Sn	44.4 "	3.0	73	19.0 "	1.9	29
Sr	54.3 "	3.3	28	114.3 "	2.1	22
V	65.4 "	1.6	76	86.4 "	1.4	31
W	—	—	34	—	—	0
Y	13.0 "	2.6	50	22.2 "	1.9	27
Zn	207.1 "	1.9	64	371.1 "	1.6	29
Zr	25.7 "	3.8	59	57.3 "	2.5	29
Hg	0.04 "	2.0	72	0.03 "	1.9	29

Table 10. Geometric means and deviations for elements in tactites. Subdivision into barren, low grade, and high grade tactites is based on tungsten contents of less than 50 ppm (barren), 50 to less 1000 ppm (low grade) and equal to or greater than 1000 ppm (high grade).

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s	Low Grade Tactites			High Grade Tactites		
No. of Values	Geom. Mean	Geom. Dev.	No. of Values	Geom. Mean	Geom. Dev.	No. of Values
28	9.98%	1.54	10	11.78%	1.45	35
31	1.45%	1.71	10	1.22%	1.77	35
31	12.88%	1.64	10	13.17%	1.42	35
31	0.14%	2.71	10	0.05%	2.47	35
24	5.6 ppm	2.9	10	9.7 ppm	2.3	35
30	11.9 "	2.8	9	6.2 "	2.6	24
30	32.6 "	5.1	9	8.8 "	4.2	26
17	25.8 "	13.3	10	78.0 "	8.2	33
12	17.8 "	2.3	5	—	—	3
5	2.8 "	4.2	4	86.5 "	2.3	35
24	20.6 "	2.5	9	37.9 "	2.2	34
31	19.5 "	2.3	10	8.0 "	2.1	32
27	7.1 "	2.5	7	2.8 "	2.1	12
29	35.9 "	2.2	10	102.0 "	2.2	34
22	56.9 "	7.5	4	—	—	2
31	81.8 "	1.5	10	48.0 "	1.6	35
0	90.5 "	1.7	10	—	—	24
27	18.2 "	2.2	8	—	—	15
29	250.1 "	1.4	9	267.1 "	2.2	26
29	37.0 "	4.2	8	11.5 "	3.1	22
29	0.04 "	2.2	9	0.05 "	2.0	34

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mean divided by the geometric deviation (9.70 ÷ 1.52) to the geometric mean times the geometric deviation (9.70 x 1.52); the range is 6.4 to 14.7 percent. Approximately 95 percent of the concentrations should lie in the range $9.7 \div (1.52)^2$ to $9.7 \times (1.52)^2$; this range is 4.2 to 22.4 percent.

The statistical summary of data for the Black Rock tactites is shown in table 10. Blanks in the table indicate insufficient data for that element. Geometric mean and geometric deviation could not be estimated for cases in which the values were mostly less than or greater than the analytical sensitivity. The table shows also the number of recorded values for each element from which estimates of geometric mean and geometric deviation were made.

Comparison of elemental abundances in barren, low grade, and high grade tactites suggest differences in concentrations of certain elements besides tungsten. Some elements are higher in high grade tactites than in barren tactites and others are lower. As expected, low grade tactites generally have concentrations intermediate between those of barren and high grade tactites. Elements which apparently are present in higher concentrations in high grade tactite than in barren tactites are Fe, Be, Cu, Mo, Nb, and Sn. Those present in higher concentrations in barren tactites are Ti, Co, Cr, Ni, Sc, V, Y, Zn, and Zr. There is either little or no difference in concentration, or insufficient data, for the elements Mg, Ca, La, Sr, and Hg.

It is desirable to test whether these apparent differences in the means of the concentrations of many elements between barren and high grade tactites are significant or whether they may be reasonably be attributed to chance. One way to do this is to perform an analysis of variance test of the data. Several assumptions underlie this test.

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The first assumption is that the data represent random sampling. Generally, strict random sampling is difficult if not impossible to achieve in geologic sampling, especially in the present study where most of the sampling was confined to underground workings. Samples were collected so as to be as unbiased and representative as possible so that, in general the sampling approximated random sampling. We shall also have to assume that all of our samples come from populations having normal distributions with identical standard deviations. Histograms were prepared for the data and, in most cases, a lognormal distribution was approximated and comparison of geometric means (antilogarithm of the standard deviation of the logs of the analyses) shows that the standard deviations are essentially the same for all elements (with the possible exception of copper). Therefore, after making log transforms, a valid test of analysis of variance could be performed.

The computer program used in performing the analysis of variance is one of the standard statistical programs in current use by the U.S. Geological Survey. Eighteen elements were tested for significant differences between 31 barren tactites and 35 high grade tactites at the 0.05 probability level. At this level significant differences in the following elements were noted: Fe, Ti, Be, Co, Cr, Cu, Mo, Nb, Ni, Sc, Sn, V, Y, Zr, and W. There were no significant differences in the means of Mg, Ca, and Zn. With the exception of Zn, these results are the same as suggested by visual comparison of means.

Although the analysis of variance test indicates significant differences in many elements between barren and high grade tactites, it tells us nothing about the element associations we are interested in. Specifically we would like to find out whether there are relationships between elements and groups of elements which are indicative of the ore-forming processes. A widely used measure of the strength of the linear relationship between two variables is the correlation coefficient, r.

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Using a computer program, the correlation coefficients were calculated for 19 elements and 76 tactite samples. Correlation coefficients could be calculated only where there were recorded (not less than or greater than) values for both of the paired elements. The number of pairs which were used in the calculations varied from a low of 20 to a high of 76 pairs. The significance of each of the correlation coefficients was tested using the relationship:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}}$$ (Moroney, 1964, p. 311)

and a table of Student t-test values (Croxton and Cowden, 1955, p. 750-751). The correlation coefficients were evaluated at the 0.001, 0.01, and 0.05 probability levels; the ones which were significant at these levels are shown in tables 11, 12, and 13 respectively.

Pairs of elements for which the correlation coefficients exceed the 0.001 probability level (table 11) can be subdivided into two groups designated A and B. All elements of group A show negative correlation coefficients (significant at the 0.001 level) with elements of group B. Within each group of elements there are a number of subgroups of three or more elements, all of which show significant positive correlations (0.001 probability) with every other element of that subgroup. For example, Fe-Be-Sn-Nb is a subgroup within group A. The groups and subgroups are:

Group A	Group B
Fe-Be-Sn-Nb	Mg-Ti-Cr-Ni-Zr
Fe-Cu-Nb	Ti-Cr-Ni-Sc-V-Y-Zr
Fe-Mo-Nb-Sn	Ca
Mo-W-Sn	

Other correlation coefficients which are significant at the 0.01 but not the 0.001 probability levels are shown in table 12. Again, group A elements show negative correlations with group B elements. Elements showing positive correlations are Be-Cu and Nb-W of the group A elements and Mg-Ca of group B.

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The distinction between group A and group B elements is not as apparent in correlation coefficients which are significant at the 0.05 but not the 0.01 probability level (table 13). Positive correlations in group A elements are Fe-W, Be-W, Cu-Sn, and Cu-W. In group B elements there are positive correlations for Mg-Y and Ca-Ti. The correlations between group A elements and those of group B are mostly negative. However, at this level of significance, there are a number of positive correlations between the elements, Co, Zn, and Hg, and elements of either group A or Group B. This suggests a third group of elements consisting of Co, Zn, and Hg which show only low degrees of association with either group A or group B elements or no significant association at all.

The correlation coefficient does not measure cause and effect; therefore it is safer to interpret it as a measure of association rather than causation (Freund, 1962, p. 336). However, in this case, the element associations shown by the correlation analysis support evidence drawn from other sources which suggest cause and effect relationships. This evidence includes that from comparison of means, mineralogic and petrologic studies, and field relationships.

The statistical analysis of the results of spectrographic analyses of tactites shows that there is a suite of elements which have significantly higher concentrations in high grade scheelite-bearing tactites than in barren tactites: Fe, Be, Cu, Mo, Nb, Sn, and W. Each element of this group has a positive correlation with every other element of the group and negative correlations with most other elements in the tactites. The conclusion is that this suite is representative of tungsten mineralization and is brought in during the ore-forming stage of metasomatism.

A second group of elements, also indicated by statistical analysis, similarly shows significant differences in concentration between high grade and barren tactites. Elements of this group show mutual association (positive correlation) and

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	Ti	Be	Cr	Cu	Mo	Nb	Ni	Sc	Sn	V	W	Y	Zr
Fe	-.511	+.525	-.483	+.530	+.495	+.549	-.539		+.648				
Mg	+.584		+.448	-.518			+.569		-.387				+.3
Ca				-.551									
Ti		-.528	+.856	-.589		-.445	+.786	+.814	-.704	+.665	-.482	+.692	+.874
Be						+.535			+.515				
Cr				-.501	-.666		+.770	+.681	-.618	+.559		+.536	+.870
Cu						+.568							
Mo						+.572	-.560	-.722	+.738	-.389	+.745		-.752
Nb									+.432				
Ni								+.810	-.788	+.546		+.649	+.772
Sc									-.632	+.611		+.798	+.783
Sn										-.535	+.607	-.485	-.676
V												+.633	+.557
Y													+.710

Table 11. Correlation coefficients for elements in tactites which exceed the 0.1 percent probability level.

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	Ca	Cr	Cu	Mo	Nb	Ni	V	W	Zr
Fe									-.417
Mg	+.364								
Ca					-.347				
Ti				-.444					
Be		-.355	+.376				-.369		
Cu						-.406			
Mo							-.389		
Nb						-.330	-.335	+.480	-.364
Ni								-.397	
V								-.455	
W									-.505

Table 12. Correlation coefficients for elements in tactites which exceed the 1 percent but not the 0.1 percent probability levels.

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	Mg	Ti	Co	Nb	Ni	Sc	Sn	V	W	Y	Zn	Zr	Hg
Fe	-.267		+.291					-.310	+.324				
Mg										+.300	+.313		
Ca		+.276											+.237
Be			+.338		-.259	-.356			+.341			-.334	+.256
Co					+.307						+.269		
Cr				-.339					-.415				
Ca							+.267	-.297	+.334			-.326	
Mo										-.511			
Nb						-.366							
Ni											+.259		
Sc									-.493				
Sn													+.299

Table 13. Correlation coefficients for elements in tactites which exceed the 5 percent but not the 1 percent probability levels.

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negative correlation with elements of the ore suite. This group, consisting of Ti, Cr, Ni, Sc, V, Y, and Zr, is unrelated to the tungsten mineralization and probably reflects the original character of the parent rock. These elements are all higher in barren tactites and most are closer in concentration to the levels in calc hornfels (analyses shown in appendix). The geometric means for these elements in calc hornfels, siliceous hornfels, and barren tactites are:

	Calc hornfels	Siliceous hornfels	Barren tactites
Ti	0.28%	0.44%	0.22%
Cr	57 ppm	110 ppm	49 ppm
Ni	11 "	15 "	28 "
Sc	10 "	15 "	10 "
V	132 "	160 "	86 "
Zr	180 "	87 "	57 "

One may conclude from these data that the high grade tungsten tactites were developed as a result of metasomatism of fairly pure marble and, in general, barren tactites were derived from impure marbles and calc hornfels. This is in agreement with field relations and petrographic studies. These results agree with studies by Nesterenko, et al. (1958, p. 290), who also found higher concentrations of Ni, Cr, V, Ti, and Zr in skarns developed from hornfels relative to skarns from marbles.

Associations for some elements are not clear, and statistical analysis suggest that they may be independent of the tungsten content of the tactites. Elements in this group are Mg, Ca, Zn, Co, and Hg. Although Mg and Ca show positive correlations with most of the characteristic elements there is no significant difference in concentration in barren tactites, but they, like Zn and Hg, show positive correlation coefficients with elements of both the ore suite and the barren tactite suite. The conclusion is that these elements are not indicative of either the parent rock or tungsten mineralization.

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Spectrographic Analyses of Tactite Minerals

Mineral separates of garnet, pyroxene, actinolite, and scheelite were analyzed by a semiquantitative spectrographic procedure developed for this study (see appendix). In all, 22 samples of garnet, 6 of pyroxene, 9 of actinolite, and 14 of scheelite were analyzed. The separation procedures are described in the appendix. All were analyzed for the elements Be, Ti, V, Ni, Sn, Cu, Y, Sc, and Co. In addition, MnO was determined in garnets, pyroxenes, and actinolite and Mo and Mn were determined in scheelite. The results of spectrographic analyses are given in tables 14, 15, 16 and 17. The limits of sensitivity and precision of the analyses are discussed in the appendix. In the tables the minerals are grouped according to the grade (tungsten content) of the tactites from which they were separated.

Beryllium.--The divalent ion of Be has an ionic radius of 0.33Å (all the ionic radii in this section from Green, 1959) and is amphoteric like Al, occupying an intermediate position between typical cations and complex-forming elements. The coordination number is 4 and in natural compounds it is surrounded by 4 oxygen ions forming compact $[BeO_4]^{6-}$ tetrahedra which resemble silicon-oxygen tetrahedra and aluminum-oxygen tetrahedra, for either of which it may substitute in silicate structures. Be is concentrated during the end-stages of magmatic crystallization and may be incorporated in minerals of pegmatites or pneumatolytic rocks. Skarns bearing Be are commonly associated with tungsten- or tin-bearing intrusive complexes (Beus, 1962).

In garnets of the Black Rock area, Be is low, reaching concentrations of 1 ppm or more in only three samples of the 22. In actinolites Be is present in concentrations of 7 to 29 ppm, appreciably higher than in garnet. The highest concentrations of Be, however, are found in pyroxene, especially in those from scheelite-bearing tactites. In five of the six pyroxene samples the Be content was above

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Sample No.	Be	Ti	V	Ni	Sn	Cu	Y	Sc	Co	MnO%
65-1	<<1	2100	92	14	<2	5	11	2	nd	<0.4
65-3	<1	2650	118	3	2	<5	13	3	nd	3.1
6-24-4	<<1	2900	88	1	<2	<5	17	6	nd	<0.4
6-24-7	<<1	3300	81	<1	<2	<5	36	7	nd	0.6
7-6-25	<1	<500	73	nd	6	54	5	2	nd	25.3
7-6-27	<1	500	118	nd	14	240	13	8	nd	25.3
67-1	nd	2000	53	nd	25	<5	20	1	nd	4.2
67-3	<<1	887	73	<1	21	<5	<5	<1	nd	5.2
6-24-12	nd	2900	128	nd	nd	<5	16	10	nd	<0.4
66-1	<1	560	72	nd	69	11	nd	nd	nd	10.5
66-2	<1	660	24	<1	41	6	7	<1	nd	3.7
66-3	<1	2100	88	1	8	<5	26	3	nd	9.0
66-4	<1	1500	123	nd	<2	9	13	2	nd	7.0
66-5	<1	1500	32	<1	65	<5	10	2	nd	4.2
67-6	1	760	70	nd	26	135	<5	<1	<5	17.4
67-7	1	3600	150	<1	4	9	75	8	nd	31.5
67-9	nd	2550	69	nd	24	11	16	2	nd	8.5
67-10	nd	1650	77	nd	53	<5	13	2	nd	8.8
7-6-11	<<1	<500	33	<1	65	9	<5	<1	nd	4.2
7-6-22	1.2	1500	260	<1	33	73	10	<1	nd	16.0
7-14-1	<1	1350	67	nd	42	11	10	2	nd	8.5
7-14-2	<1	1200	58	<2	34	5	10	1	nd	5.0

Table 14. Concentration of trace elements in garnets determined by spectrographic analysis. Results given in ppm except for MnO which is in percent. Symbols are: nd = not detected, < = detected but below analytical lower limit, << = much below analytical limit, and > = greater than analytical upper limit. Analyses by J. Elliott.

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Y	Sc	Co	MnO%	Remarks
11	2	nd	<0.4	from barren garnet tactite
13	3	nd	3.1	same
17	6	nd	<0.4	same
36	7	nd	0.6	same
5	2	nd	25.3	from barren pyrrhotite tactite
13	8	nd	25.3	same
20	1	nd	4.2	from low grade scheelite-bearing garnet tactite
<5	<1	nd	5.2	same
16	10	nd	<0.4	same
nd	nd	nd	10.5	from high grade scheelite-bearing garnet tactite
7	<1	nd	3.7	same
26	3	nd	9.0	same
13	2	nd	7.0	same
10	2	nd	4.2	same
<5	<1	<5	17.4	same
75	8	nd	31.5	same
16	2	nd	8.5	same
13	2	nd	8.8	same
<5	<1	nd	4.2	same
10	<1	nd	16.0	from high grade scheelite-bearing pyrrhotite tactite
10	2	nd	8.5	from high grade scheelite-bearing garnet tactite
10	1	nd	5.0	same

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Sample No.	Be	Ti	V	Ni	Sn	Cu	Y	Sc	Co	MnO%	Remarks
6-24-12	2.8	<<500	7	99	nd	<5	<<5	25	70	1.45	from low grade scheelite-bearing garnet tactite
66-2	150	<<500	6	3	<2	<5	<<5	1	16	6.1	from high grade scheelite-bearing garnet tactite
67-10	78	<<500	6	17	<<2	<5	<<5	2	18	4.0	same
7-6-11	38	<<500	6	34	<<2	16	<<5	<1	67	12.5	same
7-6-22	53	<<500	17	<2	<<2	20	<<5	<1	nd	4.6	from high grade scheelite-bearing pyrrhotite tactite
7-14-1	54	<<500	<5	12	<<2	16	<<5	4	46	4.6	from high grade scheelite-bearing garnet tactite

Table 15. Concentration of trace elements in pyroxene determined by spectrographic analysis. Results in ppm except for MnO which is in percent. Symbols same as in Table 11. Analyses by J. Elliott.

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Sample No.	Be	Ti	V	Ni	Sn	Cu	Y	Sc	Co	MnO%	Remarks
65-1	11	870	40	56	<<2	5	<<5	8	70	2.48	from barren garnet tactite
65-3	9	920	28	25	3	<5	nd	2	31	2.00	same
67-1	8	580	21	24	14	<5	nd	<1	6	2.55	from low grade scheelite-bearing tactite
66-1	15	<500	16	<2	12	<5	<5	nd	5	2.86	from high grade scheelite-bearing garnet tactite
66-2	17	670	9	<2	9	<5	<5	1	16	2.90	same
66-3	15	520	17	78	3	<5	<5	3	13	2.25	same
66-4	8	550	25	<2	<2	32	<5	2	20	1.96	same
67-10	7	520	16	4	12	<5	nd	<1	23	2.70	same
7-14-1	29	<500	12	<2	<2	24	<<5	5	34	3.82	same

Table 16. Concentration of trace elements in actinolites determined by spectrographic analysis. Results in ppm except for MnO which is in percent. Symbols same as in Table 11. Analyses by J. Elliott.

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Sample No.	Mo%	Mn	Other
66-1	0.86	330	
66-2	0.64	380	
66-3	0.42	107	
66-4	0.41	96	
66-5	4.15	200	Sn 5 ppm
67-1	1.50	110	
67-6	0.39	240	
67-7	0.16	290	Y 13 ppm
67-9	6.30	85	
67-10	1.14	120	
7-6-11	0.95	390	
7-6-22	0.13	55	Y 17 ppm
7-14-1	1.42	270	
7-14-2	6.60	160	

Table 17. Manganese content (in ppm) and molybdenum content (in percent) of scheelites determined by spectrographic analysis. (Be, Ti, V, Ni, Cu, Sc, and Co were below analytical sensitivity, as were Sn and Y in all but the samples noted.) Analyses by J. Elliott.

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the sensitivity limit of 30 ppm and the values were estimated by extrapolation. Be was below sensitivity in scheelite. In pyroxenes and amphiboles, $[BeO_4]^{6-}$ tetrahedra may substitute for $[SiO_4]^{4-}$ with the resulting charge imbalance compensated by the simultaneous substitution of Ti^{4+} for Mg^{2+} (Beus, 1962, p. 29):

$$Ti^{4+} + [BeO_4]^{6-} \rightarrow Mg^{2+} + [SiO_4]^{4-}.$$

Pyroxene shows appreciable enrichment in Be relative to actinolite and particularly to garnet. Considering mineral pairs and coexisting minerals, the order of enrichment is pyroxene > actinolite > garnet with the enrichment factors of pyroxene over actinolite of 2:1 to 9:1 and for pyroxene over garnet of 47:1 to more than 150:1. Also the pyroxene from high-grade tactites show much higher content of Be than the one sample of pyroxene from a low-grade tactite. This means that Be, one of the ore suite elements, in pyroxene may be used as an indicator of tungsten mineralization. Enrichment of Be in pyroxene relative to garnet has also been noted by Nesterenko, et al. (1958, p. 295) in skarn minerals. In this study it was noted that pyroxene had contents of Be up to 50 ppm while in garnet Be did not exceed 10 ppm.

Both pyroxene and amphibole have appreciably higher Be contents than found in these minerals from Grenville skarns, where Be contents of pyroxenes ranged from trace to 19 ppm (mean of 3.5 ppm) and of amphibole from trace to 14 ppm with a mean of 5.0 ppm. There was no notable enrichment of Be in pyroxene relative to amphibole (Shaw, et al., 1963, p. 605).

Titanium.--Titanium may occur in minerals either as the quadrivalent ion, Ti^{4+}, with an ionic radius of 0.68Å or as the trivalent ion, Ti^{3+}, with a radius of 0.76 Å. The quadrivalent ion may replace silicon diadochically, but owing to a notable difference in radii of the Si^{4+} (0.40 Å) and Ti^{4+} the replacement must be limited. The trivalent ion

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with a coordination number of 6 may replace Al^{3+} (0.51 Å), Fe^{3+} (0.64 Å) and, in part, also Mg^{2+} (0.66 Å) (Rankama and Sahama, 1949, p. 561). In skarn minerals the substitution of Ti for Mg and Fe in pyroxenes and amphiboles is thought by Shaw, et al. (1963, p. 590) to be important while Nesterenko, et al. (1958, p. 293) regard Ti replacement of Al in garnet to be the most common site of Ti.

In minerals of the Black Rock tactites, titanium is preferentially concentrated in garnet in which the concentration range is <500 to 3600 ppm. In actinolite the range is <500 to 920 ppm. In pyroxene and scheelite titanium is present in amounts much below the sensitivity limit of the spectrographic method.

In coexisting minerals, the order of enrichment is garnet $\geq$ actinolite > pyroxene, a sequence of decreasing Al_2O_3 content. There is also a correlation between garnet composition and Ti-content with the highest Ti in grossular-rich garnets and lowest Ti in garnets having the highest proportion of spessartine or andradite. Again, this shows a correlation with Al content and suggests that substitution of Ti for Al is the most important type of Ti occurrence in skarn minerals. Other studies of Ti in skarn minerals have also shown relative enrichments of garnet > pyroxene (Nesterenko, et al., 1958, p. 293) and amphibole > pyroxene (Kretz, 1960, p. 189; Shaw, et al., 1963, p. 605). The concentration of Ti in skarn minerals from Black Rock tactites is comparable to that found in these other studies.

Vanadium.--Vanadium occurs in the igneous environment in three stable oxidation states, as tri, quadri, and quinquevalent ions. Their radii are 0.74 Å (V^{3+}), 0.63 Å (V^{4+}), 0.56 Å (V^{5+}, coordination 4) and 0.59 Å (V^{5+}, coordination 6) and all, particularly V^{5+}, tend to form complexes with oxygen and partly also with sulfur. In mafic minerals, vanadium is mostly present as V^{4+} and V^{5+} replacing Fe^{3+} and Al^{3+} (Rankama and Sahama, 1949, p. 595-597).

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In the Black Rock tactites, vanadium occurs in detectable amounts in all four minerals analyzed, but is below sensitivity limits in scheelite. The ranges of concentration for garnet, actinolite, and pyroxene are 24-260, 9-40, and <5-17, respectively, and the order of enrichment is garnet > actinolite > pyroxene. The decrease from garnet to actinolite to pyroxene is a reflection of the available Fe^{3+} or Al^{3+} sites, garnet having the highest proportion of these sites and pyroxene the least.

The V content of pyroxenes and amphiboles in Black Rock tactites is somewhat lower than that noted by Shaw, et al. (1963, p. 584), who found V contents in pyroxene of 7 to 76 ppm (mean 32 ppm) and in amphibole of 28 to 86 ppm (mean 57 ppm). Kretz (1960, p. 166-167) noted contents of 40 to 55 ppm for pyroxene and 40 to 93 ppm for amphibole.

Nickel, Cobalt.--The two elements, cobalt and nickel, are closely related chemically. They are members of the iron family and are the closest relatives of iron in the Periodic System. Both elements show a strong affinity for sulfur, but in igneous rock they are mostly incorporated in silicate minerals. Nickel and cobalt may substitute for magnesium and ferrous iron, particularly in the mafic minerals (Rankama and Sahama, 1949, p. 677-682). The ionic radii of the four metals are : Mg^{2+} = 0.66 Å, Ni^{2+} = 0.69 Å, Fe^{2+} = 0.74 Å, and Co^{2+} = 0.72 Å.

In garnets, cobalt was below the sensitivity limit of 5 ppm in all samples. Nickel was also low in garnet, occurring in measurable quantities of 1 to 14 ppm in only 4 of the 22 samples. Detectable amounts of both nickel and cobalt occur in actinolite, Co concentrations ranging from 5 to 70 ppm and Ni from <2 to 78 ppm. The concentration of Ni and Co in pyroxenes is approximately the same as in actinolites; nickel ranges from <2 to 99 ppm and Co from 16 to 70. In coexisting minerals, the order of enrichment is pyroxene $\geq$ amphibole > garnet. There is an apparent higher

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content of Ni and Co in pyroxenes and actinolites from barren tactites. In one pyroxene sample, 7-6-22, Ni is <2 ppm and Co is below detection. The presence of sulfur as pyrrhotite may explain the low concentration of Ni and Co in this pyroxene since both have strong affinity for sulfur and may be concentrated as sulfides in this sample. Co was not detected in any of the scheelite separates and Ni was <2 ppm in all of these.

The content of Ni and Co in pyroxenes is comparable to that found in other studies (Nesterenko, et al., 1958, p. 292; Shaw, et al., 1963) and confirms the contention that skarn pyroxenes are more "pure", i.e., the content of most trace elements is relatively lower, in comparison with igneous pyroxenes (Shaw, et al., 1963, p. 588). For example, several groups of igneous pyroxenes studied by Snyder (1959) show average values of 0.0116 to 0.0422 percent for NiO and average values of 0.0067 to 0.0148 percent for CoO.

Tin.--Tin occurs in igneous rocks as the divalent and quadrivalent ions. Tin is strongly enriched in late crystallates during magmatic differentiation and the highest contents are generally found in pneumatolytic rocks. In silicate structures the Sn^{4+} ion (0.71 Å) may replace Fe^{2+} (0.74 Å) and Sn^{2+} (0.93 Å) substitute for Ca^{2+} (0.99 Å). In addition, quadrivalent tin may replace quadrivalent tungsten in wolframite (Rankama and Sahama, 1949, p. 732). Tin is a common associate of tungsten in many deposits of these metals. It may be expected that tin would be more highly concentrated in silicates associated with tungsten deposits. In tungsten- and molybdenum-bearing skarns of Tyrny-Auz tin contents of garnet average 0.2 percent and of pyroxene 0.01 percent (Nesterenko, et al., 1958, p. 291).

In garnets from barren tactites Sn is low, ranging from <2 to 14 ppm. In garnets from low-grade tactites Sn is present in low to moderate amounts (up to 25 ppm). The highest concentration of tin in garnet is found in those

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from high-grade tactites with 1,000 or more ppm tungsten. Most of the Sn values in these are >25 ppm with a high value of 69 ppm in 66-1. In actinolite, Sn is present in low concentrations of <2 to 14 ppm. One scheelite sample has 5 ppm and in the remainder of the scheelite samples Sn is less than 2 ppm. Tin is below sensitivity limits in all of the pyroxene separates. The order of enrichment is garnet > actinolite > pyroxene in coexisting minerals.

Copper.--Copper is mainly chalcophile, having one of the highest affinities for sulfur. Copper will enter silicate structures only in the absence of sulfur and may replace ferrous iron. The reason for the substitution is the similarity of the radii of Cu^{2+} (0.72 Å) and Fe^{2+} (0.74 Å) (Rankama and Sahama, 1949, p. 697).

In silicate minerals from the Black Rock tactites, copper values are generally low with occasional high values. In garnets, for example, 18 samples have Cu contents ranging from <5 to 11 ppm. The remaining 4 have high values of 54, 73, 135, and 240 ppm, three of the high values being from high sulfide tactites. It is likely that these high values of Cu are due not to diadochy but to minute inclusions of copper sulfides in the garnets. Both actinolite and pyroxene have generally low values of copper, <5 to 32 ppm. Again the higher values may be due to inclusions rather than substitution in the silicate structure. In scheelite, copper values are less than 5 ppm in all samples. Another factor suggesting presence of Cu as sulfide inclusions is a lack of consistent order of enrichment in coexisting minerals as is generally shown when an element is present as a substitution in the silicate structure. For Cu the apparent order of enrichment varies from sample to sample.

Yttrium.--Yttrium is commonly classified along with scandium and the lanthanides as a rare-earth element. Yttrium is a common constituent of minerals and rocks in low concentrations. In igneous processes, it is enriched

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in residual liquids during crystallization and commonly is concentrated as rare-earth minerals in granite and nepheline syenite pegmatites. In silicate minerals yttrium as Y^{3+} (0.92 Å) may substitute for calcium, Ca^{2+} (0.99 Å), because of similar ionic size. This replacement probably takes place in pyroxenes, amphiboles, and garnet. Yttrium may be considerably enriched in garnet (yttrium almandite), in concentrations up to several hundred ppm (Rankama and Sahama, 1949, p. 518-526). Yttrium concentrates in garnet, up to 0.9 percent, and in scheelite, up to 0.014 percent, at the Maikhura tin-tungsten deposit (Mogarovskii and Rosseikin, 1961, p. 561).

Garnets from Black Rock tactites consistently show low to moderate amounts of yttrium, the values ranging from less than 5 to 75 ppm. Yttrium was less than 5 ppm in all samples of actinolite and pyroxene and in all but two of the scheelite separates; the two exceptions had values of 13 and 17 ppm. The enrichment of Y is garnet > amphibole, pyroxene.

Scandium.--In igneous rocks part of the scandium is seized by mafic minerals during the main stage of crystallization. The size of the Sc^{3+} (0.81 Å) permits it to substitute for Mg^{2+} (0.66 Å) and Fe^{2+} (0.74 Å) in mineral structures. The remainder of the Sc becomes enriched in final crystallization stages of minerals of pegmatites and pneumatolytic rocks. In this case, it is preferentially concentrated in minerals of the Mg^{2+} - Fe^{2+} - Mn^{2+} group of minerals of the cassiterite-wolframite paragenesis (Rankama and Sahama, 1949, p. 511-513).

In the garnets from Black Rock tactites, 16 show Sc concentrations of 1 to 10 ppm, and the others are less than 1. The highest content of scandium is found in pyroxene (25 ppm in no. 6-24-12), but in general, Sc is low in both pyroxenes and actinolites. In coexisting minerals, the Sc content is approximately equal and low in

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value. Like Ni and Co, the highest concentrations of Sc in these minerals are found in those separated from barren tactites. In scheelites, Sc is below 1 ppm for all samples.

Other studies also show general low values of Sc in skarn pyroxenes and amphiboles. Scandium contents of 16 ppm in pyroxene and 26 ppm in amphibole were found by Kretz (1960, p. 166-167), and Shaw, et al. (1963, p. 584) recorded Sc ranges of trace to 48 ppm (mean 8.9 ppm) for pyroxene and trace to 23 ppm (mean 8.2 ppm) for amphibole.

Manganese.--Manganese is related to iron in its chemical properties and is a member of the iron family. In silicate minerals and igneous rocks, manganese occurs as Mn^{2+} ions accompanying ferrous iron during the main stage of crystallization. There is a difference between the behavior of iron and manganese in late-stage crystallization, during which Mn may be considerably concentrated in the late magmatic crystallates--pegmatites and pneumatolytic rocks. In igneous rocks manganese may substitute for other ions of similar size. The ions and their radii (for 6-fold coordination) are:

Mn^{2+}	0.80 Å
Fe^{2+}	0.74 Å
Mg^{2+}	0.66 Å
Zn^{2+}	0.74 Å
Ca^{2+}	0.99 Å

Of the possible replacements, that of Fe^{2+} by Mn^{2+} is the most common and geochemically the most important.

In the silicate minerals from the Black Rock area, manganese commonly occurs in quantities of greater than 1 percent. In some of the garnets, it is a major component. The garnet, pyroxenes, and actinolites are all unusually manganese-rich, as previously mentioned in the section on mineralogy. Pyroxene and garnet have higher MnO contents than amphibole. In general, Mn is higher in minerals from W-bearing tactites than barren tactites. In Black Rock

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skarn minerals MnO is higher than found in studies by Kretz (1960, p. 166-167) and Shaw, et al. (1963, p. 584), in which MnO ranged from 0.035 to 0.36 percent for pyroxenes and amphiboles from skarns.

In scheelites, $CaWO_4$, manganese is a trace constituent, occurring in amounts ranging from 55 to 390 ppm. In this mineral it probably substitutes diadochically for calcium.

Molybdenum.--Molybdenum was determined only in scheelite in which it is a minor component. Molybdenum is a common associate of tungsten in tungsten deposits and occurs in solid solution with tungsten in scheelite. The scheelites from the Black Rock mine contain 0.27 to 13.8 mol. percent powellite component, $CaMoO_4$.

Correlation analysis. Correlation coefficients were calculated for the data obtained in trace element analyses of the tactite minerals. The calculations were performed to test 1) element associations especially between elements of the ore suite elements, Be, Sn, and Cu, 2) associations between elements in minerals and tungsten content (grade) of the parent tactite, and 3) zonation expressed by the Mo content in scheelite. Correlation coefficients were calculated for each of the four minerals with the tungsten content of the tactite from which the minerals were separated added as an additional variable. Also zonation of Mo in scheelite was tested by considering the horizontal distance of each sample from the projected contact of the quartz monzonite stock as an additional variable.

For garnet, positive correlation coefficients which were significant at the 0.001 probability level were found for Ti-Y and Ti-Sc. Coefficients significant at the 0.05 level were positive correlations for the pairs V-Sc, Y-Sc, and Cu-MnO, and a negative correlation for Ti-Sn. There were no significant correlations between W content and any of the other variables.

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Three correlation coefficients significant at the 0.05 probability level were found in the analysis of data on pyroxenes. Positive correlation was shown for Be-W and MnO-W. MnO-Sc had a negative correlation coefficient.

Data for actinolite showed positive correlation coefficients for the pairs Be-MnO and Sn-MnO significant at the 0.05 level. There was no significant correlation between W and the other variables.

For scheelite, the only significant correlation coefficient was between Mo and horizontal distance from the intrusive contact of the quartz monzonite stock. This coefficient was significant at the 0.05 probability level.

The analysis of trace elements in tactite minerals and correlation analysis of the resulting data was mainly inconclusive in answering questions of tactite genesis. This study did confirm, in part, information gained by the spectrographic analysis of whole-rock tactite samples. Some of the elements of the ore suite showed positive correlation with other elements of the suite, e.g., Be-W, and negative correlation with non-ore elements, e.g., Ti-Sn. Positive correlations between MnO and ore suite elements as well as negative correlation with non-ore elements, e.g., MnO-Sc, suggest that Mn is an additional member of the suite of elements associated with tungsten mineralization. This confirms conclusions based on petrography and partial chemical analyses.

A disappointing result of the trace element in minerals study is the general lack of positive correlations between tungsten content of tactites and elements of the constituent minerals. Be-W in pyroxene was the only association of this type noted. Perhaps more data on additional samples would suggest additional associations. Also, except for Mo content of scheelite, the amount of data for tactite minerals was insufficient to test zonation. Also it is doubtful whether any meaningful information could be obtained regarding zonation by a study of trace elements in garnets, pyroxenes,

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or amphiboles because of complications arising due to variation in major components, possibility of substitution in two or more sites, and other factors. Perhaps a large number of additional samples would be helpful but the anticipated results probably would not justify the expenditure of funds and time needed to purify and analyze these minerals.

The tactite mineral trace element study confirms, in general, thoughts by other workers that trace element determinations have been only rarely successful in the solution of classic and specific geologic problems (Turekian, 1963, p. 3). On the other hand the whole-rock tactite trace element study was significantly successful in delineating the element suite accompanying tungsten mineralization from elements present in the parent rocks.

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GENESIS OF THE BLACK ROCK TACTITES

Source and Character of Metasomatism

The tactites of the Black Rock mine area are the product of additive or contact metasomatic metamorphism of relatively pure and impure marble and calc-hornfels that are interbedded with siliceous hornfels. The marbles have been most affected by metasomatism, the calc-hornfelses less so, and the siliceous hornfelses hardly at all. The widespread metasomatism resulted in drastic changes in the composition of the country rocks accomplished by the addition and subtraction of large quantities of chemical constituents and produced great volumes of tactite.

An important question on the origin of the tactites of the Black Rock area is: What is the source of the fluids and metals which produced the observed physical and chemical changes? Much of the large quantities of iron, alumina, and silica and other constituents must have come from a source other than the metasediments themselves. Also a medium such as a hydrothermal fluid is required for the transfer of matter into and out of the area of active metasomatism. An external source of energy in the form of heat is required to produce the observed mineral assemblages. Outside the immediate mine area the calcareous sediments were little affected, except for recrystallization, by the regional metamorphism and succeeding contact metamorphism. A likely source for the hydrothermal fluids, the metals, and the thermal energy is the quartz monzonite stock exposed west of the Black Rock mine or a concealed portion of this stock beneath the mine area. The best evidence of genetic connection between this igneous body and the tactites is the spatial proximity, especially the localization of the tungsten ore bodies nearer to the intrusive in the west-dipping limb and crest of the anticline. A feature of the

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stock suggesting this genetic connection is the occurrence of a more leucocratic altered phase of quartz monzonite in the portion of the stock nearest the mine area.

Local variations in the physical and chemical properties of the metasomatizing fluids and in the character of the country rock resulted in the development of several types of tactite. The tactites may be grouped into three main types: barren, scheelite-bearing, and sulfide tactites, although gradations between all three exist. The barren tactites are, by far, the most widespread. Of primary concern in this study is the distinction between the genesis of the high grade scheelite-bearing tactites and that of the tactites which generally contain little or no scheelite, both the barren type and the sulfide type.

Stratigraphic evidence indicates that the scheelite-bearing tactites are the result of replacement of relatively pure marble. The tungsten tactites are continuous with marble beds to the south and, in underground exposures, grade into calcite marbles. Residual blocks of unreplaced marble in ore grade tactites are seen in exposures in open pit workings. Results of spectrographic analyses of tactites provide chemical evidence that the scheelite-bearing tactites are derived from purer marbles. These tactites show significantly lower concentrations of Ti, Cr, Ni, Sc, V, Y, and Zr compared with barren tactites. These elements are all higher in calc-hornfels than in marble and reflect the detrital content of the original sediment. Much of the barren tactite may have developed from the less pure marble and calc-hornfels. The greater reactivity of clean marble to mineralizing solutions and the selective development of tungsten-bearing tactites in clean marbles relative to impure calcareous metasediments was also noted in the Bishop district (Bateman, 1965).

The tactites of the Black Rock mine area have developed by both diffusive and infiltration metasomatism (Korzhinskii, 1964). Infiltration metasomatism was, by far, the dominant process but diffusive metasomatism may have been important

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at the igneous contact and along lithologic contacts such as marble-calc-hornfels contacts. Many ore bodies are localized at or near these contacts suggesting that diffusive metasomatism may have been the dominant process in their formation.

According to Korzhinskii's classification (1964, p. 1926) the metasomatic process represented at the Black Rock mine would be "early alkaline postmagmatic metasomatism." By Eskola's (1939) and Mehnert's (1969) classification the Black Rock metasomatism would be a combination of iron-magnesia-silicate metasomatism and hydrothermal ore metasomatism.

The metamorphism of the rocks of the Black Rock area is a combination of non-additive and additive processes. Calc-hornfelses, siliceous hornfelses, marbles, and a minor amount of tactite are probably the result of non-additive contact metamorphism. The tactites formed in this manner are localized along marble-hornfels contacts and contain vugs indicating a loss in volume. The metasomatic stage of metamorphism resulted in the widespread development of tactite containing little or no scheelite and the more restricted development of scheelite-bearing tactites and sulfide-rich tactites.

The barren type of tactite may have developed earlier than the scheelite-bearing tactites under conditions of rising temperature and from fluids which were poorer in iron, manganese, and ore-forming constituents than those which formed the scheelite-bearing tactites. Increasing temperature and more concentrated fluids produced, locally, the scheelite-bearing tactites which are characterized by iron- and manganese-rich silicates, fluorite, and scheelite. Evidence of a two-stage process of metasomatism is found in garnets. The common garnet of barren tactites is colorless or light brown, isotropic, and grossular-rich. In scheelite-bearing tactites, the garnets are typically brown, strongly anisotropic, and contain higher amounts of iron and manganese.

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In many of the scheelite-bearing tactites, the garnets consist of grossular-rich, colorless cores rimmed by brown, more iron and manganese rich rims suggesting a two-stage formation. However, an alternate explanation for the origin of the barren tactites is that they are a product of cooler, less concentrated fluids which also produced scheelite-bearing tactites closer to the intrusive and were now depleted of the ore suite of elements.

The waning states of metasomatism are represented by the development of actinolite, epidote, quartz, calcite, and sulfides. The change from iron oxide as magnetite to iron sulfide as pyrrhotite implies a change in the relative fugacities of oxygen and sulfur.

The Environment of Ore Deposition

Although no direct evidence of pressure and temperature conditions prevailing during tactite formation was obtained in this study, estimates of these conditions may be made based on 1) consideration of the grade of metamorphism, 2) results of studies in similar environments, and 3) appraisal of experimental work.

In the calc-hornfelses the common assemblage is calcite + epidote + (actinolite-tremolite). This assemblage is characteristic of the albite-epidote-hornfels facies (Winkler, 1965, p. 54). The occasional occurrence of diopside shows that, at least locally, conditions of the hornblende hornfels facies were attained. Assemblages characteristic of the albite-epidote facies are common in the siliceous hornfelses. Common assemblages are: quartz + muscovite + biotite + chlorite in quartz sericite hornfels and quartz + biotite + muscovite + potassium feldspar in biotite hornfels. The appearance of andalusite in graphite andalusite hornfels is indicative of temperatures of the upper part of the albite-epidote hornfels facies (Winkler, 1965, p. 56). Assemblages characteristic of the hornblende hornfels facies such as

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calcite + diopside + grossular are common in tactites. The presence of actinolite and epidote suggests that conditions of the albite-epidote-hornfels facies prevailed locally especially during the waning stages of metasomatism. Assemblages coexisting with scheelite in tungsten tactites are of the hornblende-hornfels facies, suggesting that the minimum temperature for ore deposition may be placed at the boundary between albite-epidote-hornfels and hornblende-hornfels facies. This boundary has been placed at 520°C at 1000 bars P_{H_2O} and 530°C at 2000 bars P_{H_2O} (Winkler, 1965, p. 56). Most of the hornfels were produced at temperatures lower than this and most of the tactites developed at temperatures near or above approximately 525°C.

The Black Rock mine area is part of the Sierra Nevada batholithic complex and the metamorphic rocks of this area are similar in composition and metamorphic facies to the metamorphic rocks in the main part of the Sierra Nevada batholith to the west. Studies by Bateman, et al. (1963, p. 11) across the central part of the batholith indicate that the facies of metamorphic rocks correspond to H_2O pressures of 6000 bars and 400-600°C. If the water pressure equaled the load pressure then the depth of burial would have been about 11 miles. In a study of the Mt. Tallac roof remnant, Loomis (1966) found the contact metamorphic rocks to vary in facies from actinolite hornfels to pyroxene-hornfels facies. Hornblende hornfels facies rocks surround most plutons. The maximum temperature attained in pyroxene-hornfels rocks was 750°C. The total overburden was estimated at 20,000 to 25,000 feet, corresponding to about 1500 and 1900 bars, respectively (Loomis, 1966, p. 243). Evernden and Kistler (1970, p. 14) concluded on the basis of mineralogical data that the metamorphic rocks in the Sierra Nevada were the result of temperatures between 600°C and 700°C and pressures of 800 to 3000 bars with no more refined specification possible.

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There are few experimental data which can be applied to the genesis of the Black Rock tactites. The small amount of data available on the synthesis of skarn minerals only indicates minimum temperatures of formation. Mill and Kalinin (1966) provide experimental data showing that andradite garnet may form from Na_2CO_3 solution by the replacement of $CaCO_3$ at temperatures of 460-475°C and constant pressure of 1500 atm. One reaction which has been investigated experimentally is the reaction of epidote to andradite plus anorthite. Experimental attempts to reproduce the reaction indicate that the equilibrium temperature is between 575° and 600°C at 2000 bars H_2O pressure (Loomis, 1966, p. 232). Petrographic studies of Black Rock tactites indicate that this reaction may have taken place in the ore forming process in the conversion of barren tactites to scheelite-bearing tactites. The presence of late epidote as a replacement of garnet in tungsten tactites indicates that the reverse of the above reaction took place also.

If the tactite deposits of the Black Rock area formed from hydrothermal fluids emanating from the crystallizing and cooling quartz monzonite then experimental data on the melting of granites may provide reasonable maximum temperatures of ore deposition. It is postulated that the tactites were formed from hydrothermal aqueous fluids which separated from the intrusive during the latest stages of crystallization. The temperatures of 650° to 675°C have been obtained for the solidus of the Westerly and Quincy granites (Tuttle and Bowen, 1958, p. 83) for H_2O pressures of 4000 to 2000 bars. The tungsten ores likely formed below these temperatures as the fluids cooled in moving outward and upward away from the crystallizing melt into the surrounding country rocks.

Based on these considerations it seems reasonable to propose that most of the tactites of the Black Rock area formed at temperatures and pressures greater than 525°C and 1000 bars P_{H_2O} and less than 650°C and 5000 bars P_{H_2O}. This

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is in agreement with the model for ore formation for the Pine Creek mine (Darling, 1967, p. 66) in which the temperature of 650°C and pressure of 5000 bars H_2O pressure was postulated.

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CONCLUSIONS

The Black Rock tungsten deposits consist of scheelite-bearing tactites which are metasomatic replacements of Paleozoic calcareous metasediments. Barren, low grade, and high grade scheelite-bearing tactites may be distinquished according to tungsten content. The ore bodies, consisting of high grade scheelite-bearing tactite, occur mainly along tactite-hornfels contacts which were originally marble-hornfels contacts in the west-dipping limb and crest of an asymmetric north-plunging anticline.

The tactites of the Black Rock area have developed as a result of a combination of iron-magnesia-silicate metasomatism and hydrothermal ore metasomatism. The principal additions have been of SiO_2, Fe, Al_2O_3, and MnO amounting to approximately 60 percent increase by weight of the tactite. The presence of high sulfide zones in the lower levels of the mine indicates a considerable addition of sulfur also in certain areas. The principal losses in the original marble have been of CO_2 and CaO, amounting to approximately 55 percent loss by weight of marble.

A likely source for the hydrothermal fluids which produced the Black Rock tactites and associated tungsten ore bodies is a quartz monzonite stock exposed immediately west of the mine area. This conclusion is based on the spatial relations of the stock and the ore bodies and on alteration of the stock. Aqueous hydrothermal fluids migrated updip along the west dipping limb of the anticline in folded metasediments and away from the cooling crystallizing melt and reacted with the calcareous rocks to produce tactites and tungsten deposits. Consideration of the metamorphic grade in the contact aureole, results of other studies of the Sierra Nevada batholith, and experimental work makes it possible to put limits on the temperatures

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and pressures prevailing during the formation of the tactites and associated tungsten deposits. The lower and upper limits for temperatures are 525° and 650°C respectively and for pressure 1000 and 5000 bars H_2O pressure respectively.

Mineralogic studies of tactite minerals indicate that amphibole, garnet, pyroxene, have high contents of iron and manganese. In general the contents of iron and manganese in these minerals are higher in ore grade tactites than in the same minerals from barren and low grade tactites. Three types of garnets can be distinquished: an almandine-spessartine type typical of low grade or barren sulfide-rich tactites, an andradite type typical of high grade scheelite-bearing tactites, and a grossular type from low grade or barren low-sulfide tactites.

Trace element studies of tactites and tactite minerals indicate that tungsten was accompanied by a suite of elements consisting of Fe, Be, Cu, Mo, Nb, Sn, and Mn in the formation of scheelite-bearing tactites. Other elements consisting of Ti, Cr, Ni, Sc, V, Y, and Zr are derived from the pre-existing calcareous sediments and their greater abundance in barren relative to high grade tactites indicates that many of the barren tactites were derived by replacement of calc-hornfels and impure marble whereas the high grade scheelite-bearing tactites are the result of replacement of relatively pure marble.

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APPENDIX

Modal Analysis of Stained Rock Slabs

A total of 19 specimens of quartz monzonite were prepared for staining by cutting of slabs, grinding each to a flat surface, impregnating with Canada balsam, and etching with hydrofluoric acid. All the slabs were stained for potassium feldspar and some for plagioclase according to the method described by Laniz, et al. (1964). In some cases plagioclase was not stained since it can be readily distinguished from quartz after etching with HF, and the identification of mafics and accessories was easier if plagioclase was left unstained. Also the low An content and the high degree of alteration of the plagioclase tended to give poor results from staining. Slabs were counted using a mechanical stage designed for use with a binocular microscope with counting intervals of 0.8 and 1.25 mm., varying according to the grain size of the rock. In general, the entire surface of the slab was counted, the number of points ranging from 532 to 901 and averaging 697.

Measurement of Specific Gravities and Porosities

Measurement of powder and bulk densities of samples of marble and tactite was done on a Model 930 Beckman Air Comparison Pycnometer. In measuring the bulk densities, the rock fragments were coated and sealed with paraffin to prevent air from entering pore space and cracks. Entrance of air would result in an erroneously low calculated porosity. The precision of the specific gravity measurements was estimated based on 10 replications of a powdered sample of marble. For two-thirds confidence limits, the coefficient of variation is 0.44 percent.

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Mineral Separation Procedures

A total of 52 mineral separates were prepared from 23 tactite samples representing barren, low-grade, and high-grade tactites with tungsten contents ranging from nil to 1 percent. The mineral separates consisted of 23 garnets, 9 actinolites, 6 pyroxenes, and 14 scheelites.

The preparation of mineral separates was by standard procedures. After selection of samples, the rocks were crushed to pass a 20 mesh (0.84 mm opening) sieve using a jaw crusher and roller crusher. The samples were then elutriated to remove the very fine material and dried. By sieving, a fraction of the sample between 100 mesh (0.149 mm) and 250 mesh (0.062 mm) was separated. A heavy concentrate was then obtained from this fraction using methylene iodide (S.G. = 3.32) or bromoform (S.G. = 2.90) in a large separatory funnel. This heavy concentrate was generally mostly garnet but also commonly contained pyrrhotite, pyroxene, amphibole, calcite and other heavy minerals. The heavy concentrate was then run on a Frantz magnetic separator. Garnet, actinolite, and pyroxene concentrates were obtained by repeated runs at low amperage since these minerals have a rather high magnetic susceptibility. Scheelite was concentrated in the nonmagnetic fraction.

The scheelites were purified by repeated runs on the Frantz separator at maximum amperage and by handpicking. In some cases, because of the presence of binary grains and/or inclusions, scheelite was reground in a ceramic mortar to minus 200 mesh, using a nylon screen, and rerun on the Frantz. The final separates contained less than 1 percent impurities as determined by petrographic microscope.

The final separates of garnet, actinolite, and pyroxene were obtained using clerici solution. Clerici solution is a mixture of thallium malonate, thallium formate, and small amounts of distilled water with which densities up to 4.2 can be obtained. The specific gravity of clerici solution

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may be calibrated by using glass beads of a known specific gravity; thereafter since a linear relationship exists between S.G. and refractive index for clerici solution, the specific gravity may be obtained by measuring the refractive index of the solution on a refractometer. In this way, approximate specific gravities of garnets were measured.

The sink-float method using a centrifuge and specially designed centrifuge tubes of 15 ml. capacity was used to obtain mineral separates of garnet, actinolite, and pyroxene of 98 percent or better purity. These tubes are constricted near the bottom so that a plug may be inserted to seal the top containing the light fraction from the bottom containing the heavy fraction. Then, with the plug held in place, the light fraction may be poured off while the heavy fraction is retained in the tube. The final separates were prepared by repeated runs in clerici solution and regrinding to finer size where necessary because of binary grains or inclusions. The final separates of these minerals were minus 250 mesh (0.062 mm) to plus 400 mesh (0.037 mm). Purity was checked by immersion of grains in oil and using a petrographic microscope.

Measurement of Refractive Indices and Unit Cells for Garnets

Refractive indices of garnets were measured by immersion and matching with appropriate oils. After matching the oil (by mixing if necessary) the refractive index of the oil was measured using a Leitz-Jelley microrefractometer and a sodium light source.

Unit cell measurements were made on the purified mineral separate by diffraction methods on a Picker X-ray unit. Using CuK_{α} radiation and NaCl as an internal standard, the unit cell edge, a, was measured with a precision of ±.004 Å. In preparing the sample for X-ray analysis, 30 mg. of garnet and 5 mg. of NaCl (ratio of 6:1) were weighed, mixed, and placed on a glass slide. A solution of Duco cement dissolved

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in methanol was added with an eyedropper forming a slurry with the sample. On drying, the sample formed a thin smooth layer bonded to the surface of the glass slide. The glass slide was then placed in the sample holder on the X-ray goniometer and scanned at 1° per minute both forward and reverse through 2θ angles of 28° to 34°. The {400} and {420} peaks of garnet and the {200} of NaCl were measured. An average was obtained for the two scans, the NaCl peak was corrected to the accepted value, $2\theta_{Cu}K_1 = 31.69°$ (d = 2.821 Å), the correction factor was applied to the 2θ readings of the garnet peaks, 2θ values were converted to d-spacings, and unit cells were calculated. For garnet (cubic system) the unit cell edge, a, is related to d by the equation $a = d\sqrt{h^2 + k^2 + l^2}$. Therefore,

$a = 4d$ for {400} and $a = \sqrt{20}\,d$ for {420}.

Semiquantitative Spectrographic Analyses of Tactites

For this study 103 samples of tactite, hornfels, marble, and igneous rocks were analyzed for 30 elements by a 6-step semiquantitative spectrographic method and mercury was determined by an atomic absorption method. These analyses were done by laboratories of the U.S. Geological Survey. Tables 18, 19, and 20 show results of analyses of barren, low grade, and high grade scheelite-bearing tactites respectively. Analyses of siliceous hornfelses, calc-hornfelses, and marbles are listed in table 21.

To test the precision of the spectrographic analyses 40 of the 103 samples, selected at random, were analyzed in duplicate and the standard errors of replicate samples were computed. The standard error is computed according to the formula:

$$S.E. = \left(\frac{\Sigma(x-x')^2}{2n}\right)^{1/2}$$

where x and x' are duplicates and n is the number of pairs of duplicate analyses (Youden, 1951, p. 16). The standard

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FIELD NO.	Fe%	Mg%	Ca%	Ti%	Mn	Ba	Be	Co	Cr	Cu
65-1	7	2	20	0.2	G*	N	2	15	15	N
65-3	10	2	20	0.5	G	10	3	15	100	L
67-5	G(20)	0.7	5	0.07	G	10	20	100	5	5000
67-16	10	2	15	0.2	G	10	7	10	70	10
6-24-1	7	2	15	0.5	5000	N	L	20	150	15
6-24-4	7	2	20	0.5	G	N	L	15	200	15
6-24-7	10	1.5	20	0.7	G	30	1	10	50	50
7-6-23	G(20)	1	7	0.01	G	N	50	100	5	5000
7-6-25	G(20)	1	2	0.07	G	N	L	20	10	1500
J 10	7	1.5	20	0.2	G	10	3	10	70	7
J 11	15	2	15	0.7	G	N	7	50	300	100
J 12	10	2	15	0.3	G	10	5	20	100	5
J 13	7	2	10	0.2	G	N	10	15	50	5
J 14	7	2	10	0.3	G	N	2	15	150	L
J 17	7	1.5	10	0.3	G	N	3	15	70	L
J 18	7	2	10	0.2	G	N	5	15	50	L
J 19	7	1.5	15	0.3	G	N	2	15	100	5
J 20	5	1.5	10	0.15	G	N	5	10	30	L
J 25	15	0.7	3	0.07	G	N	5	5	10	2000
J 31	7	1.5	10	0.3	G	N	5	15	100	L
J 33	5	1.5	10	0.3	5000	N	1	7	30	5
6-19-1	5	1.5	10	0.5	5000	50	2	15	100	L
6-19-7	5	2	10	0.3	1000	N	1	10	70	L
6-22-7	5	1	15	0.3	1500	100	1	10	70	7
S-10	10	1.5	15	0.3	G	10	1.5	15	150	L
S-11	5	1	10	0.2	5000	100	L	10	100	L
S-12	7	1.5	15	0.3	5000	N	L	10	100	L
S-13	5	1.5	15	0.2	5000	N	L	10	100	L
S-14	7	1.5	15	0.3	5000	N	L	7	70	L
S-19	15	0.5	20	0.07	G	N	5	N	N	10
S-20	10	1.5	20	0.2	G	N	5	15	5	5
Lower limit of determination	.05	.02	.05	.002	10	20	1	5	5	5

*Greater than 5000 ppm

Table 18. Spectrographic and mercury analyses of barren tactites containing less than 50 ppm W. Fe, Mg, Ca, and Ti reported in %; all other elements reported in ppm. Results reported in the series; 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, etc. G = greater than value shown, L = detected, but below lower limit of determination, N = not detected at limit of detection. Elements looked for but not found were As, Au, Cd, and Sb. Elements mostly below limits of detection and their lower limits of determination are Ag(0.5), B(10), Bi(10), and Pb(10). Lower limits of determination for the 6-step spectrographic method are shown at the bottom of table. Mercury was determined by an atomic absorption method. Spectrographic analyses by E. L. Mosier and mercury analyses by J. V. Desmond, both of the U.S. Geological Survey.

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Co	Cr	Cu	La	Mo	Nb	Ni	Sc	Sn	Sr	V	W	Y	Zn	Zr	Hg
15	15	N	N	N	N	30	10	30	300	100	N	30	500	50	0.1
15	100	L	N	10	15	30	15	30	N	100	N	30	500	200	0.06
100	5	5000	N	N	50	20	N	50	N	100	N	N	300	N	0.07
10	70	10	N	N	15	30	15	30	N	70	L	30	200	100	0.03
20	150	15	20	10	10	50	15	20	150	150	L	20	700	150	0.05
15	200	15	N	5	10	30	15	20	100	100	N	50	500	200	0.05
10	50	50	N	N	10	30	20	20	100	150	N	100	300	100	0.08
100	5	5000	N	N	30	30	N	30	N	50	N	N	500	20	0.05
20	10	1500	N	N	50	7	N	30	N	100	N	N	300	10	0.08
10	70	7	N	N	10	30	10	30	100	100	N	30	200	70	L
50	300	100	100	N	100	70	20	10	300	70	N	30	700	200	0.03
20	100	5	N	N	20	50	15	15	100	100	N	30	300	100	0.03
15	50	5	50	10	10	30	10	20	100	70	N	20	500	50	0.05
15	150	L	50	5	10	30	15	10	300	100	N	50	300	100	L
15	70	L	N	N	15	30	15	20	N	70	L	30	200	100	0.02
15	50	L	30	N	20	30	10	15	200	70	N	30	500	50	0.02
15	100	5	N	N	10	30	15	15	150	100	N	30	300	70	0.04
10	30	L	N	N	L	20	7	20	100	50	N	20	300	70	0.03
5	10	2000	N	N	50	10	5	50	N	30	L	10	200	N	0.02
15	100	L	30	N	20	50	15	20	300	150	L	30	300	50	0.03
7	30	5	100	N	10	20	10	15	200	70	N	15	700	50	0.03
15	100	L	50	N	10	30	15	15	100	100	N	30	500	100	0.02
10	70	L	30	N	L	30	10	10	500	70	N	20	300	70	0.02
10	70	7	30	N	10	30	10	N	500	70	N	20	L	70	0.03
15	150	L	N	N	L	50	15	N	100	70	N	30	700	100	0.04
10	100	L	N	N	L	30	10	10	100	100	N	15	300	70	0.03
10	100	L	20	N	L	20	10	20	150	100	N	20	500	70	0.06
10	100	L	20	N	N	30	10	10	100	70	N	20	700	70	0.04
7	70	L	N	N	10	30	10	10	100	100	N	20	700	70	0.03
N	N	10	N	N	20	10	N	100	N	150	N	N	N	10	0.05
15	5	5	N	N	10	30	15	30	N	100	N	50	500	30	0.02
5	5	5	20	5	10	5	5	10	100	10	50	10	200	10	0.01

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Field No.	Fe%	Mg%	Ca%	Ti%	Mn	Ba	Be	Co	Cr	Cu	La
67-1	7	2	20	0.5	G*	150	3	10	150	5	50
67-3	10	1	20	0.05	G	N	7	5	10	15	N
67-12	20	0.7	5	0.07	G	20	1	15	5	2000	N
67-13	10	3	20	0.3	G	10	15	15	200	5	50
67-14	10	1.5	15	0.15	G	N	10	N	50	5	N
67-19	20	0.7	7	0.02	G	N	30	100	N	5000	N
6-24-12	5	3	15	0.3	5000	N	3	15	100	5	20
J-9	10	2	20	0.3	G	30	1.5	20	100	7	20
68-3	10	1	10	0.1	G	N	7	15	10	10	N
J-26	7	1.5	10	0.2	G	N	10	5	100	20	50
Lower limit of determination	.05	.02	.05	.002	10	20	1	5	5	5	20

*Greater than 5000 ppm

Table 19. Spectrographic and mercury analyses of low grade tactites containing 50 ppm to less than 1000 ppm W.

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Cr	Cu	La	Mo	Nb	Ni	Sc	Sn	Sr	V	W	Y	Zn	Zr	Hg
150	5	50	N	10	30	20	20	1000	100	50	30	300	100	0.05
10	15	N	N	15	10	N	70	N	50	70	10	300	10	0.06
5	2000	N	20	50	7	L	30	N	70	100	L	200	N	0.04
200	5	50	20	20	50	20	50	700	150	200	50	L	200	0.06
50	5	N	N	10	20	7	50	N	70	70	20	200	50	0.14
N	5000	N	N	70	5	N	70	N	70	200	N	500	N	0.03
100	5	20	5	L	50	15	10	200	100	50	30	300	150	0.03
100	7	20	N	10	50	15	10	300	150	50	50	300	100	L
10	10	N	N	50	15	5	70	N	70	100	15	200	30	0.04
100	20	50	10	50	20	10	70	N	50	150	20	200	70	0.02
5	5	20	5	10	5	5	10	100	10	50	10	200	10	0.01

grade
) ppm W.

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FIELD NO.	Fe%	Mg%	Ca%	Ti%	Mn	Ba	Be	Co	Cr	Cu	La	Mo
66-1	10	1	20	0.03	G*	N	15	N	10	30	N	10
66-2	15	1.5	20	0.15	G	N	15	N	20	20	N	7
66-3	5	2	20	0.3	G	N	5	15	70	L	70	5
66-4	7	2	20	0.15	G	N	7	5	50	20	N	2
66-5	15	1.5	20	0.2	G	10	20	5	50	15	N	20
67-4	20	1	20	0.05	G	N	10	N	10	2000	N	10
67-6	20	1.5	10	0.02	G	N	20	N	10	2000	N	20
67-7	20	2	10	0.3	G	N	30	15	300	500	70	5
67-9	15	2	20	0.1	G	N	10	30	30	20	N	7
67-10	15	3	20	0.1	G	N	20	20	30	15	N	20
67-11	20	0.7	20	0.05	G	N	5	N	20	200	N	15
67-15	10	5	10	0.05	G	20	15	50	20	10	N	30
67-17	15	1.5	10	0.03	G	N	30	N	5	7	N	20
67-20	7	0.7	10	0.02	G	10	7	5	N	2000	N	7
67-21	10	1	10	0.05	G	N	20	10	5	1000	N	10
7-6-11	15	1	15	0.01	G	N	15	10	5	100	N	10
7-6-11A	15	1	15	0.05	G	N	7	15	5	100	N	10
7-6-20	10	0.7	10	0.02	G	10	50	15	N	10000	N	1
7-6-22	20	0.5	15	0.005	G	N	50	N	N	700	N	1
7-14-1	10	1.5	10	0.1	G	N	7	7	30	50	N	10
7-14-2	15	2	15	0.1	G	N	15	20	30	50	N	20
J 2	15	1.5	20	0.03	G	N	3	7	5	150	N	30
J 6	20	1.5	15	0.03	G	N	7	15	5	500	N	30
J 7	10	3	20	0.05	G	N	15	10	5	20	N	10
J 8	10	2	20	0.07	G	N	10	10	5	20	N	20
J 15	7	1	7	0.03	G	N	3	5	N	200	N	3
J 16	10	1	10	0.03	G	N	5	7	5	200	N	5
J 21	10	0.7	10	0.02	G	N	2	N	N	100	N	7
J 23	15	0.7	10	0.05	G	N	7	N	20	L	N	5
J 27	10	1	10	0.03	G	N	15	N	N	700	N	7
J 30	7	1.5	7	0.07	G	30	3	5	30	80	N	10
68-1	10	0.5	10	0.03	G	N	10	5	N	70	N	15
68-2	10	0.7	10	0.03	G	N	10	N	N	10	N	10
68-4	10	0.3	10	0.02	G	N	3	5	N	70	N	5
S-15	7	1.5	10	0.1	G	N	2	10	50	5	20	5
Lower limit of determination	.05	.02	.05	.002	10	20	1	5	5	5	20	5

* Greater than 5000 ppm
**Greater than 10,000 ppm

Table 20. Spectrographic analyses of high grade scheelite-bearing tactites containing 1000 ppm or more W.

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	La	Mo	Nb	Ni	Sc	Sn	Sr	V	W	Y	Zn	Zr	Hg
0	N	100	20	5	N	200	N	70	2000	N	200	20	0.12
0	N	70	20	5	L	200	N	50	5000	10	300	50	0.10
L	70	50	20	30	10	50	100	70	5000	30	200	70	0.06
0	N	20	L	15	5	20	N	100	1000	20	700	50	0.08
5	N	200	20	10	5	200	N	70	5000	20	200	50	0.03
0	N	100	50	5	N	200	N	50	10000	N	200	10	0.26
0	N	200	150	5	5	100	N	50	G**	N	200	N	0.06
0	70	50	200	50	20	50	N	100	G	100	200	200	0.05
0	N	70	20	15	5	100	N	70	10000	10	500	20	0.05
5	N	200	150	15	5	150	N	70	G	10	700	15	0.26
0	N	150	50	5	L	200	N	50	10000	N	L	10	0.06
0	N	300	100	50	7	30	N	20	G	10	1000	10	0.03
7	N	200	100	5	N	200	N	50	G	N	200	10	0.03
0	N	70	100	L	N	100	N	100	G	N	200	N	0.03
0	N	100	70	15	N	100	N	70	10000	N	200	N	0.05
0	N	100	20	7	N	200	N	20	G	N	200	N	0.03
0	N	100	20	7	N	200	N	70	10000	N	N	10	0.06
0	N	10	50	L	N	150	N	30	2000	N	500	N	0.12
0	N	10	20	L	N	N	N	30	10000	N	1000	N	0.06
0	N	100	50	10	5	150	N	50	10000	10	300	30	0.08
0	N	200	50	20	5	100	N	50	G	15	1000	30	0.03
0	N	300	50	5	L	300	N	50	G	15	300	N	0.03
0	N	300	50	5	L	200	N	50	G	N	N	N	0.03
0	N	100	15	7	L	150	N	20	7000	N	1000	N	L
0	N	200	50	5	L	100	N	50	10000	N	500	N	0.03
0	N	30	30	7	L	70	N	50	10000	10	300	20	0.03
0	N	50	30	5	N	30	100	50	5000	N	L	N	0.05
0	N	70	20	5	N	100	N	30	5000	N	L	N	0.04
L	N	50	30	5	N	150	N	30	5000	N	200	20	0.02
0	N	70	100	10	L	70	N	50	G	N	L	N	0.04
0	N	100	50	15	7	50	N	30	10000	30	N	20	0.03
0	N	150	30	10	N	150	N	30	10000	N	N	20	0.09
0	N	100	50	5	N	150	N	50	10000	N	L	10	0.04
0	N	50	15	5	N	150	N	50	2000	10	L	10	0.03
5	20	50	10	15	5	70	N	70	2000	10	1000	30	0.13
5	20	5	10	5	5	10	100	10	50	10	200	10	0.01

ring

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FIELD NO.	Fe%	Mg%	Ca%	Ti%	Mn	Ba	Be	Co	Cr	Cu	La	Mo
Siliceous hfls.												
J44	7	1.5	0.1	0.5	700	700	1.5	7	150	10	50	10
6-29-3	2	0.5	0.05	0.7	20	1000	N	N	200	50	70	N
7-7-7	3	0.5	0.1	0.3	200	300	2	15	70	7	30	10
7-13-7	1	0.3	0.07	0.3	70	500	1	N	50	50	20	10
S-21B	7	0.7	0.1	0.5	200	700	3	10	150	30	50	10
Calc-hfls.												
6-18-1	7	0.5	10	0.5	1000	1000	L	5	150	30	70	N
6-22-1	3	2	20	0.2	1000	50	L	7	70	L	30	N
S-22D	3	1	20	0.3	1500	300	L	5	50	10	30	N
S-23	2	.03	7	0.2	G(5000)	20	L	N	20	7	20	N
Marble												
6-19-1	0.1	1	G(20)	0.007	30	N	N	N	5	L	N	N
6-19-2	0.7	0.7	G(20)	0.015	500	30	N	N	7	L	N	N
Lower limit of determination	.05	.02	.05	.002	10	20	1	5	5	5	20	5

Table 21. Spectrographic analyses of hornfelses and marble.

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Cr	Cu	La	Mo	Nb	Ni	Sc	Sn	Sr	V	W	Y	Zn	Zr
150	10	50	10	L	20	15	N	100	100	N	20	L	70
200	50	70	N	10	5	20	10	150	200	N	30	N	100
70	7	30	10	15	30	15	N	200	70	N	20	N	70
50	50	20	10	10	10	7	N	N	500	N	10	200	100
150	30	50	10	20	30	20	N	N	150	N	30	N	100
150	30	70	N	15	15	20	N	5000	300	N	50	N	100
70	L	30	N	L	20	10	N	1000	50	N	20	200	70
50	10	30	N	10	10	10	N	700	200	N	30	L	500
20	7	20	N	20	5	5	N	100	100	N	30	N	300
5	L	N	N	N	N	N	N	2000	20	N	N	N	N
7	L	N	N	N	N	N	N	2000	L	N	N	N	N
5	5	20	5	10	5	5	10	100	10	50	10	200	10

d marble.

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Element	Number of Pairs	Standard Error
Fe	40	1.34%
Mg	40	1.30"
Ca	40	1.38"
Ti	40	1.41"
Mn	12	1.33ppm
Ba	16	1.41 "
Be	36	1.34 "
Co	17	1.32 "
Cr	29	1.34 "
Cu	35	1.62 "
La	13	1.30 "
Mo	23	1.49 "
Nb	24	2.02 "
Ni	37	1.40 "
Sc	21	3.66 "
Sn	29	1.29 "
Sr	13	1.27 "
V	38	2.96 "
W	14	1.95 "
Y	25	1.28 "
Zn	10	1.80 "
Zr	28	1.38 "

Table 22. Standard errors of semiquantitative spectrographic analyses.

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errors and number of pairs of duplicates used in the computation are shown in table 22. The number of pairs varies since qualified values (N, L, or G values) that may be present can not be used in the standard error calculation.

The precision of the mercury analyses was estimated by making ten replicate analyses each of four samples and calculating the standard deviation and coefficient of variation. The average standard deviation of the four samples is 0.032 ppm and the coefficient of variation is 44 percent.

Spectrographic Analyses of Tactite Minerals

Standards. The analytical method chosen for analysis of trace elements in tactite minerals was emission spectrography. Because of limited time a rapid semiquantitative procedure was sought by which trace element variations in minerals could be studied. A method suggested by Dr. Paul Reitan was used in which the standard samples, G-1, W-1, T-1, Syenite, and Sulfide were used to establish working curves for the elements Be, Co, Cu, Mn, Ni, Sc, Ti, V, and Y. This method was advantageous since it required no preparation of artificial standards (usually a major part of any spectrographic procedure) and the values for the standards are based on many analyses by various methods. The concentrations of the 10 elements in the standard samples are shown in table 23. The underlined values are ones used in this study. One additional standard for Y was prepared by mixing equal parts of T-1 and Syenite giving a standard containing 235 ppm Y.

In addition to these standards, it was necessary to prepare standards for the determination of MnO in garnet, actinolite, and pyroxene and Mo in scheelite. Standards for MnO were prepared using spectrographically pure Mn_3O_4, an analyzed rock sample, lepidolite standard, and Syenite. For Mo determination, standards were mixed from three prepared synthetic scheelites containing 0, 4.8, and 9.6 percent Mo.

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Element	G-1	W-1	T-1	Syenite	Sulfide
Be	3	0.8	1.1	24	1
Co	2.4	50	11	20	510
Cu	13	110	62	30	8470
Mn	230	1320	750	3200	1000
Ni	1-2	78	7.5	30	15100
Sc	3	34	11	11	21
Sn	4	3	32	5.6	3.0
Ti	1500	6400	3400	2900	4700
V	16	240	90	84	210
Y	13	25	21	450	15

Table 23. Concentration (in ppm) of trace elements in standard samples used in this study. Values for G-1 and W-1 are from Fleischer (1965, p. 1268-1276; 1969, p. 65-79) and for T-1, Syenite, and Sulfide from Ingamells and Suhr (1963, p. 909). Underlined values were used for semiquantitative analysis of mineral separates.

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The starting materials and their MnO content used in the preparation of MnO standards were:

1. Mn_3O_4, spectrographically pure grade.
2. Rock sample #9094, an andesite supplied and analyzed by Dr. C. O. Hutton containing 0.23 percent MnO.
3. Lepidolite, standard #60-1252, supplied by Dr. Paul Reitan, containing 2.19 percent MnO.
4. Syenite, standard silicate sample containing 0.41 percent MnO (Ingamells and Suhr, 1963, p. 908).

The andesite sample was mixed with Mn_3O_4 to give standards Mn-1, 2, 3, and 4 containing 10, 4, 2.5, and 1.25 percent MnO respectively. The procedure was as follows:

1. 1412.0 mg of #9064 was split from bulk rock sample with microsplitter.
2. 166 mg. of Mn_3O_4 added to #9064 and mixed in ceramic mortar for 5 minutes.
3. Mixture placed in plexiglass vial containing plexiglass beads and mixed for 15 minutes in a Spex Mill.
4. Mixture was ground to minus 325 mesh in ceramic mortar and then mixed for 15 minutes in acetone in agate mortar.
5. Mixture then mixed again on Spex Mill with plexiglass vial and beads for 2 hours.

This gave Mn-1 containing 10 percent MnO. Sample #9064 was ground to minus 325 mesh and was used to prepare Mn 2, 3, and 4 by successive dilution and mixing in agate mortar and Spex Mill. Mn-2 was prepared by dilution of Mn-1 by #9064 1:1 and mixing, Mn-3 was prepared by dilution of Mn-2 with an equal weight of #9064 and mixing, etc. Lepidolite and Syenite samples were used as standards without alteration.

Synthetic scheelite was made containing 9.6 (Mo-1), 4.8 (Mo-2), and 0 percent Mo and used for Mo standards for

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determining the Mo content of the scheelite separates. The procedure is as follows:

1. Prepare solutions of $NaWO_4 \cdot 2H_2O$ and $NaMoO_4 \cdot 2H_2O$ dissolved in H_2O in the following proportions:
   - 4 gm. $NaWO_4 \cdot 2H_2O$ + 1 gm. $Na_2MoO_4 \cdot 2H_2O$ in 100 ml. H_2O
   - 4.5 gm. $NaWO_4 \cdot 2H_2O$ + 0.5 gm. $Na_2MoO_4 \cdot 2H_2O$ in 100 ml. H_2O
   - 5 gm. $NaWO_4 \cdot 2H_2O$ + 0 gm. $Na_2MoO_4 \cdot 2H_2O$ in 100 ml. H_2O
2. Prepare solution of 50 gm. $CaCl_2 \cdot 2H_2O$ dissolved in 500 ml. H_2O.
3. Add, in excess, solution containing Ca^{++} to tungstate-molybdate solution to obtain precipitate of $Ca(W,Mo)O_4$.
4. Filter precipitate, being careful to retain all, and wash with boiling water to remove all Na^+ and Cl^- ions.
5. Transfer to platinum crucible and sinter in muffle furnace at approximately 850° C for 4-5 hours.
6. After fusion, grind in ceramic mortar to minus 250 mesh.

Two additional standards were prepared by successive dilution of Mo-2 (4.8% Mo) to give standards Mo-3, Mo-4, and Mo-5 containing 1.6, 0.4, and 0.1 percent Mo respectively. Mixing was done with plexiglass vials and beads in Spex Mixer Mill for 30 minutes.

Lutetium was used as an internal standard in this spectrographic procedure. The mixture containing Lu had been previously prepared by Dr. Paul Reitan and was available for use in the spectrographic laboratory at Stanford University. To prepare this standard, spectrographic pure grade Lu_2O_3 was added to $Na_2B_4O_7$ and fused. The resulting bead was crushed and mixed physically and this procedure of

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fusing and mixing was repeated several times. The resulting internal standard mixture contained 0.1 percent Lu_2O_3.

Spectrographic Procedure. The samples (standards and unknowns) were mixed with internal standard and ultra-purity graphite and loaded into preformed graphite electrodes. The proportion of sample:internal standard mixture:graphite was 4:1:5. For standards the weights used were 72 mg. sample, 18 mg. internal standard, and 90 mg. graphite. For unknowns they were 48 mg. sample, 12 mg. internal standard, and 60 mg. graphite. After weighing, the components were placed into plexiglass vials with plexiglass beads and mixed on Spex Mixer Mill for 15 minutes each. This sample mixture was then loaded into preformed ultra-purity graphite electrodes No. 5790 and packed lightly with glass rod. The capacity of the electrodes when loaded in this manner was 31.5-32.0 mg. Three electrodes of each standard were loaded for burning in triplicate and two electrodes each of unknowns for duplicate burns. The upper electrodes were made by sharpening 1/8" graphite rod No. U40-1, density grade U-1.

The spectrochemical analysis was done with a Model 70-000 Jarrell-Ash 3.4 meter plane grating spectrograph with a first order dispersion of 5.0 Å per millimeter. The spectral range of the instrument is 1,800 to 30,000 angstroms. All standards and samples were burned and recorded with a grating angle setting of 627 and one plate in the spectrograph camera. The spectral range thus covered was approximately 2400 Å to 3600 Å. Kodak SA-3 4 x 10 in. spectrographic plates were used. Other spectrographic settings and conditions were:

1. amperage: 10 amp.
2. pre-burn: 0 sec.
3. burn time: completion (approximately 120 sec.)
4. electrode gap: 4 mm.
5. slit width: 15 microns.
6. slit height: 10 mm.

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All samples were burned with a rotating step sector included in the optical path. A controlled CO_2-atmosphere stage was used with each standard and sample burn to reduce background and to control the effect of CN bands.

The developed plates were read on a Model 21-000 Jarrell-Ash nonrecording projection microphotometer. The percent transmission is projected numerically on a visual scale which is read rapidly and simply by constant rate mechanical scanning. Normally 2 to 4 steps of each line on each burn could be read. The element emission lines of analyzed elements and internal standard are shown in table 24.

Calculation of results was done on a calculating board. Use of this calculating board makes it unnecessary to prepare standard working curves for each element. The final value assigned to each element in each sample is an average of 4 to 8 separate measurements because of duplicate burns and the reading of 2 to 4 steps for each burn.

Analytical Precision. The precision of the semiquantitative technique was evaluated by replicate analysis and calculation of standard deviation and coefficient of variation. The error or variation is expressed as the coefficient of variation.

The precision of analyses of Ti, V, Sn and MnO was checked by making 10 replicate burns of garnet no. 67-3. For Cu, Y, and Sc, 10 replicate burns of garnet no. 67-7 were made. Precision for Be, Ni, Co, and MnO was measured in 7 replicate burns of actinolite no. 65-3. Six replicate burns of scheelite no. 66-3 gave precision for Mn and Mo. These data, mean, standard deviation, and coefficient of variation are shown in table 25. The method is most precise for MnO (1.0 percent for garnet, 1.7 percent for actinolite) and the least precise for Ni (28.2 percent for actinolite) and Cu (25.1 percent for garnet). The coefficient of variation for the other elements is from 5.7 percent (Be) to 17.1 percent (Mn in scheelite).

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Element	Range	Line	Internal Standard (Lu) Line
Be	1 - 35 ppm	3131.07 Å	3077.6 Å
Co	5 - 700	3453.505	3281.74
Cu	5 - 300	3273.96	3281.74
Mn	70 - 6000	2939.30	2911.39
Ni	1 - 150	3050.82	3077.6
Sc	1 - 40	3353.73	3281.74
Sn	2 - 200	3175.02	3077.6
Ti	450 - 10000	3103.8	3077.6
V	5 - 500	3102.3	3077.6
Y	5 - 500	3327.88	3281.74
Mo	0.1 - 10 %	3112.12	3077.6
MnO	0.4 - 25 %	2889.58	2911.39

Table 24. Analytical limits and emission lines for individual elements and internal standard used in semiquantitative spectrochemical analysis.

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Sample No.	No. of burns	Element or oxide	$\bar{x}$	S	V
67-3 (garnet)	10	Ti	887 ppm	65.5 ppm	7.4%
"	"	V	72.8 "	4.5 "	6.2
"	"	Sn	21.0 "	1.9 "	9.0
67-7 (garnet)	10	Cu	9.1 "	2.3 "	25.1
"	"	Y	75.2 "	7.7 "	10.2
"	"	Sc	7.9 "	0.6 "	8.0
65-3 (actinolite)	7	Be	12.0 "	0.7 "	5.7
"	"	Ni	16.1 "	4.5 "	28.2
"	"	Co	35.3 "	2.2 "	6.2
"	"	MnO	3.1 %	0.05 %	1.7
67-3 (garnet)	10	MnO	5.2 "	0.05 "	1.0
66-3 (scheelite)	6	Mn	107 ppm	18.3 ppm	17.1
"	"	Mo	0.42 %	0.07 %	16.9

Table 25. Precision of the semiquantitative spectrochemical technique expressed as coefficient of variation (V). Other parameters are mean, $\bar{x}$, and standard deviation, S.

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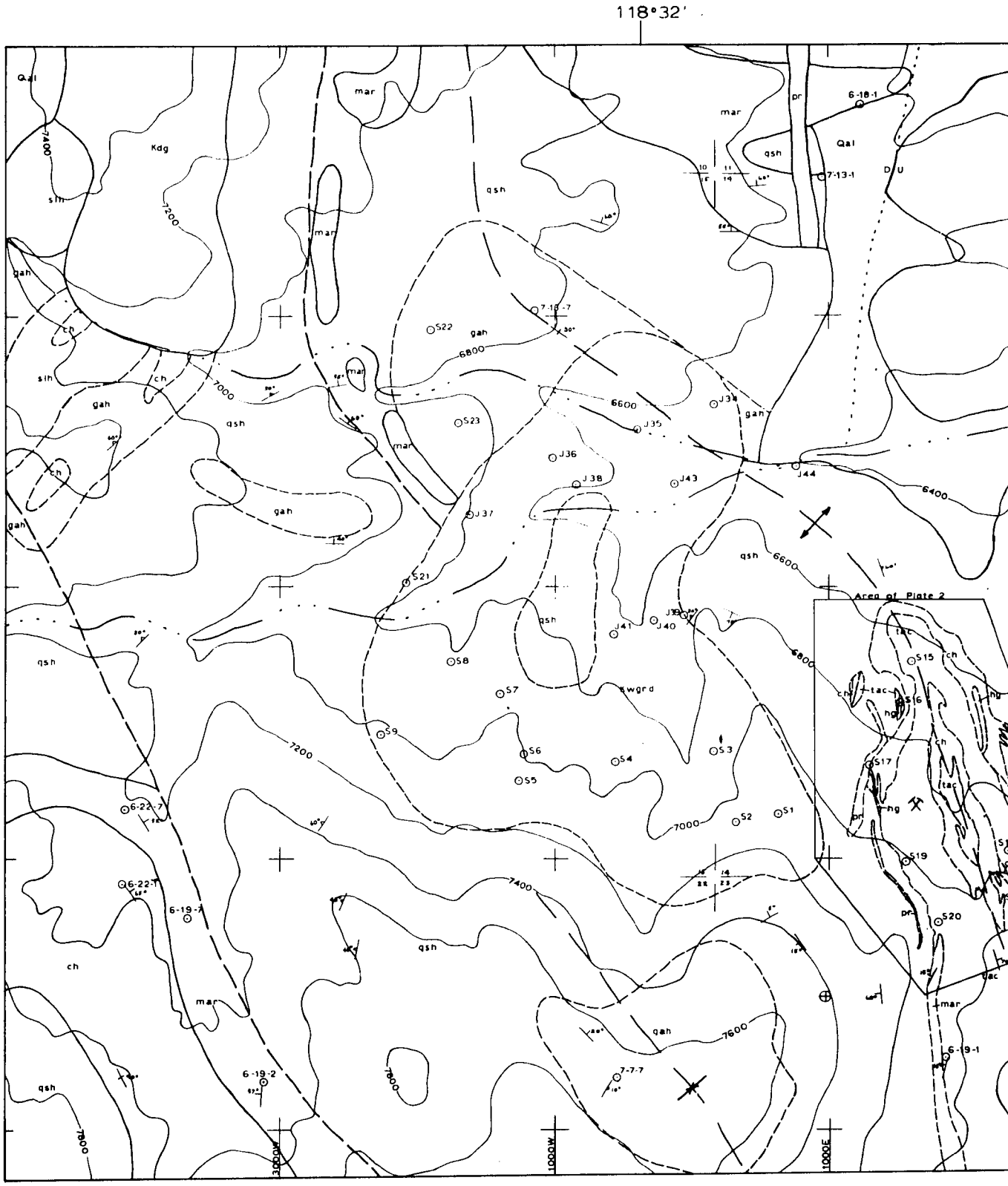
PLATE 1. GEOLOGIC MAP OF A PORTION OF THE CASA DIABLO QUADRANGLE IN THE VICINITY OF THE BLA



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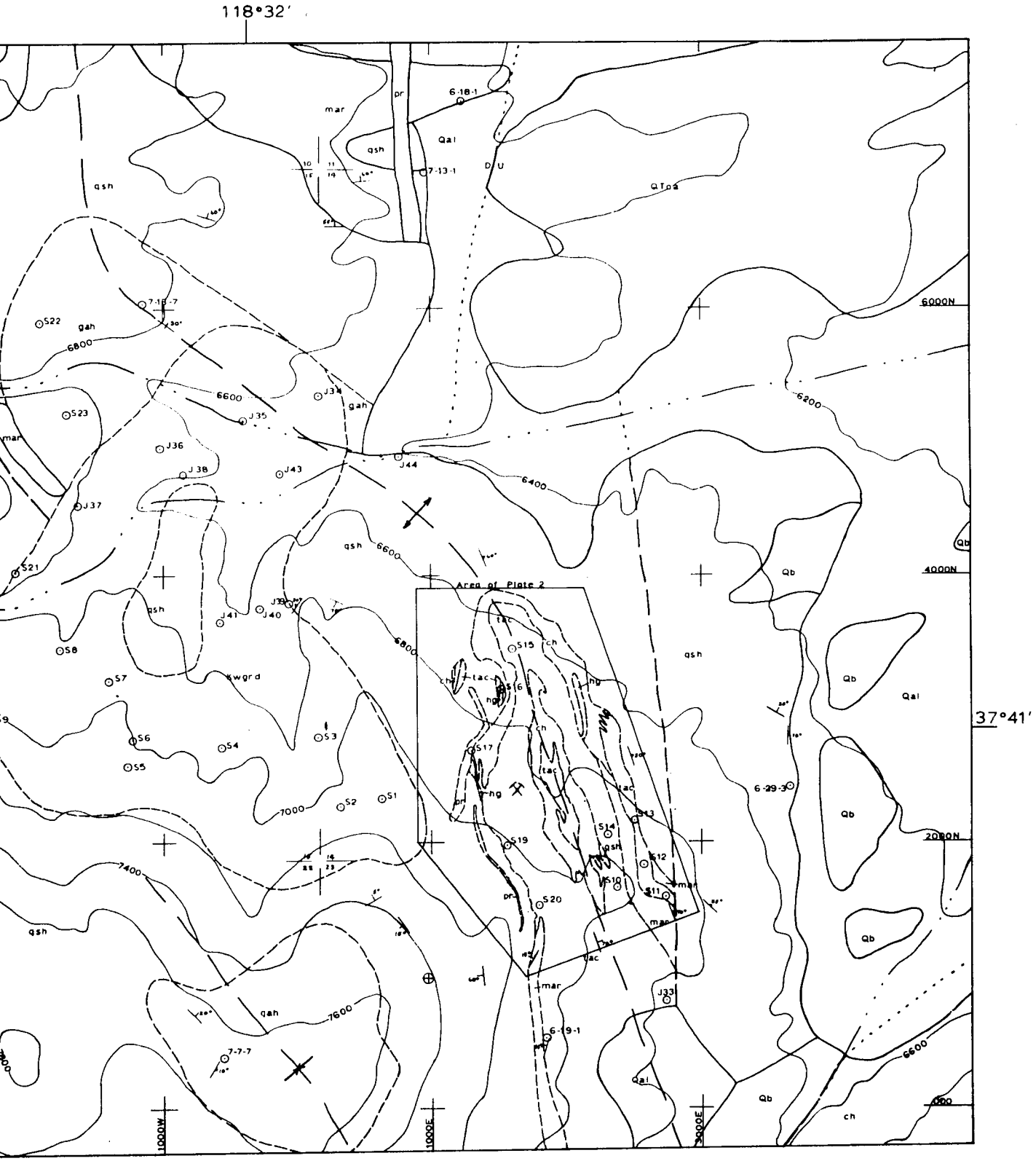
' THE CASA DIABLO QUADRANGLE IN THE VICINITY OF THE BLACK ROCK MINE.



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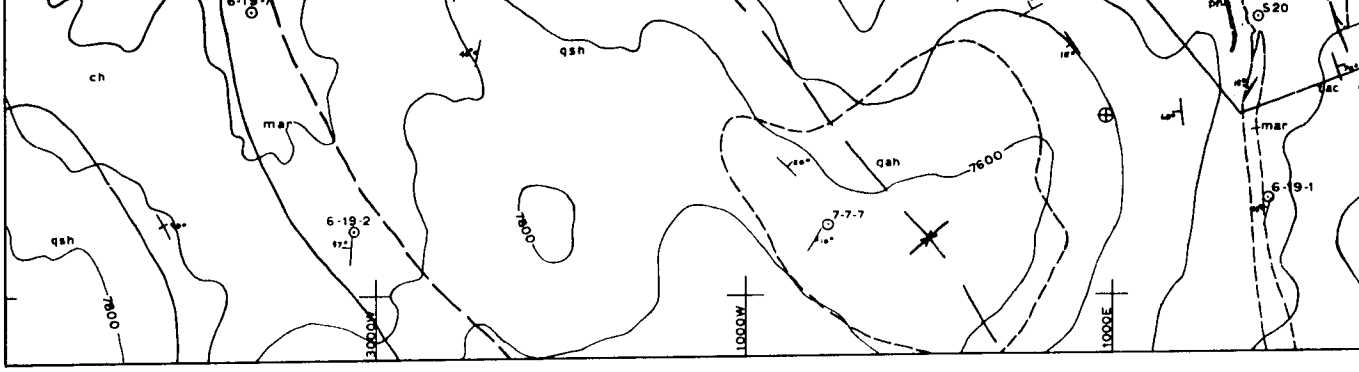

0 1000 2000 3000 ft.

Scale 1:12000

200 ft. contours shown

EXPLANATION

QUATERNARY

Qal Alluvium- Valley fill, slope wash.

Qb Bishop tuff- Rhyolitic ignimbrite, in part welded.

Qtoa Older alluvium- Older alluvium on dissected, east-sloping pediment surface.

MESOZOIC

hg Hornblende gabbro- Porphyritic dike rock consisting of phenocrysts of hornblende and plagioclase in fine-grained groundmass.

Kdg Diorite-gabbro- Medium- to coarse-grained rock composed predominantly of calcic plagioclase and hornblende.

pr Porphyritic rhyolite- Consists of well-formed phenocrysts of quartz, microcline, and sodic plagioclase in a dense groundmass of gramular to micropegmatitic quartz and potash feldspar.

Kwgrd Quartz monzonite phase of the granodiorite of the Benton Range- Medium- to coarse-grained, commonly porphyritic rock, prominent biotite.

PALEOZOIC(?)

tac Tactite- Fine- to coars grained, locally vuggy, brown to dark-green roc sisting of varied amoun garnet, pyroxene, amphi epidote, and lesser amo other minerals.

mar Marble- Fine-grained, c well-layered, gray, pur marble, with minor lens hornfels and tactite.

ch Calc-hornfels- Predomin fine-grained, gray to g hornfels composed chief amounts of pyroxene, ep clinozoisite, amphibole plagioclase, garnet, ve and wollastonite.

qsh Quartz-sericite hornfel Fine-grained, gray, tan brown spotted hornfels sericite, biotite, anda quartz, and plagioclase

gah Graphite-andalusite hor Fine-grained dark-gray hornfels composed of qu sericite, graphite, and lusite.

slh Siliceous hornfels- Fin grained, dark-brown to hornfels containing chi and plagioclase with mi of sericite, biotite, a

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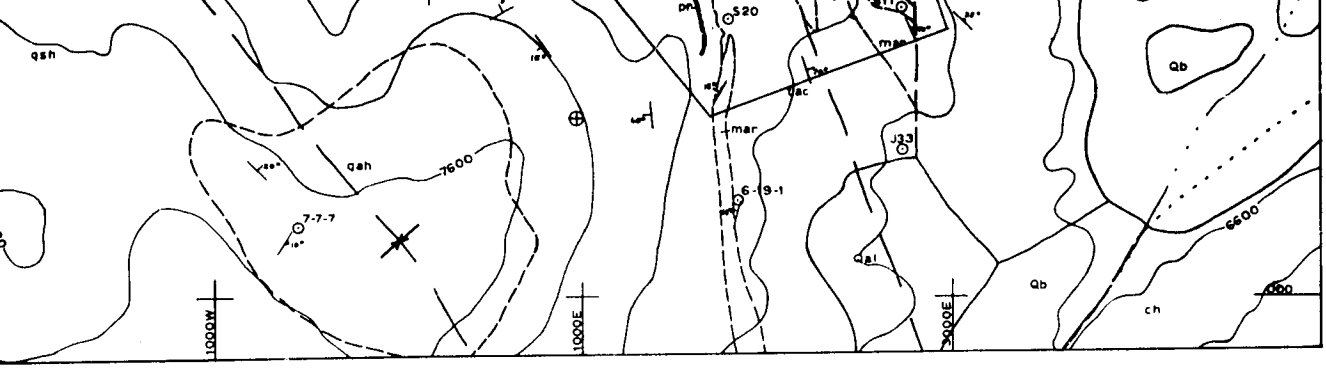

0 1000 2000 3000 ft.

Scale 1:12000
200 ft. contours shown

N 17°

EXPLANATION

PALEOZOIC(?)

alley fill,

- Rhyolitic ignim-
art welded.

ium- Older allu-
sected, east-
iment surface.

gabbro- Porphyritic
consisting of pheno-
ornblende and plagio-
ne-grained groundmass.

bro- Medium- to
ned rock composed
ly of calcic plagio-
ornblende.

rhyolite- Consists
med phenocrysts of
rocline, and sodic
in a dense ground-
nular to micropegma-
z and potash feldspar.

onite phase of the
e of the Benton Range-
coarse-grained, commonly
rock, prominent bio-

tac	Tactite- Fine- to coarse-grained, locally vuggy, red-brown to dark-green rock consisting of varied amounts of garnet, pyroxene, amphibole, epidote, and lesser amounts of other minerals.
mar	Marble- Fine-grained, commonly well-layered, gray, pure calcite marble, with minor lenses of calc-hornfels and tactite.
ch	Calc-hornfels- Predominantly fine-grained, gray to green calc-hornfels composed chiefly of varied amounts of pyroxene, epidote-clinozoisite, amphibole, quartz, plagioclase, garnet, vesuvianite, and wollastonite.
qsh	Quartz-sericite hornfels- Fine-grained, gray, tan, to red-brown spotted hornfels containing sericite, biotite, andalusite, quartz, and plagioclase.
gah	Graphite-andalusite hornfels- Fine-grained dark-gray to black hornfels composed of quartz, sericite, graphite, and andalusite.
slh	Siliceous hornfels- Fine-grained, dark-brown to dark-gray hornfels containing chiefly quartz and plagioclase with minor amounts of sericite, biotite, and chlorite.

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QUATERNARY

Qal — Alluvium- Valley fill, slope wash.

Qb — Bishop tuff- Rhyolitic ignimbrite, in part welded.

Qtoa — Older alluvium- Older alluvium on dissected, east-sloping pediment surface.

MESOZOIC

hg — Hornblende gabbro- Porphyritic dike rock consisting of phenocrysts of hornblende and plagioclase in fine-grained groundmass.

Kdg — Diorite-gabbro- Medium- to coarse-grained rock composed predominantly of calcic plagioclase and hornblende.

pr — Porphyritic rhyolite- Consists of well-formed phenocrysts of quartz, microcline, and sodic plagioclase in a dense groundmass of granular to micropegmatitic quartz and potash feldspar.

Kwgrd — Quartz monzonite phase of the granodiorite of the Benton Range- Medium- to coarse-grained, commonly porphyritic rock, prominent biotite.

PALEOZOIC(?)

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ch — Calc-hornfels- Predominan fine-grained, gray to gre hornfels composed chiefly amounts of pyroxene, epid clinozoisite, amphibole, plagioclase, garnet, vesu and wollastonite.

qsh — Quartz-sericite hornfels- Fine-grained, gray, tan, brown spotted hornfels co sericite, biotite, andalu quartz, and plagioclase.

gah — Graphite-andalusite hornf Fine-grained dark-gray to hornfels composed of quar sericite, graphite, and a lusite.

slh — Siliceous hornfels- Fine-grained, dark-brown to da hornfels containing chief and plagioclase with minc of sericite, biotite, and

SYMBOLS

Contact
Dashed where approximately located.

Fault
Dashed where approximately located; dotted where concealed; U, upthrown side; D, downthrown side.

Probable anticline or syncline.

Strike and dip of bedding.

Strike and dip of schistosity.

Sample location of surface samp for this study; red for type I zonite, blue for type II quartz open circles for remainder of

(Geology compiled from Rinehart 1956, 1957; modified by Elliott descriptions from Rinehart and

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PALEOZOIC(?)

lley fill,

Rhyolitic ignim-
rt welded.

m- Older allu-
ected, east-
ent surface.

abbro- Porphyritic
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rnblende and plagio-
e-grained groundmass.

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ately located.

ately located; dotted
pthrown side; D, down-

syncline.

20 — Strike and dip of bedding.

10 — Strike and dip of schistosity.

⊙ ⊙ ⊙ Sample location of surface samples collected for this study; red for type I quartz monzonite, blue for type II quartz monzonite, open circles for remainder of samples.

(Geology compiled from Rinehart and Ross; 1956, 1957; modified by Elliott. Rock descriptions from Rinehart and Ross, 1957)

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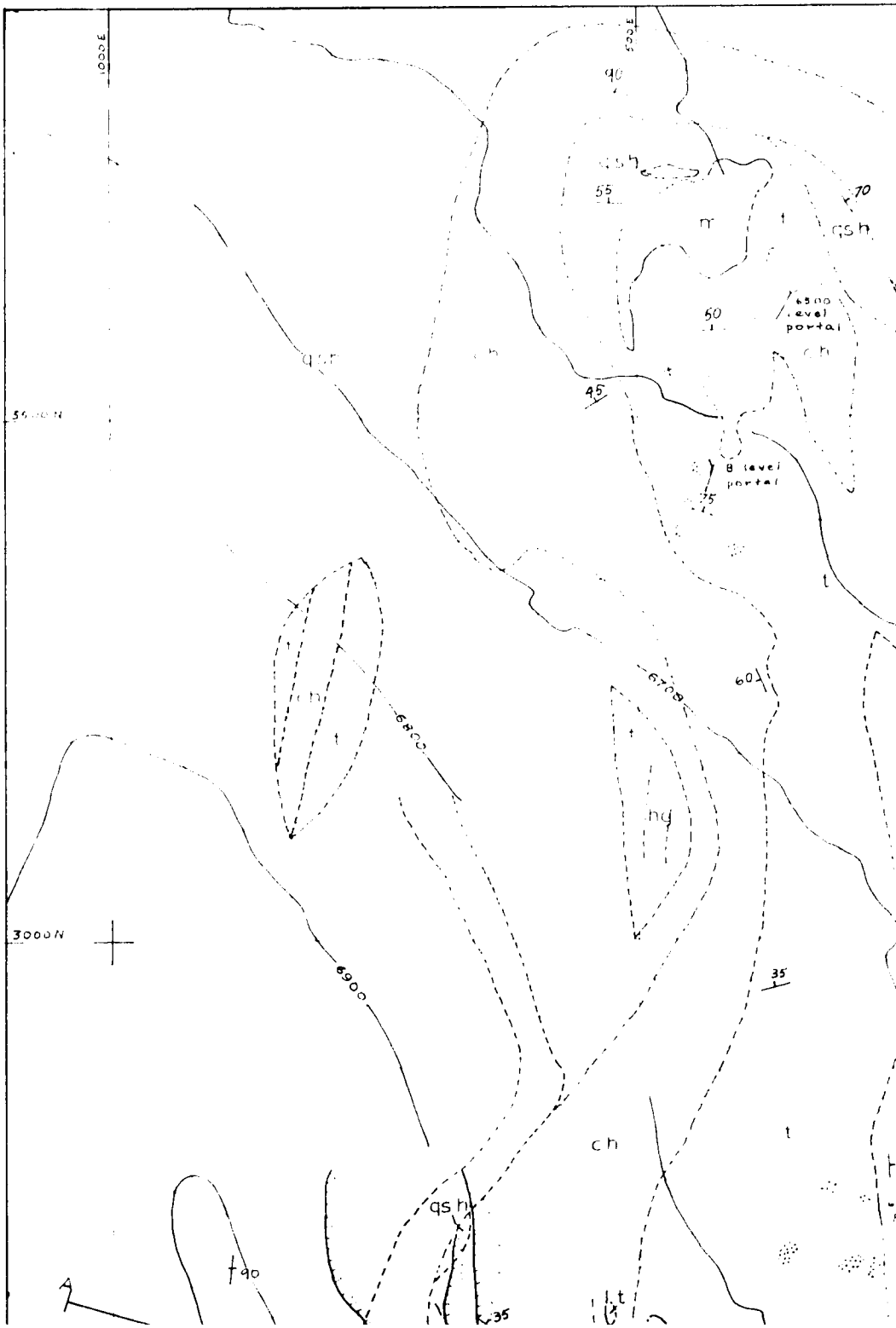
PLATE 2. GEOLOGIC MAP OF THE BLACK ROCK MINE, MONO COUNTY, C
(from Rinehart and Ross, 1956).



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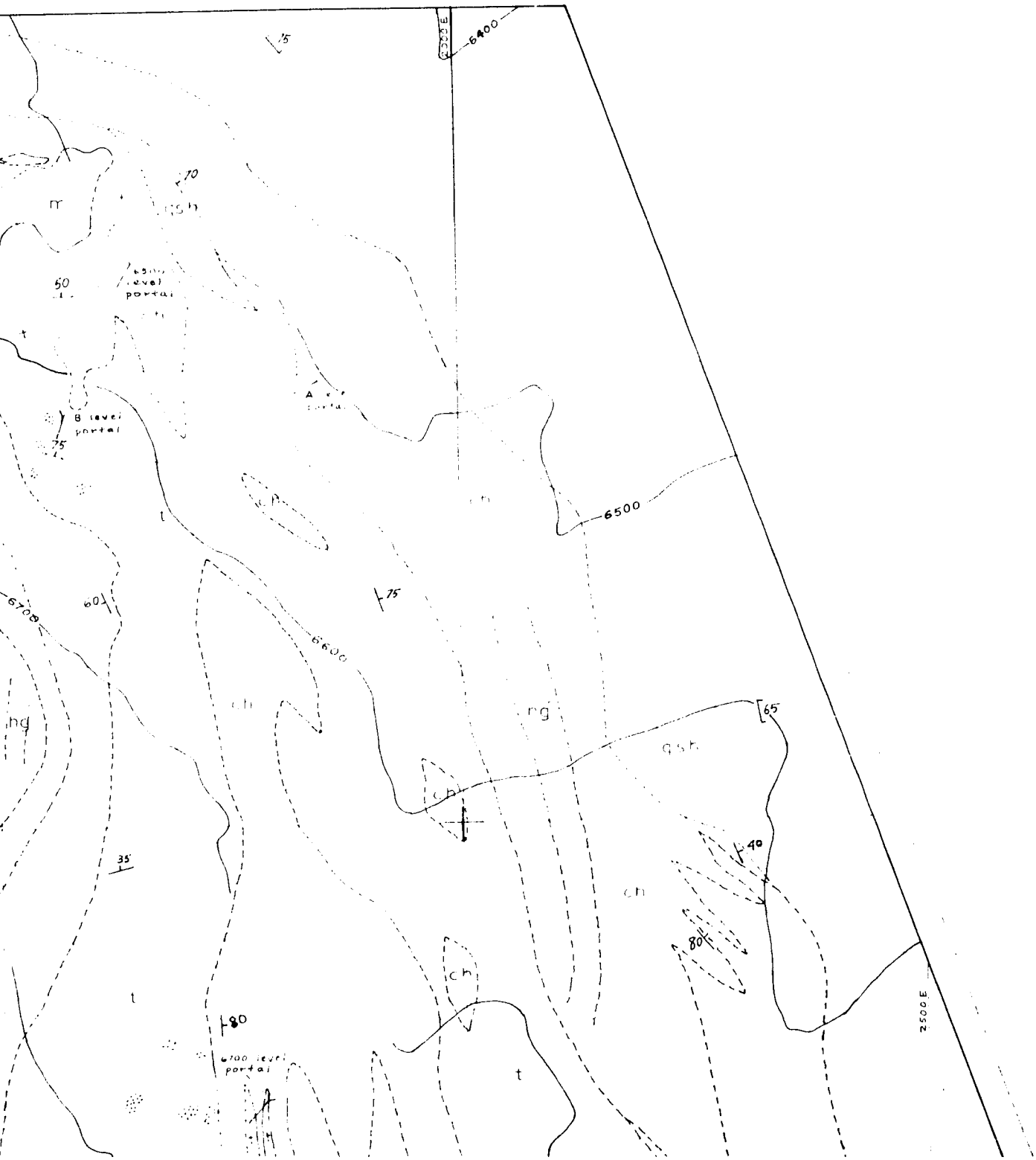
NE, MONO COUNTY, CALIFORNIA



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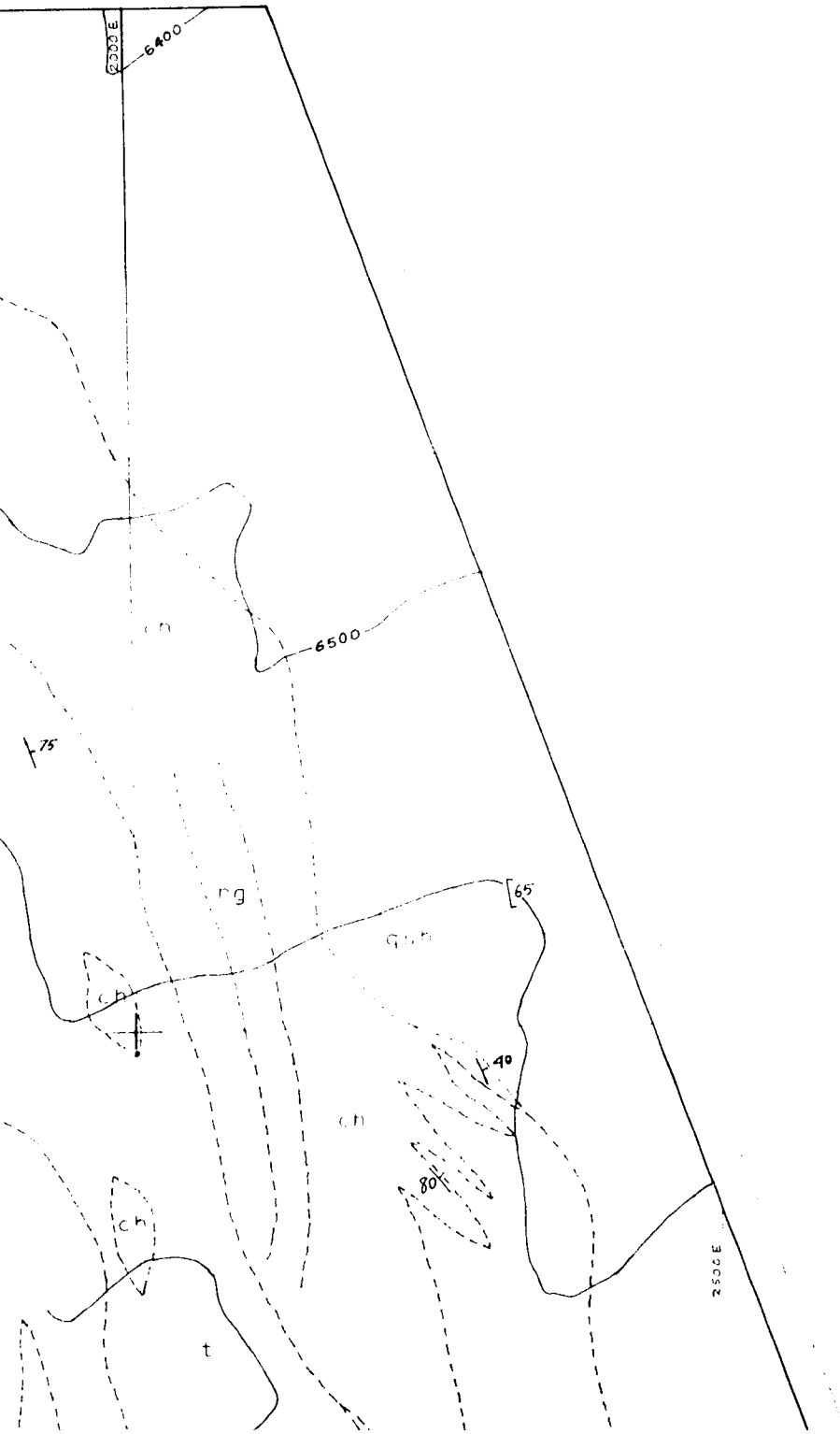

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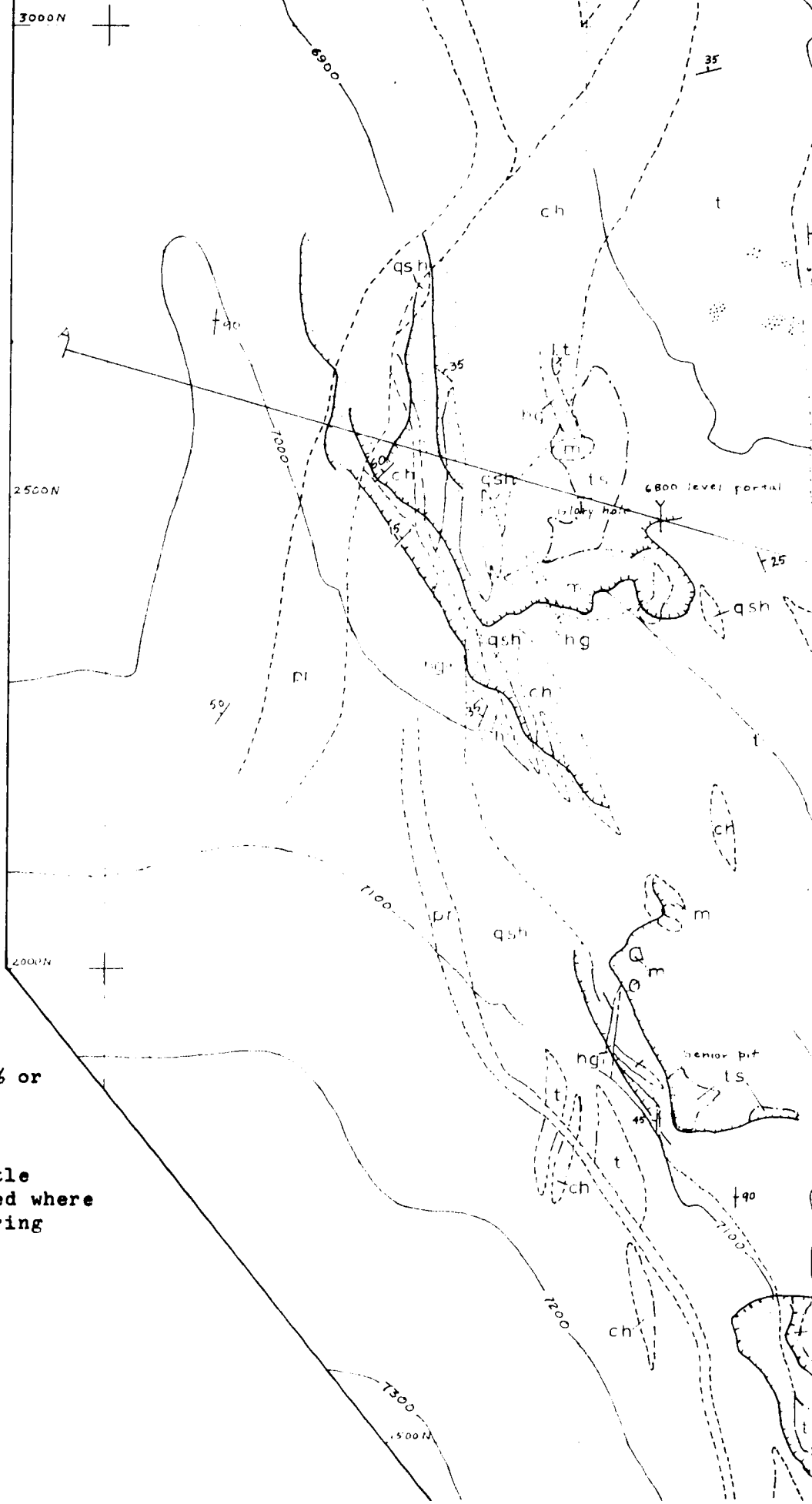

EXPLANATION

ts

Tactite- contains 0.5% or more scheelite

t

Tactite- contains little or no scheelite; dotted where locally scheelite-bearing

pr

Porphyritic rhyolite

hg

Hornblende gabbro

ch

Calc-hornfels

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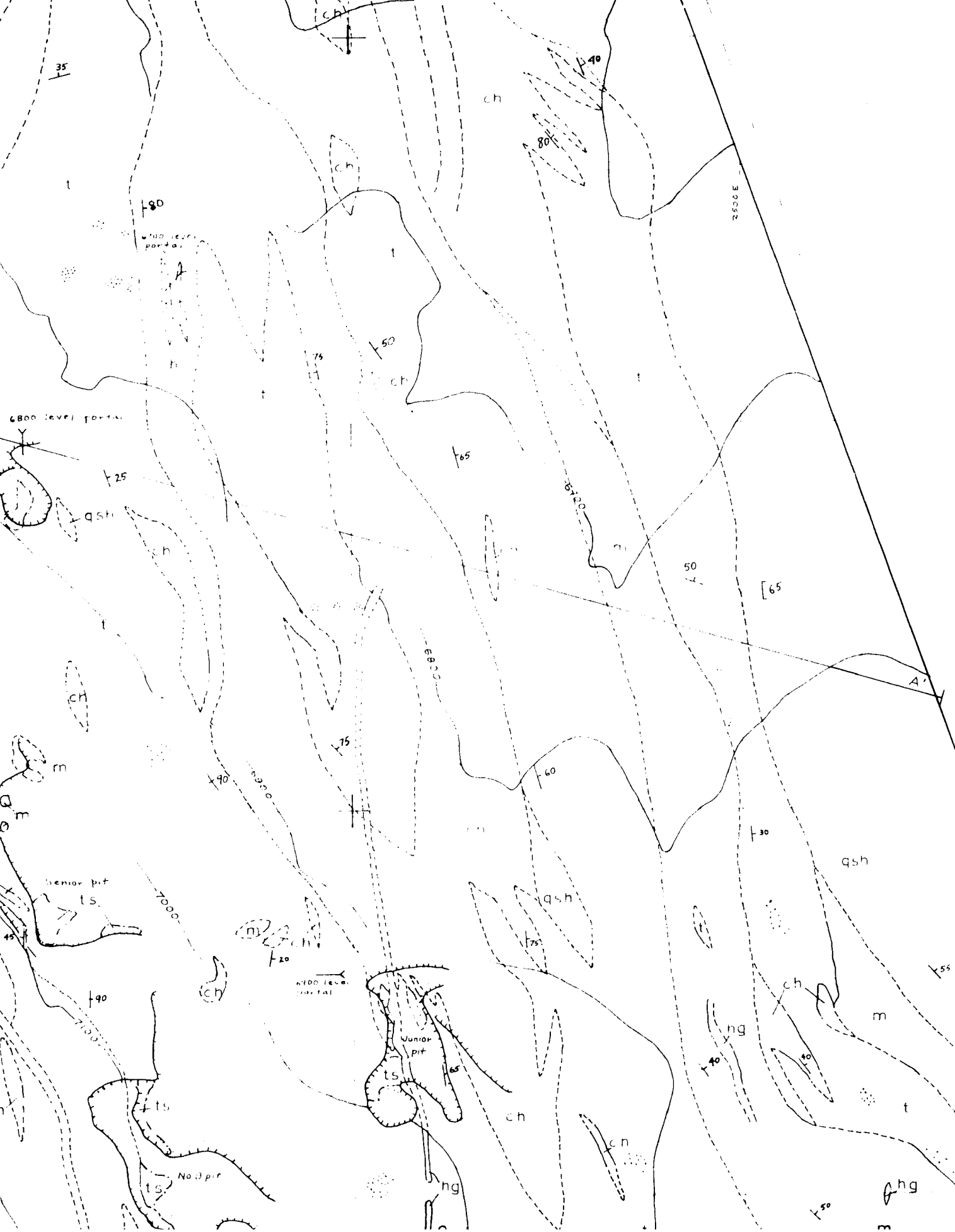

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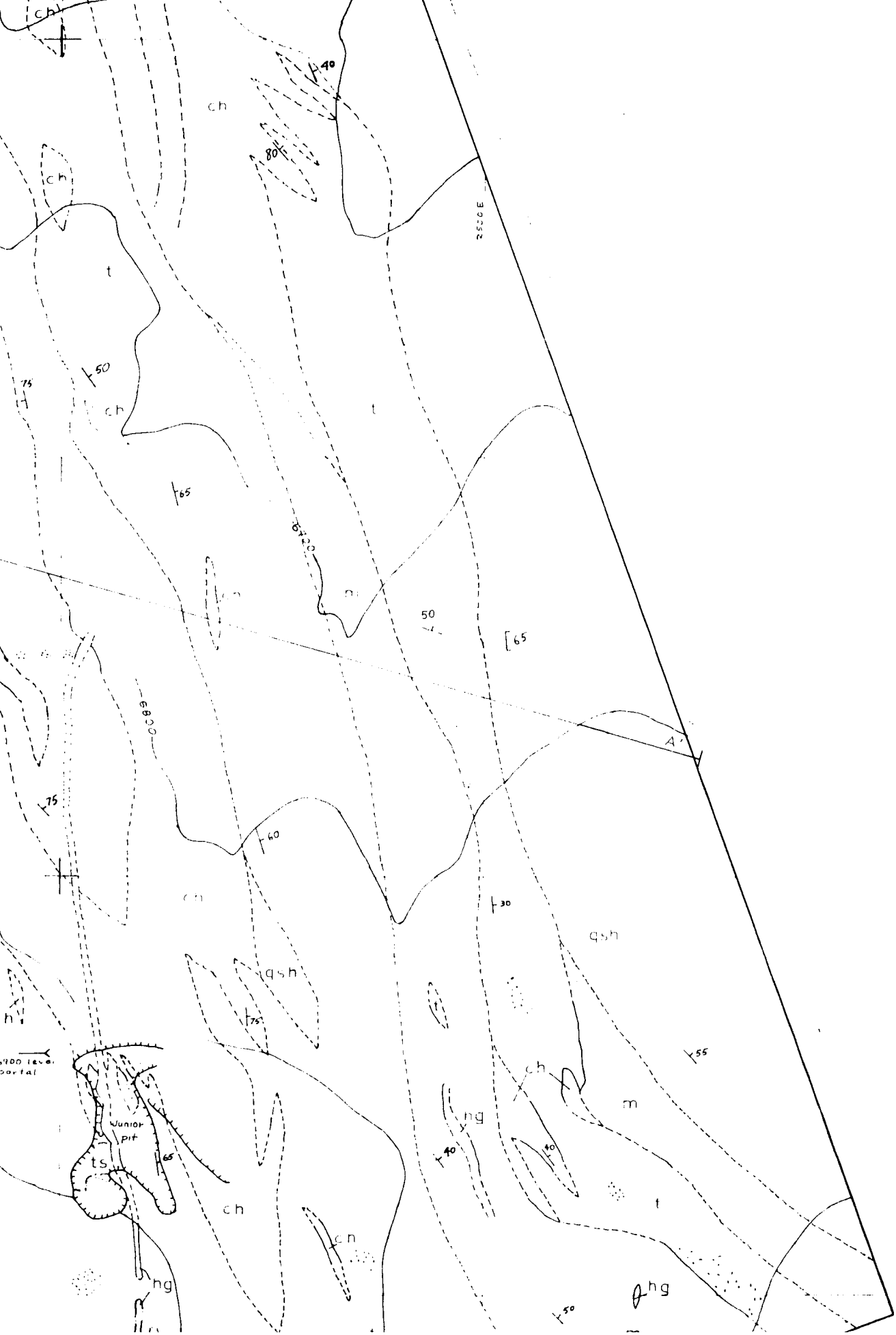

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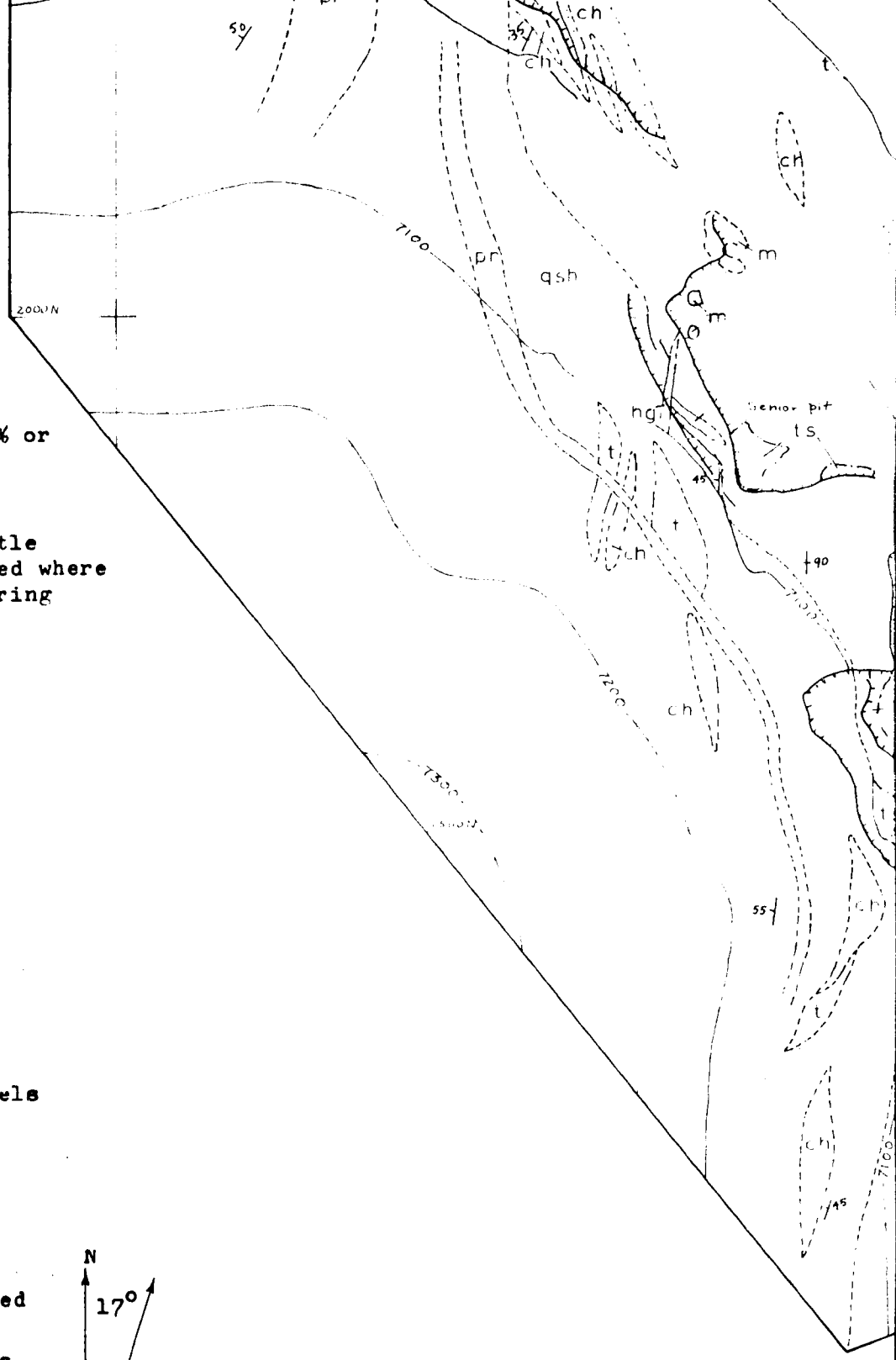

EXPLANATION

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t

Tactite- contains little or no scheelite; dotted where locally scheelite-bearing

pr

Porphyritic rhyolite

hg

Hornblende gabbro

ch

Calc-hornfels

m

Marble

qsh

Quartz-sericite hornfels

SYMBOLS

Contact, dashed where approximate or inferred

60°

Strike and dip of beds

Top Bottom

Surface pit or open cut

Portal of adit

N

17°

0 150 300 ft.

Scale 1:1800

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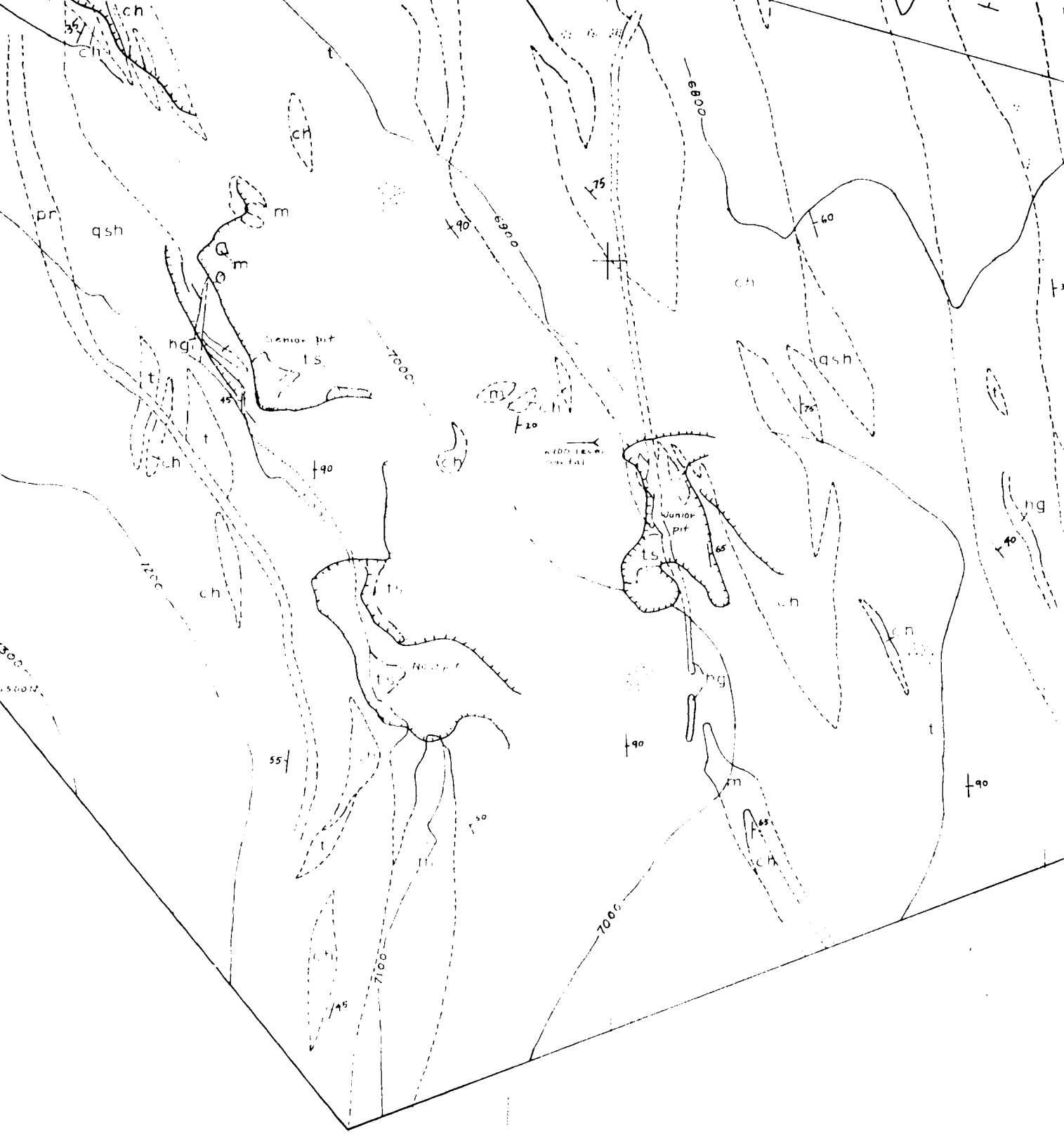

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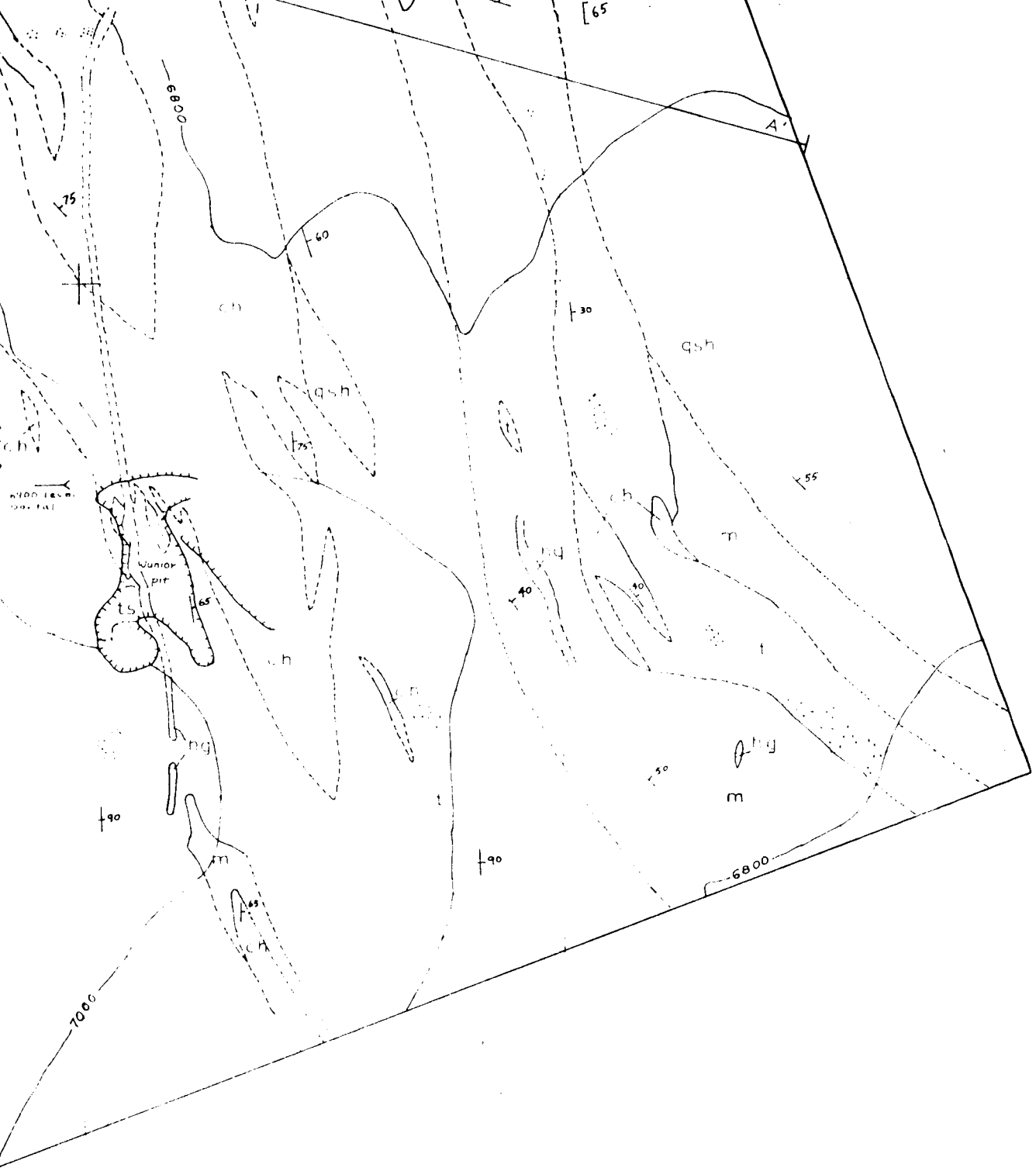

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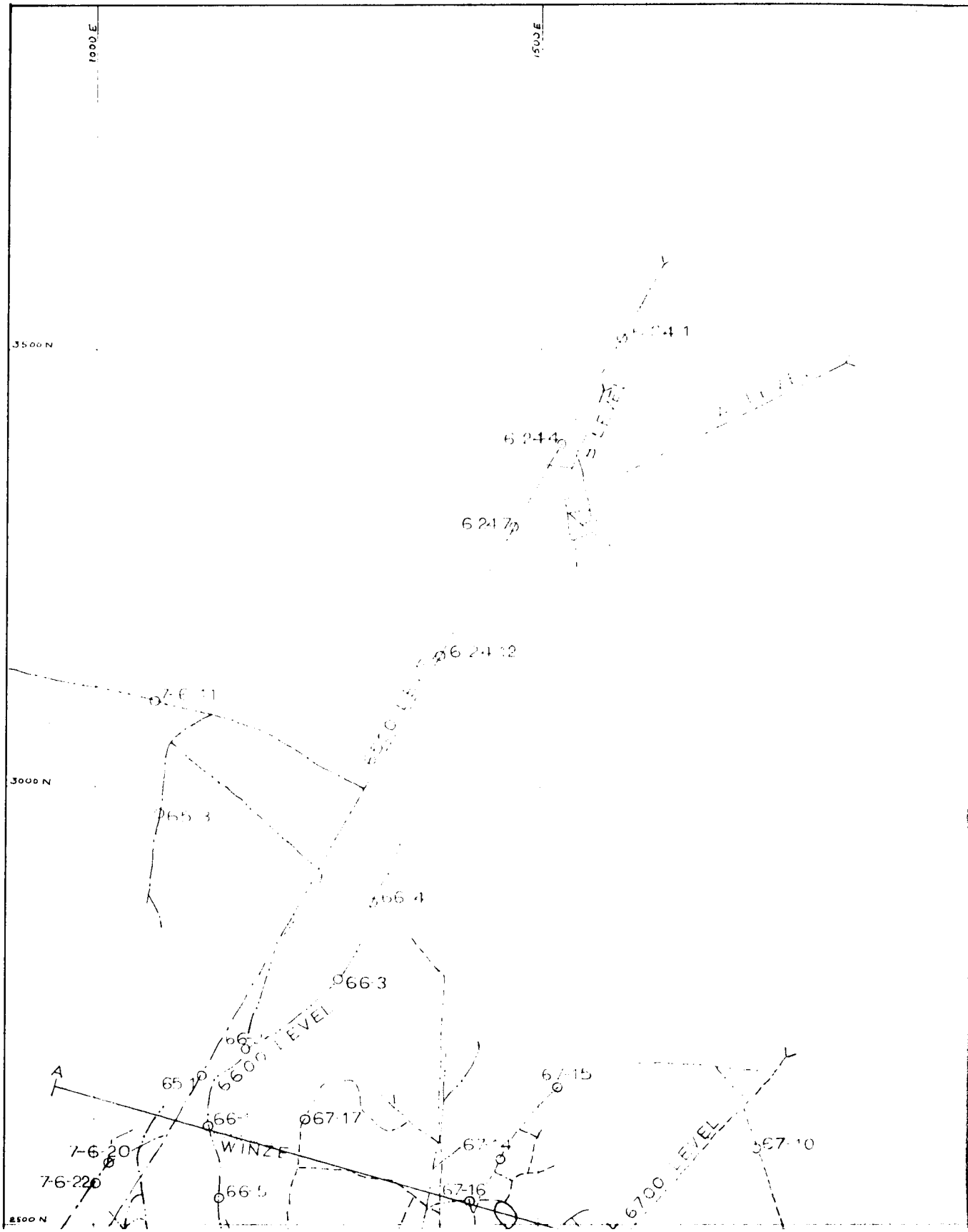
PLATE 3. COMPOSITE PLAN MAP OF UNDERGROUND WORKINGS AND SAMPLE LOCATIONS (underground workings compiled from base maps supplied by Union Carbide Corporation)



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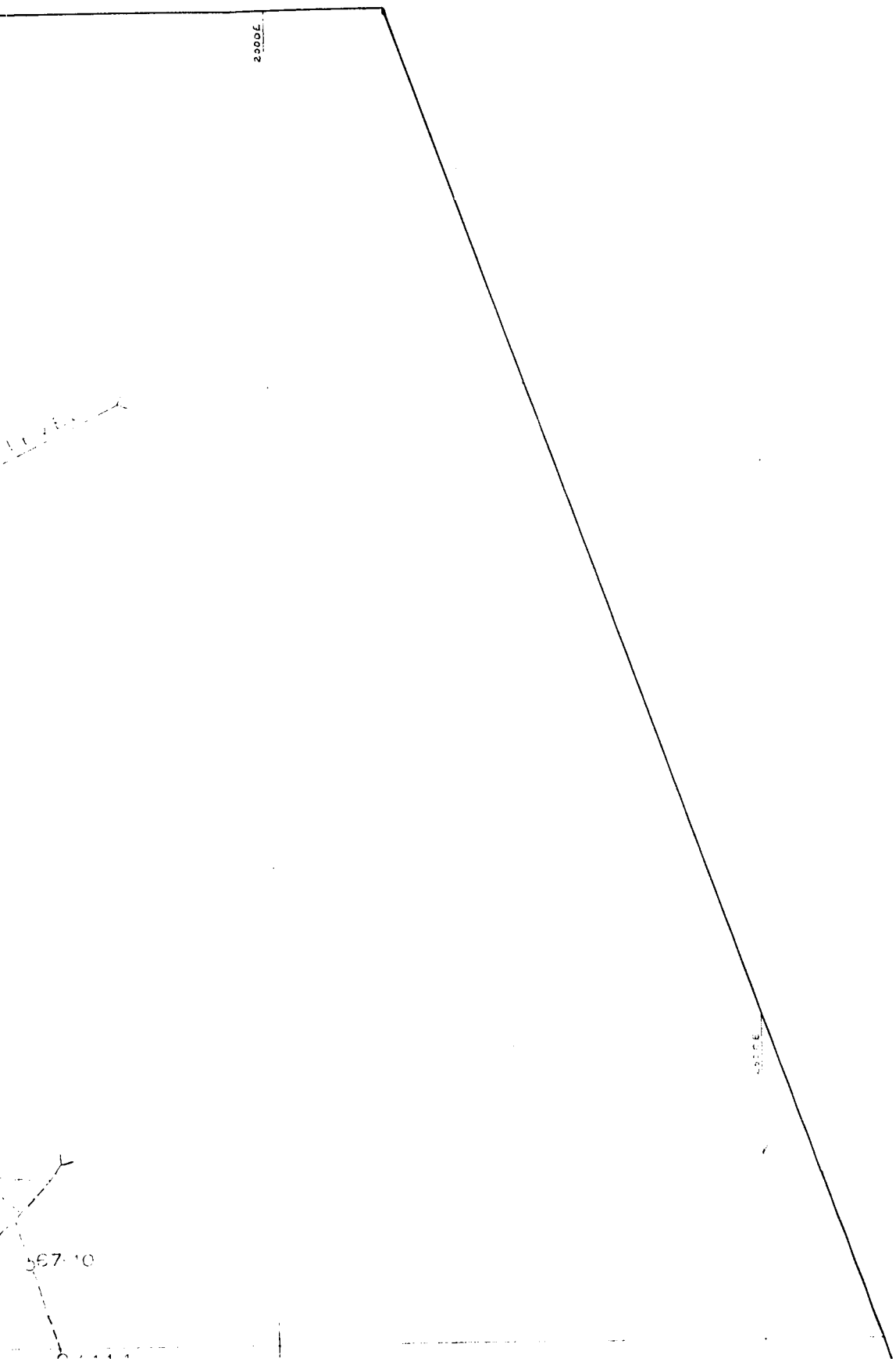
ND SAMPLE LOCATIONS
s supplied by Union



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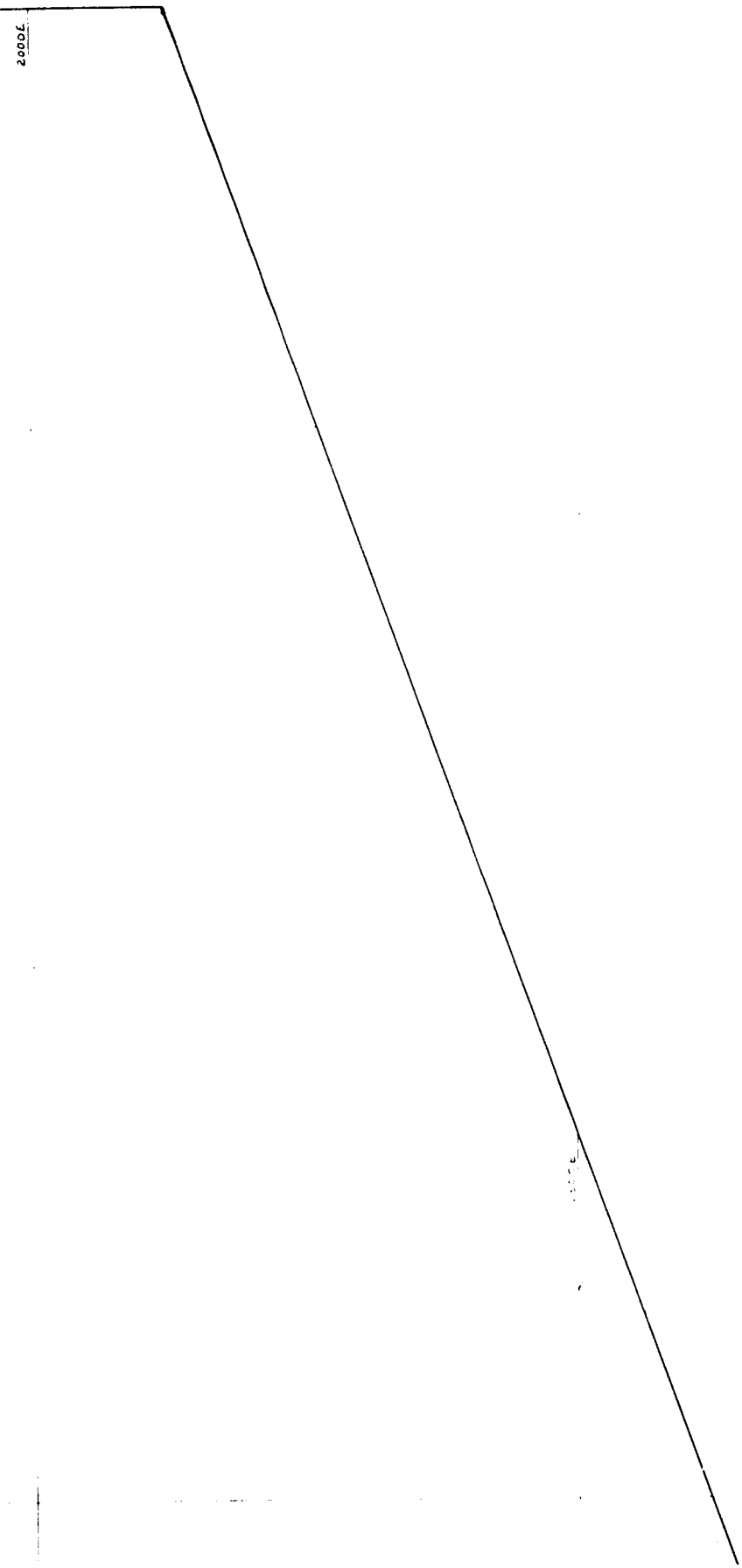

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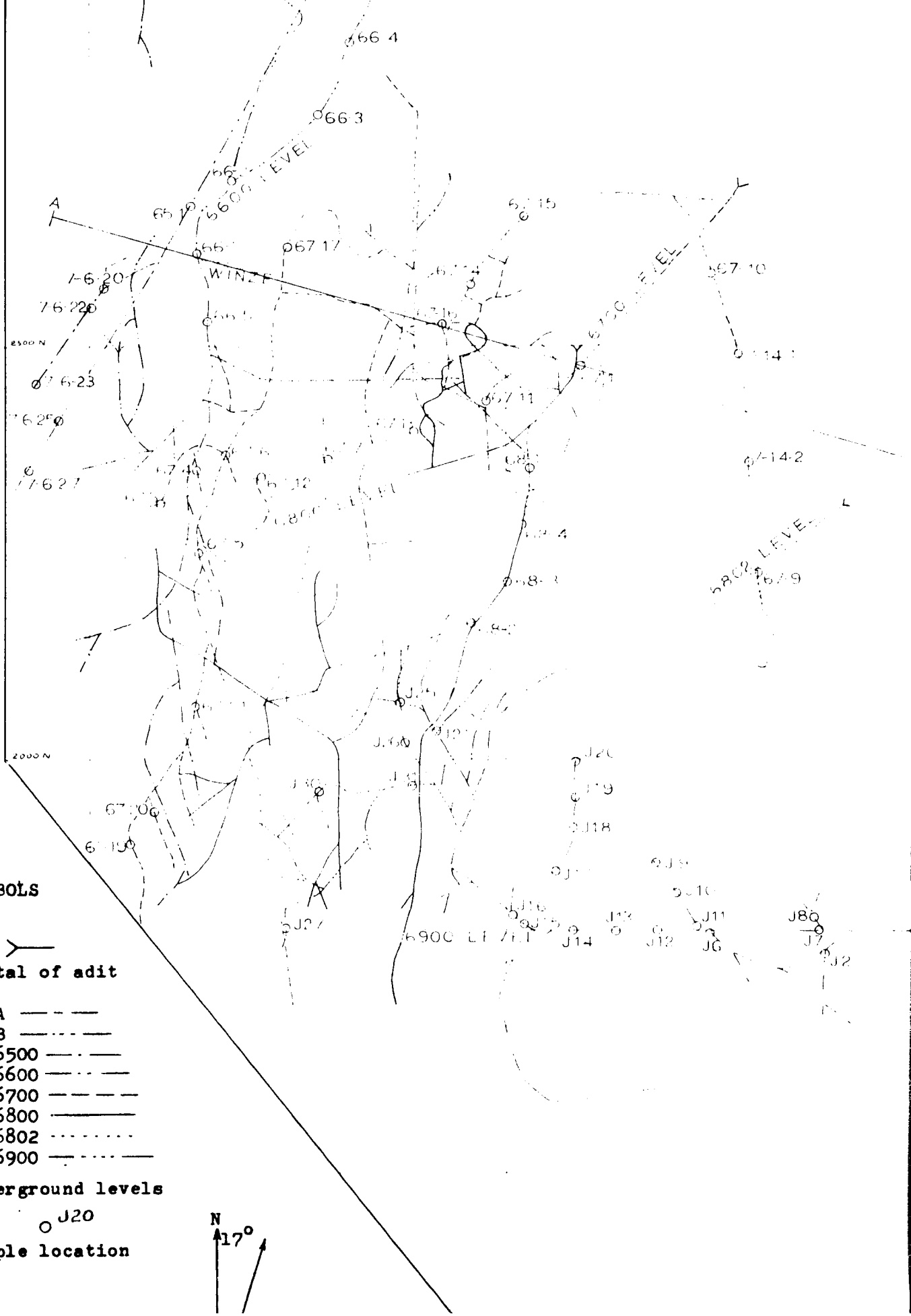

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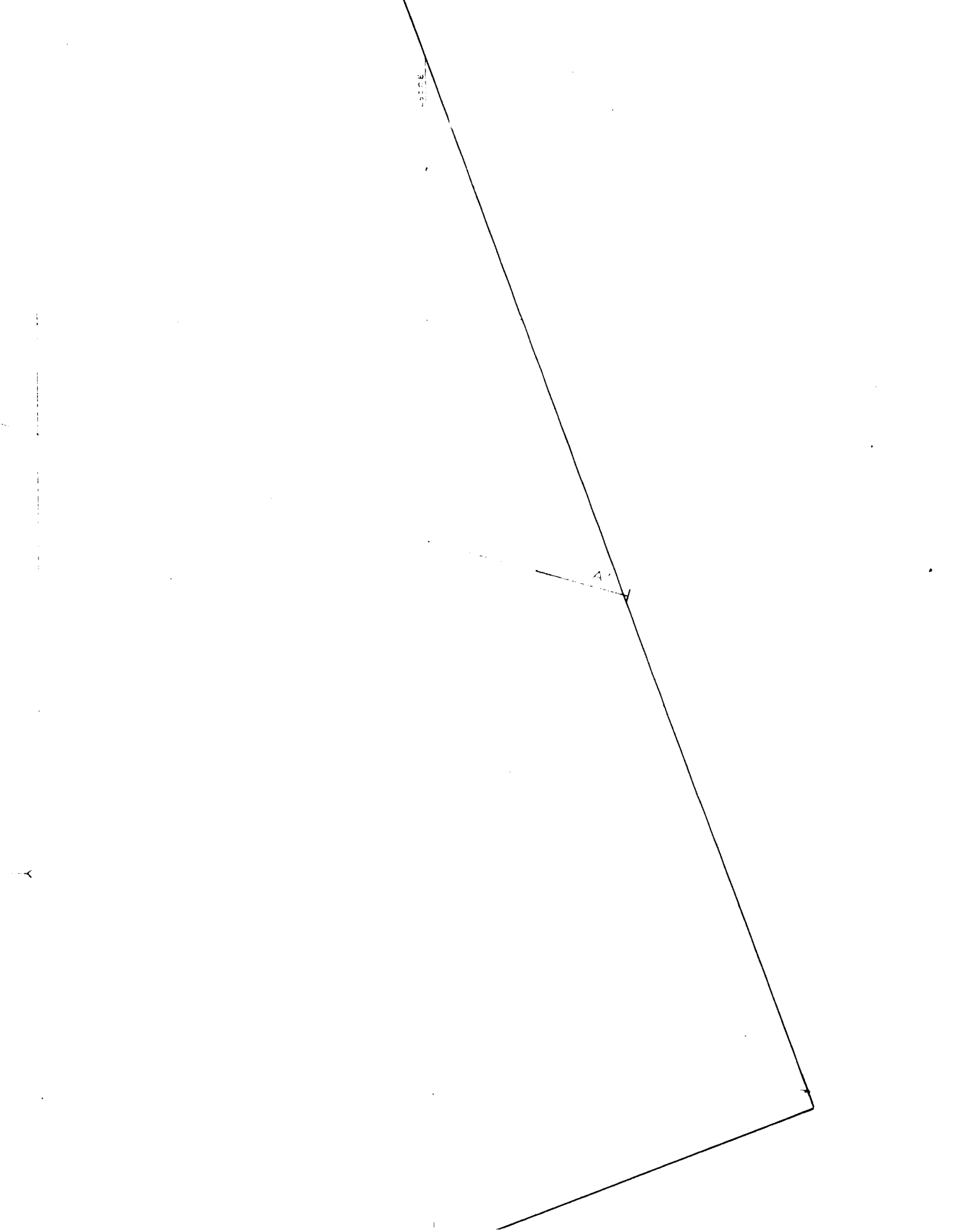

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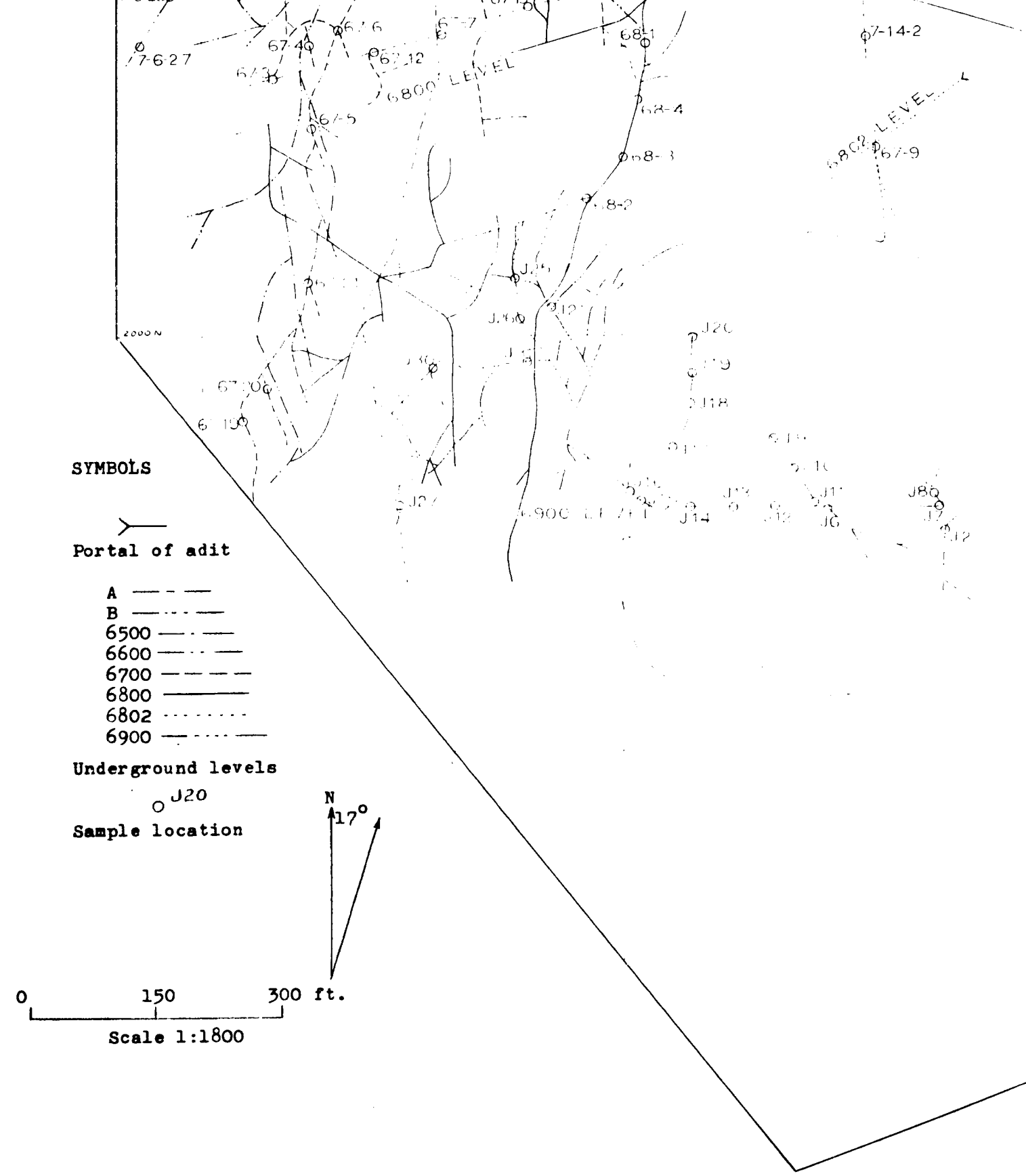

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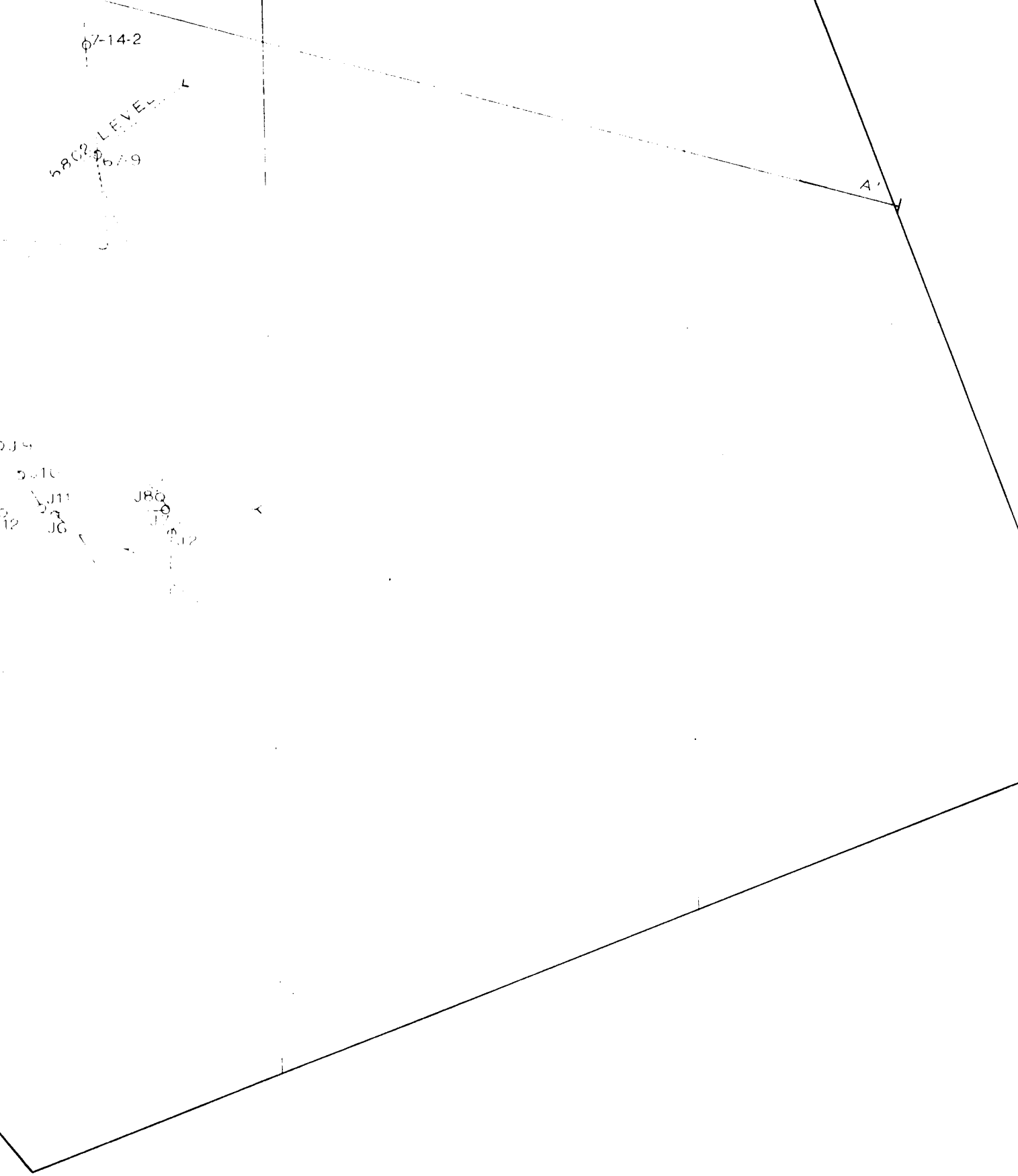

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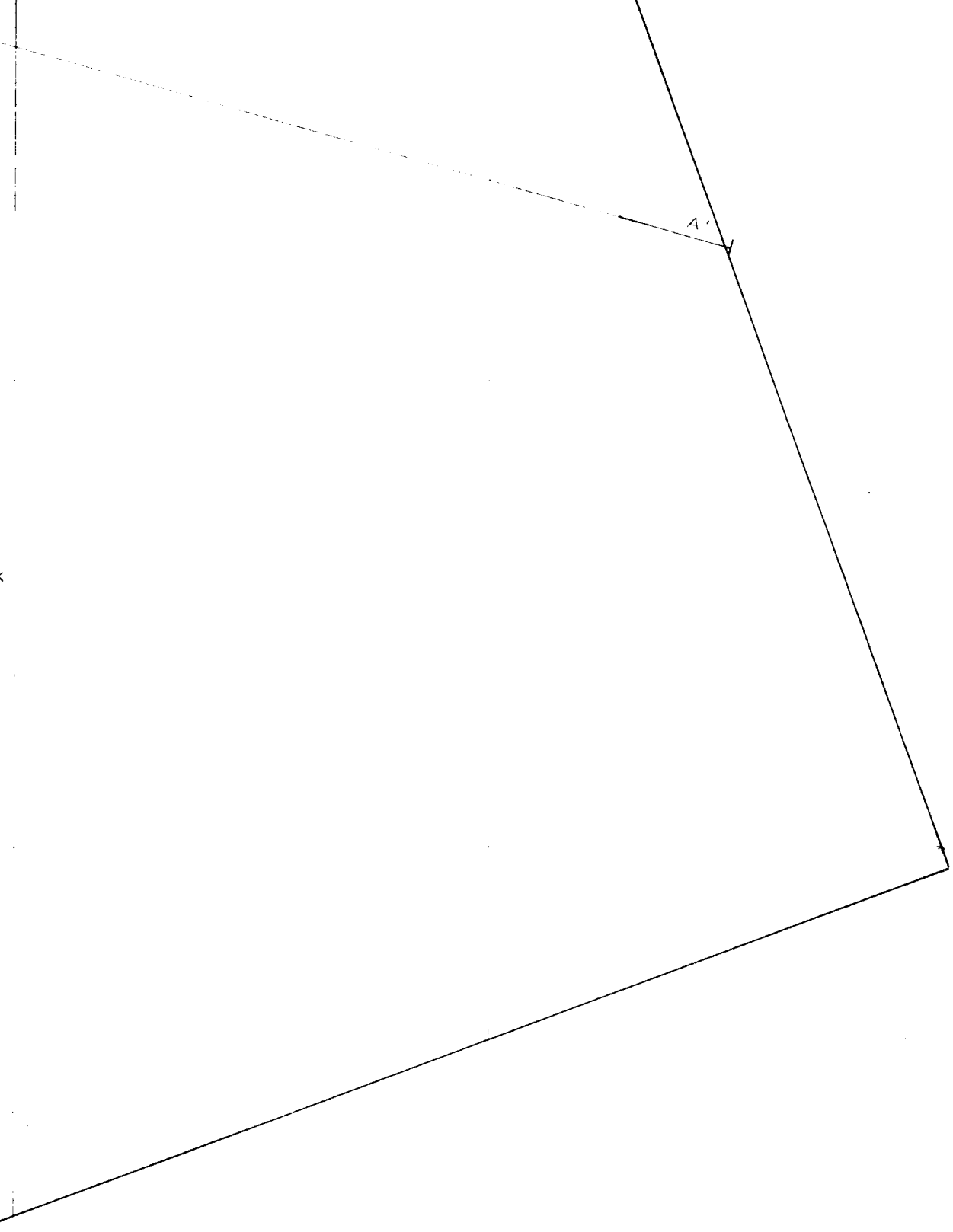

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PLATE 4. GEOLOGIC SECTION ALONG A-A' (
(from Rinehart and Ross, 1956

EXPLANATION

Rock and soil cover

ts
Tactite
contains scheelite

t
Tactite
contains little or no scheelite

pr
Porphyritic rhyolite

hg
Hornblende gabbro

ch
Calc-hornfels

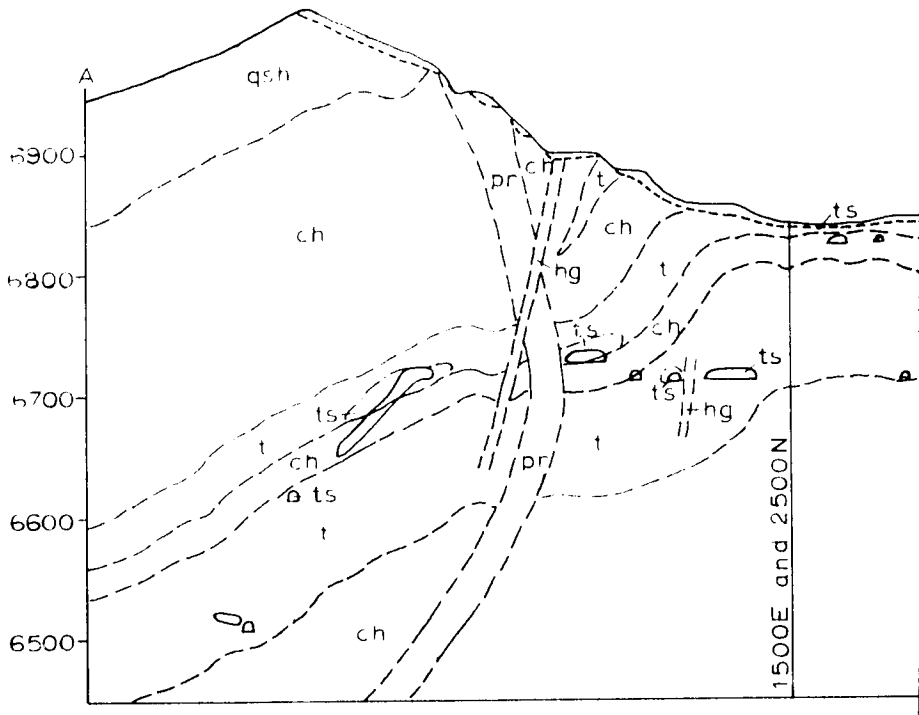
m
Marble

qsh
Quartz-sericite hornfels

SYMBOLS

Contact, dashed where approximate or inferred

Mine Workings



0 150 300 ft.
Scale 1:1800

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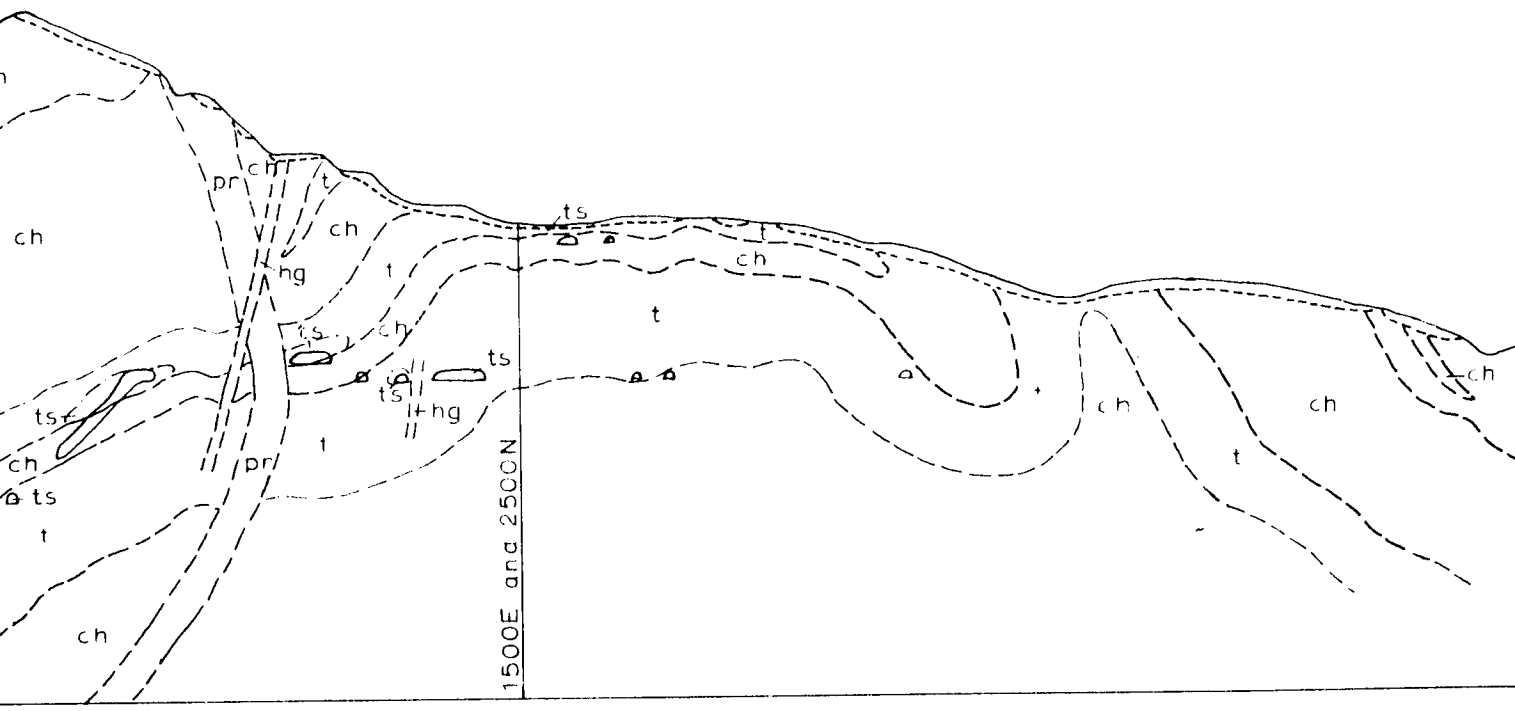
LATE 4. GEOLOGIC SECTION ALONG A-A' (pl. 2), BLACK ROCK MINE.
(from Rinehart and Ross, 1956)



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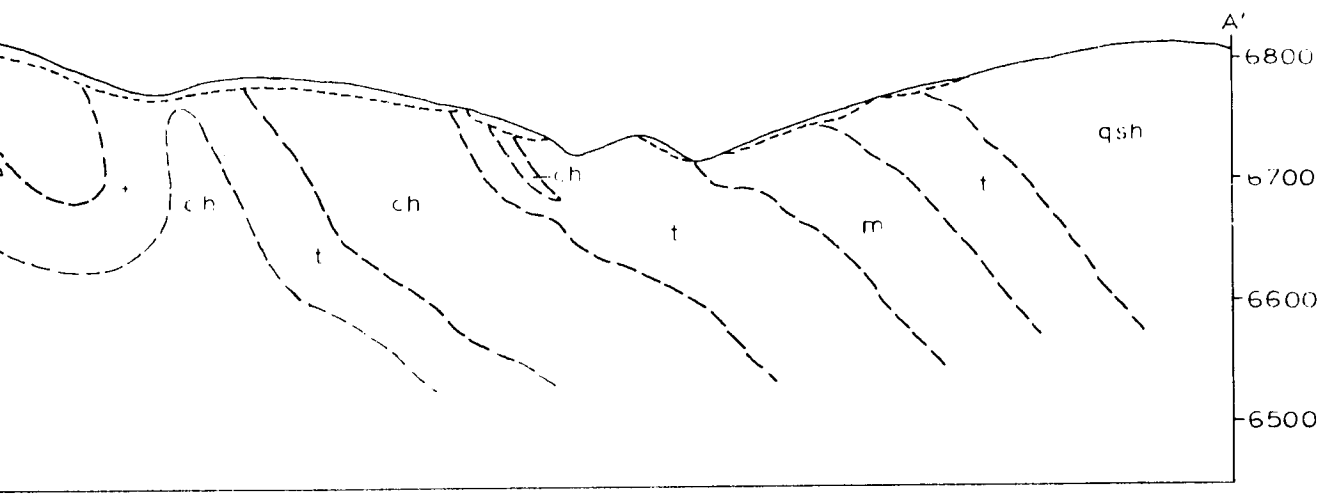
OCK MINE.



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