scarce in some places and plentiful in others. Its groundmass is commonly rather fine-grained. The dikes in the Climax area have abundant, conspicuous quartz phenocrysts and are very light gray except in their chilled margins, which in places are dark gray. Large feldspar phenocrysts are less plentiful than in the type locality and are absent from some dikes. The essential constituents are quartz, orthoclase, and plagioclase. The chief accessory mineral is biotite, which is almost everywhere present. Magnetite is also very common, and a few grains of apatite and titanite are generally present. Sericite is a common alteration product.

The proportions of quartz, feldspar, and biotite vary from place to place, and the dikes accordingly range in composition from quartz diorite to granite. The central portion of some, if not of all of the dikes is more alkaline and siliceous than the margin. Examination of thin sections shows a change in one dike from quartz diorite at the margin to quartz monzonite at the center. A second dike is quartz monzonitic at the margin and granitic at the center. The biotite and magnetite contents are about uniform in distribution, but the size of the biotite flakes increases from the margin to the center.

The relative age of the dikes is shown in only one place, where a diorite dike is cut by a dike of quartz monzonite porphyry. This age relationship is the same as that recorded in the Leadville district.

Sills.—The sills in the sedimentary rocks are mostly quartz monzonite. Granite sills are also present, but are apparently not as common in the sedimentary rocks as granite dikes are in the pre-Cambrian rocks. The sills are identical in mineral composition and texture with the dikes in the granite, but sericite, so common in the dikes, is not so abundant in the sills. The contacts are too much covered for a satisfactory study of the mineral changes from margin to center, but there appears to be a change similar to that shown by some of the dikes. For this reason the hornblende porphyry, Lincoln porphyry, and rhyolite porphyry west of

Little Bartlett Mountain, which Emmons[23] mapped as three distinct sills, have all been mapped as one sill on Plate I of this paper. The hornblende porphyry appears to be a basal facies grading upward into a middle facies of Lincoln porphyry, which grades into an upper facies of granite porphyry.

The sills in the sedimentaries differ from the dikes in the pre-Cambrian rocks in manner of weathering and in fracturing. The sills weather to a gravel as a result of partial decomposition of the groundmass, but the dikes in the granite break up into large massive or slabby fragments and nowhere weather to a gravel. In some parts of the weathered sills large, unbroken phenocrysts of feldspar and quartz can be picked from the gravel. In other parts, where the sills have been weakened by crushing, the large phenocrysts of feldspar and to some extent those of quartz also crumble when the groundmass disintegrates.

This extremely fractured or crushed condition is not accompanied by detectable displacement, even in thin sections. It is evident in the porphyry for several hundred feet in from the portal of the Phillipson Tunnel. This porphyry appears firm when first blasted out, but on exposure to the air it crumbles to gravel and clay. It has little supporting strength and requires close timbering. The large feldspars and some of the quartz grains appear intact, but they crumble as soon as the matrix gives way.

STRUCTURE

The structural features of the area may be divided into two broad groups—those that originated in pre-Cambrian time and those that have been formed since, mainly after the intrusion of the porphyries in Tertiary time. The pre-Cambrian features, which are only vaguely outlined by the local rocks and can be only imperfectly interpreted from knowledge of surrounding areas, have not been very influential in the localization of the molybdenum deposit and are therefore

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[23] Emmons, S. F., U. S. Geol. Survey Geol. Atlas, Tenmile folio (No. 48), 1898.

given no further attention. Any structural features developed between pre-Cambrian and Tertiary time are also little known and negligible in a practical sense. The outstanding structural features formed in Tertiary time are folds and faults.

FOLDS

The sedimentary rocks west of the Mosquito fault lie in a northward-plunging syncline whose axis, as Emmons[24] has shown, passes through Jacque Mountain, in the Tenmile district. In the vicinity of Climax, some minor folds are present, and the steep dip of the east limb of the main syncline indicates drag along the fault. The axes of the main and minor synclines trend about due north, whereas the Mosquito fault trends 15° to 20° east of north.

FAULTS AND FISSURES

Although some faulting may have occurred in this area as early as Pre-Cambrian time, the most conspicuous faults were formed in Tertiary time. Within much of the area of pre-Cambrian rocks it is not possible to separate the periods of movement. Movement has doubtless taken place along the same break at different times, possibly as widely separated as pre-Cambrian and Tertiary.

Mosquito Fault.—The Mosquito fault is one of the major structural features of the region. It extends in a general north-south direction for many miles, through most of which it is a normal fault with downthrow to the west. In the "Mountain Chief No. 6" Tunnel, north of Climax, it dips about 80°W.; in the Phillipson Tunnel at Climax, 71°W. At Climax the "Weber grits" form the west wall and pre-Cambrian rocks the east wall. North of Climax, at the Mountain Chief No. 6 Tunnel, the "Weber grits" form the west wall and the Cambrian quartzite the east. The intervening breccia zone, which is composed almost entirely of silica stained with limonite, is about 125 feet thick. The relation of this silicified zone to the molybdenite deposit has not been

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[24] Emmons, S. F., U. S. Geol. Survey Geol. Atlas, Tenmile folio (No. 48), 1898.

determined. In the Phillipson Tunnel at Climax the rocks on both sides of the fault are much broken for a distance of 100 feet, and the fault itself contains a black shale gouge from 4 to 6 feet thick. This gouge contains polished and abraded fragments of "Weber grits" and of granite. Some of the granite "pebbles" in the gouge contain pyrite and fluorite and are identical with similarly mineralized granite adjacent to the fault. The fault has evidently undergone movement since the molybdenum deposit was formed, though it may have been initiated earlier. The amount of movement of the fault in this locality is not known and cannot be determined until the sedimentary section west of the fault is known.

Other faults.—There are many other faults in the area. Most of them are in the pre-Cambrian rocks and their displacements are not easily determined. The East or "Main" fault in the Climax mine has been given considerable attention, as it has been thought by some to displace the ore body. To do so, this fault, which has a northwesterly strike and northeasterly dip, should cut and offset a prominent Tertiary dike that is clearly earlier than the mineralization; but the dike shows no displacement, and it seems, therefore, that any considerable movement along the fault must have taken place earlier than both the intrusion of the dike and the period of mineralization. There are, however, clear examples of minor faulting of Tertiary dikes, including some on Bartlett Mountain not far from the Climax mine, and there are also strong shear zones in the Tertiary dikes. Most of these shear zones are mineralized. Slickensides on quartz and other evidence indicates renewed movement along veins after mineralization.

Age of faulting.—Nothing substantial regarding the age of faulting is here added to the discussion in the latest Leadville Government report[25], which recognized that all the major faulting took place later than the intrusion of porphyry sills, and which included the Mosquito fault in a small, poorly un-

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[25] U. S. Geol. Survey Prof. Paper 148, pp. 62-97, 1927.

derstood group of composite reverse and normal faults, some formed before and others after the period of ore deposition. The wide zone of highly silicified rock in the Mosquito fault at the adit on the Mountain Chief No. 6 claim implies premineral movement, whereas the absence of silicification and the presence of fault "pebbles" in the Phillipson Tunnel proves some postmineral movement. Emmons[26] realized the possibility of premineral movement in the Tenmile district. Similar evidence has been found by Behre along the Mosquito fault at the head of Evans Gulch[27] and along the Lyddia fault at Iowa Gulch[28], in the Leadville region. At both of these places the main fault is barren, but parallel and apparently auxiliary faults are mineralized, and the inference is permissible that premineral movement was followed by postmineral movement along the main fault on so large a scale that evidence of mineralization within the main fault has been obscured, although it is preserved in the auxiliary faults, which did not undergo noteworthy postmineral movement. The age of many of the other faults cannot be closely placed, but many mineralized fissures show evidence of movement, and much of the faulting clearly preceded mineralization.

Fissures.—There can be no sharp separation of faults and fissures in the area. Many of the mineralized fissures have undergone some displacement, as shown by pronounced brecciation and slickensiding along them. Such fissures are clearly exposed on the north face of Ceresco Ridge, where they contain prominent quartz veins and locally considerable fluorite; and similar fissures with vein quartz, usually some fluorite and strongly sericitized wall rock are exposed in the Climax mine. The East fault in the Climax mine contains a little sphalerite in addition to pyrite. In many such faults there is clear evidence of some renewed movement after mineralization.

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[26] Tenmile folio, p. 4, 1898.

[27] Behre, Chas. H., Jr., personal communication, 1929.

[28] Behre, Chas. H., Jr., Revision of structure and stratigraphy in the Mosquito Range and the Leadville district: Colo. Sci. Soc. Proc., vol. 12, p. 47, 1929.

Many fissures are present in the mine, and the strikes and dips of twenty-four of the more prominent ones have been recorded. All but three have strikes ranging from 10° to 80° east of north, with southeast dips, mostly between 50° and 60°, although a few are vertical. On the surface east of the Climax mine and southwest of "Mountain Chief No. 3" Tunnel most of the prominent fissures have westerly strikes with southerly dips, but many of the smaller fissures are approximately at right angles to them in typical coordinate arrangement.

THE MOLYBDENUM DEPOSIT

CONCENTRIC ZONES OF MINERALIZATION

One of the striking features of the Tenmile Amphitheater, where the molybdenum deposit crops out, is the yellowish to reddish-brown color of the rocks that border it on both sides, as contrasted with the somber colors of the rocks in the head of the amphitheater and of the main range in general. These highly colored rocks on and between Bartlett Mountain and Ceresco Ridge outline the area in which the rocks have undergone rather intense alteration, although the color alone is not a reliable indication of its degree of alteration. This area is roughly circular, except where it is cut off by the Mosquito fault, and is approximately one mile in diameter. The high color of the altered rock is only superficial and is due to the oxidation of pyrite, but the color effect is the same whether much or little pyrite was originally present. On fresh fracture one of the most conspicuous features of alteration is the bleaching of the ferromagnesium minerals. The different kinds of rock in the mineralized area are similarly altered, but to different degrees. Granite, the most highly fractured, is the most readily altered, whereas the tougher and more flexible schist is much less readily affected. The porphyry dikes also are less altered except along shear zones, where they are as strongly altered as the granite.

The form of the molybdenum deposit is still only imperfectly known, even after the last 7 years of intensive de-

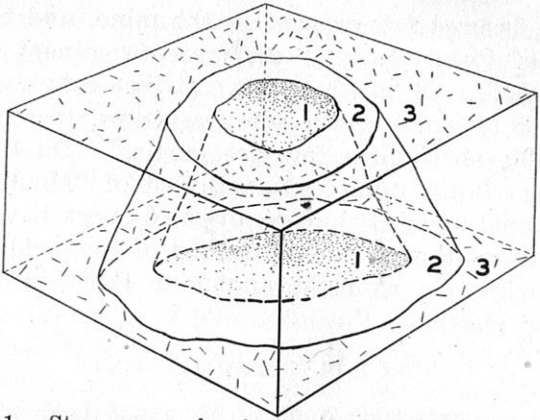

Figure 1. Stereogram showing generalized relations of different zones of the Climax molybdenum deposit. 1. Highly silicified core. 2. Ore zone with chiefly moderately silicified granite. 3. Slightly altered granite grading into unaltered granite.

velopment, but its general form is that of a circular stock enlarging downward and separable into an outer zone of weak alteration, an inner or intermediate zone of more intense alteration and ore deposition, and a highly silicified core. Figure 1 represents the idealized form of the deposit as revealed by mine development.

Transition from the surrounding unaltered area to the zone of weak alteration is indicated by a bleaching and softening of the feldspar phenocrysts as well as the groundmass, and by rock impregnated with small pyrite grains. Biotite is changed to muscovite with fine magnetite grains along its cleavage, and plagioclase is thoroughly sericitized. Scattered veinlets of fine-grained milky quartz are also present. Toward the transition to the next inner zone small buish-gray replacement veins of quartz and orthoclase, with finely divided molybdenite that gives the bluish color, are characteristic. Molybdenite is confined to the veins, while pyrite impregnates the rock. The rock is appreciably silicified, and the original phenocrysts of microcline and orthoclase have been replaced by or recrystallized into aggregates of fine-grained secondary orthoclase. Muscovite has also been replaced by orthoclase along cleavage planes and boundaries.

Where alteration of this kind is only slight there is no noteworthy decrease in the amount of alkalic feldspar, but the microcline phenocrysts, originally abundant, are practically absent, and only orthoclase phenocrysts are present. The cause of this change is not known.

Transition from the outer to the intermediate or ore zone is gradual, with respect both to rock alteration and to the increasing content of molybdenite. The rock in the ore zone is composed largely of quartz and secondary orthoclase, but the outlines of rock fragments are still readily recognized. It is impregnated with pyrite, but no more so than in the outer zone. Small veinlets, mostly less than a quarter of an inch and rarely more than three-quarters of an inch thick, cut the rock in every direction and are so closely spaced that in many places it is impossible to find a cubic inch of rock free from them.

Some veins in the outer part of the ore zone consist largely of "blue quartz" colored by minute crystals of molybdenite and containing considerable orthoclase, which in some places is concentrated along the margins and in others along the center of the veins. Characteristically veins in the ore zone contain molybdenite concentrated along their margins, and some of them also contain small amounts of fluorite along their middle portions. A few veins also contain a little pyrite. Definite veinlets of molybdenite free from quartz can also be detected, especially in the schist. Locally veins of "blue quartz" are present in the inner part of the ore zone and may be readily mistaken for ore, although their content of molybdenite is low.

Toward the central core the replacement veins become larger and more coarsely crystalline, finally coalescing and leaving only faint "shadows" of the original rock fragments. Both veins and wall rock contain more quartz and less orthoclase. The molybdenite content on the whole decreases to much below that necessary for ore, but small exceptional occurrences of ore are present within the core. The core consists essentially of rather fine-grained replacement quartz.

Original quartz grains, which resisted alteration elsewhere, have disappeared. Pyrite within the inner core is practically confined to the later veins. It is coarser grained and more conspicuous, but not appreciably more abundant than in the surrounding zones.

The preceding description is considerably idealized or conventionalized; as a matter of fact areas of moderately silicified rock are found within the highly silicified core, and extensions of the core into the moderately silicified rock are found. The zones are clearly defined, but their boundaries are not and would doubtless be mapped somewhat differently by different individuals, or even by the same individual at different times.

Later than the main silicification and the molybdenite veins are veins that cut all the zones. The most abundant of the later veins are quartz-pyrite veins which in places contain a little chalcopyrite, dark sphalerite, hübnerite, fluorite, and topaz. Probably still later than the pyrite veins are veins characterized by abundant sericite together with quartz, fluorite, and, in some at least, topaz. A little molybdenite and in some veins dark sphalerite are present. The sericitic veins seem most abundant in and near the central core, though they are present in all the zones and are especially conspicuous along the stronger fractures, where they may attain a thickness of 1 to 2 feet. They are not confined to strong fractures, however, but are also present in microscopic fractures throughout the mineralized zone.

Chemical Changes in Rock Alteration.—Chemical changes in the process of alteration are illustrated by the chemical analyses given in Table 1. Table 2 expresses these changes by the amounts of the different constituents in a given volume of each rock. Figure 2 is a graphic representation of these analyses.

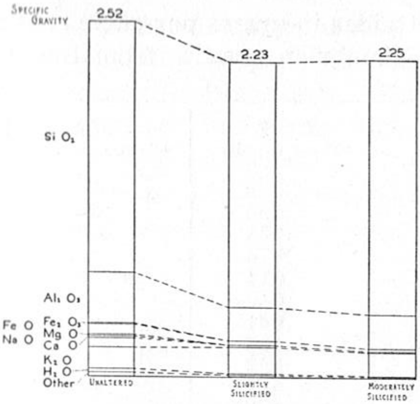

Figure 2. Oxides in grams per cubic centimeter in unaltered and altered Silver Plume granite from the Climax mining district.

TABLE 1.—Analyses of fresh and altered pre-Cambrian granite from the Climax District, Colorado.

J. G. FAIRCHILD, *Analyst*

	C19B Fresh granite	C35A Slightly silicified	C54A-4 Moderately silicified
SiO_2	70.83	78.62	80.78
Al_2O_3	14.41	10.80	9.26
Fe_2O_3	.35	.05	Trace
FeO	2.94	1.13	1.34
MgO	.56	.05	.10
CaO	.64	.05	.10
Na_2O	2.44	.76	.31
K_2O	6.21	8.11	7.68
H_2O-	.04	.10	.01
H_2O+	1.34	.43	.46
TiO_2	.24	.04	Trace
P_2O_5	.15	.10	.08
Cl	.04	.04	.04
F	.00	.00	.05
S	.01	.06	.03
BaO	.02	.03	.01
Mo	.00	.10	.12
	100.22	100.47	100.37
Specific Gravity:			
Specimen, in lump	2.52	2.23	2.25
Specimen, crushed	2.68	2.60	2.57
Weight of Specimen (grams)	95	90	85

TABLE 2.—Oxides in grams per cubic centimeter in fresh and altered pre-Cambrian granite from the Climax District.

	C19B Fresh granite	C35A Slightly silicified	C54A-4 Moderately silicified
SiO_2	1.780	1.750	1.820
Al_2O_3	.363	.241	.208
Fe_2O_3	.008	.001	-----
FeO	.074	.025	.030
MgO	.014	.001	.0025
CaO	.016	.001	.0025
Na_2O	.061	.016	.008
K_2O	.156	.189	.176
H_2O+	.038	.009	.010
Others	.013	.010	.006
	2.523	2.243	2.263
Specific Gravity	2.52	2.23	2.25

From the tables and figure it is evident that the first stages of alteration resulted in a large removal of Na_2O, CaO, MgO, and Fe_2O_3, and a reduction of FeO. There has also been a reduction, though much smaller, in Al_2O_3. SiO_2 has changed but little, whereas K_2O has been notably increased. The further change to rock that is classed as moderately silicified is not great; the notable change from the slightly silicified to the moderately silicified granite is a decrease in K_2O, indicating progress toward the stage of highly silicified rock in which all the elements except silica have been largely removed. It is evident that the general trend of the chemical alteration is a leaching of all the bases and alumina, and a residual concentration and possibly addition of silica. In the early stages of alteration there was an addition of potassium, but in the more advanced stages this also was leached. In the veins there was an addition of molybdenum, sulphur, and fluorine. Pyrite is present throughout the deposit, but the iron in the pyrite, as already suggested, may easily have been derived from the altered country rock. The solutions that accomplished the alteration, then, were of such character as to take into solution nearly all the original rockforming elements, including aluminum and in the later stage potassium, but not including silicon. The later veins contained abundant sericite with some topaz. The solutions that made these later veins must have been rich in both potassium and aluminum, as well as fluorine.

TABLE 3.—Mineral composition of fresh and altered pre-Cambrian granite as calculated from chemical analyses of the granite[1].

	C19B Unaltered	C35A Slightly silicified	C54A-4 Moderately silicified
Quartz	31.63	42.81	49.50
Orthoclase	21.86	46.11	44.31
Albite	20.68	6.70	2.32
Anorthite	2.24	....	....
Muscovite (Sericite)	.95	2.79	1.53
Biotite	20.77	....	....
Magnetite	.51	....	....
Apatite	.40	(?)	(?)
Fluorite	....	....	.12
Molybdenite	....	....	.15
Others	....	[2]1.60	[2]2.10
	99.04	100.01	100.03

[1] Minerals calculated were observed in thin sections of the rock specimens represented.

[2] A little over 1 per cent is FeO which has not been accounted for. In thin sections small grains resembling titanite have been observed that may contain the FeO, but the mineral has not been identified. A small amount of apatite is probably present, though not shown. Hand specimens show a very little limonite stain.

MINERALOGY

The minerals introduced during the epoch of mineralization that brought in the molybdenite are briefly described below in alphabetical order, and the few secondary minerals derived from them are similarly considered. These descriptions are followed by a list of the minerals that are found in small fissure veins in granite and schist and are distinctly later than the primary minerals of the molybdenite deposit.

PRIMARY MINERALS OF THE MOLYBDENUM DEPOSIT

Chalcopyrite ($CuFeS_2$).—Chalcopyrite is present, though rare, in the molybdenite deposit. It occurs with sphalerite and fluorite in the quartz-pyrite veins, and probably accounts for the occasional presence of small quantities of copper in the concentrate.

Fluorite (CaF_2).—Small amounts of colorless, green, and purple fluorite can be detected by the naked eye in the silicified rock, but it is most abundant in the sericite fissure veins, where it occurs as octahedral crystals and in irregular masses as much as several inches across. On the north slope of Ceresco Ridge a band of white fluorite 14 inches wide was observed in a fissure vein. The green and purple fluorite is readily recognized, but the colorless variety, which blends with other minerals, is easily overlooked. As much of the fluorite is colorless the mineral is probably more abundant than was formerly suspected.

Thin sections under the microscope show a wide distribution of the fluorite that is not suspected from an examination by the eye alone. Small irregular formless grains of fluorite are scattered through the silicified rock and very commonly along the middle portions of quartz or quartz-orthoclase veins. The fluorite is no more characteristic of veins that carry molybdenite than of veins without molybdenite, but on the whole is most common where molybdenite is most abundant. In molybdenite veins it occurs along the middle portions. It is also very common in the sericite veins, and in both kinds of veins it was deposited later than the molybdenite.

Hubnerite ($MnWO_4$).—Veins half an inch or less thick containing hübnerite are easy to find in the float, and several have been observed in place in the mine. The hübnerite is characterized by a reddish-brown to black color, a high luster, a distinctly red though dark streak, and good cleavage. Lathlike crystals with quartz are fairly typical. Hübnerite occurs with sericite in small quartz veins that cut the silicified rock and the molybdenite veins, and is also present in many of the quartz-pyrite veins that cut all zones of alteration, including the molybdenite veins. In these quartz-pyrite veins the hübnerite occurs in scattered laths along the walls. Only a little iron is indicated by qualitative tests. In liquids under the microscope the hübnerite is translucent, showing a deep-red color.

Molybdenite (MoS_2).—Molybdenite (60 per cent metallic molybdenum and 40 per cent sulphur) is the one economically important metallic mineral in the district. It occurs characteristically as fine specks along the margins of small ramifying veins with quartz or quartz and orthoclase gangue. In most of these veins it is the only metallic mineral present. It is readily recognized by its shiny dark metallic-gray to black color, similar to that of graphite. The crystals are flat and six-sided, but are rarely large enough for their forms to be recognized except under the microscope, where the hexagonal outline is commonly evident. Much of the molybdenite, however, even when highly magnified, appears only as tiny black specks. The uniform fine-grained character of the molybdenite at Climax is exceptional, as in most other molybdenite deposits large crystals, many an inch or more across, are common.

Orthoclase ($KAlSi_3O_8$).—The secondary finely granular orthoclase characteristic of the mineralized area can be recognized only under the microscope. In this area there has been a general finely granular recrystallization of the original microcline and orthoclase of the igneous rocks, beginning along the margins and cleavage planes of the grains. Calculations based on chemical analysis of the moderately silicified granite show 44 per cent of orthoclase and only 2 per cent of the albite molecule. This amount of albite is evidently present in unreplaced remnants of original microcline, orthoclase, and oligoclase. Little or none of it is thought to be present in the secondary orthoclase, although its absence can not be proved. Fine-grained orthoclase, very rarely with crystal outlines, also occurs along the walls or middle of many quartz veins. It is characteristic of both slightly and moderately silicified zones, but is probably a little more abundant in the moderately silicified zone.

Pyrite (FeS_2).—Pyrite occurs throughout the area as small cubes disseminated in altered rock, and as a constituent of veins that contain topaz. Much of the disseminated pyrite was formed at an early stage of mineralization, whereas the pyritic veins, which cut all the altered zones and the molybdenite veins as well, belong to a distinctly later stage. At the surface and for a few inches to a few feet below the surface the pyrite is mostly oxidized, but its former presence is always indicated by cubical cavities and by the limonite stain on the rocks.

Quartz (SiO_2).—Quartz in crystals, measuring only about 1 by 3 to 2 by 5 millimeters, appears to be confined mostly to the sericite veins. Massive quartz in veins and in large volumes of the country rock is the most abundant mineral in the district. The White Tunnel cuts about 900 feet of white well-crystallized massive fine-grained quartz which locally resembles a quartzite. In places, notably in the slightly silicified zone, the quartz in the veins is blue or bluish gray, owing to the presence of small scattered microscopic molybdenite crystals. The quartz in the larger veins looks well crystallized, but in some of the smaller veins individual crystal faces cannot be detected by the eye and the quartz looks very dense. In thin section the massive replacement quartz and the quartz in the larger veins form fairly uniform mosaics. In the smaller veins, especially in the outer zone of mineralization, the very dense quartz is also well crystallized but finer grained.

Sericite (*Muscovite*).—Sericite occurs in the slightly silicified zone and outer fringe of the mineralized area, where it replaces plagioclase and to a small extent microcline and orthoclase. It was apparently one of the first minerals to form. In parts of the ore zone a little sericite, which is intergrown with molybdenite plates, was also formed during the later stage of moderate silicification. The most extensive occurrence of sericite is in fissure veins of a still later stage, which are found throughout the mineralized area, but are most numerous in the central portions.

Sphalerite (ZnS).—Dark-brown to black sphalerite was observed with fluorite in a sericite vein and in pyrite veins. It occurs only sparingly and with minerals that formed late in the sequence of mineralization.

Topaz [$(AlF)_2SiO_4$].—Topaz is widespread at Climax, but everywhere as microscopic crystals. It occurs disseminated through silicified rock, as irregular veinlets that cut molybdenite-bearing quartz veins, and as a charactertic gangue mineral in the late pyrite veins. It mostly forms equidimensional grains and to a small extent lath-shaped grains with cleavage normal to the longer dimension. By the immersion method the maximum index of refraction was determined as not over 1.612, which is less than that of common topaz.

Unidentified Mineral.—A mineral not identified is common in small amounts, in places associated with secondary orthoclase. The mineral may occur in orthoclase veins or be disseminated through the rock. It resembles titanite, but chemical analysis of a specimen containing the mineral showed too little titanium. The analysis showed over 1 per cent of ferrous iron, which could not be accounted for and which suggests the possibility that the unidentified mineral is iron-bearing.

SECONDARY MINERALS OF THE MOLYBDENUM DEPOSIT

Jarosite ($K_2O.3Fe_2O_3.4SO_3.6H_2O$).—Jarosite is common throughout the mineralized area and occurs as ocher-yellow incrustations along fissures and in seams; but it so closely resembles limonite that its abundance is difficult to estimate.

Limonite ($Fe_2O_3.H_2O$).—Limonite stains the surface rock throughout the mineralized area, giving it a distinctive color, which even from a distance contrasts with that of the surrounding area. Where the rock is massive the limonite is confined to a thin surface zone, but along fissures and fractures it extends some distance below the surface. It has been formed by oxidation of pyrite and is mostly yellow, although locally it may be reddish.

Molybdite ($Fe_2O_3.3MoO_3.7\frac{1}{2}H_2O$).—Molybdite, or molybdic ocher, which has been formed by oxidation of the molybdenite (MoS_2), is very conspicuous in places at the surface because of its canary-yellow color. It is so finely crystalline that much of it is earthy, but in places in the mine it forms beautiful clusters of fine silky needles growing from the walls of fissures. As oxidation on the whole has been shallow, molybdite is mostly found within a few feet of the surface face, but along the more open fissures it is prominent at considerable depths. Assays of diamond-drill cores show small amounts of molybdenum oxide of no economic importance several hundred feet below the surface.

Minerals in Veins Formed Later Than the Molybdenum Deposit.—In small veins in the district the following minerals were observed, named in their approximate order of abundance: Quartz, pyrite, dark-brown sphalerite, galena, hübnerite, fluorite, brown carbonate, and magnetite. As most of these veins are only poorly exposed in old prospects a detailed study of them has not been attempted, and the above list of minerals is probably not complete.

SIZE OF THE MINERALIZED AREA

Development as yet is too incomplete to give more than a rough approximation of the size of the mineralized area. The central core of highly silicified rock extended for about 900 feet along the White Tunnel level and about 200 feet less on the upper or Leal Tunnel level. At right angles to this direction its extent is not known, but is probably somewhat less. On the Phillipson Tunnel level, about 460 feet below the White level, the maximum horizontal dimension of the highly silicified zone, less definitely determined by drilling, has increased to about 1,500 feet.

The ore zone or envelope which surrounds the central core, is undoubtedly of variable thickness, and there may be portions of it that do not contain sufficient molybdenite to be ore. Moreover, the general dip of the ore zone has not been closely determined and is still unknown in several areas. Any estimate of thickness of the ore envelope, therefore, is subject to modification and correction. Most of the development work has been done to the northwest and north of the central core. There has also been development to the southeast and south, but almost none elsewhere. If an average dip of 60° is inferred for the northwestern and northern parts of the ore zone, its thickness there, at right angles to the dip is 300 to 350 feet. Development in other areas does not yet indicate the thickness. There is some basis for the inference of a 60° dip at the north, but the dip may vary considerably from that figure, and at other points on the periphery, it may not be the same as at the north. To the present depth of development, which is mainly above the Phillipson Tunnel level, there is no consistent change in the character of the ore down the dip of the ore shoot. Drill holes 26 and 38C, which extend 368 and 480 feet respectively below the Phillipson Tunnel level, are in ore of good grade, and neither indicates any change in character of ore.

The company in October, 1930, estimated its developed ore at 50,000,000 tons. As only part of the area has been developed, and none of it to any great depth, there can be no doubt that much ore in addition to that now known will be found.

GRADE OF ORE

As there is a gradation from one mineralized zone to another, there is no sharp change in the metal content between ore and waste. The metal content necessary for ore is therefore determined by the price of the product and the cost of production. The average molybdenite content of ore milled has been about 0.83 per cent. The Climax Molybdenum Co. regards ground that averages 0.7 per cent or more of molybdenum sulphide (MoS_2) as ore. Whenever the grade of rock that can be profitably treated is materially lowered, the amount of ore available for treatment will be decidedly increased.

SUPERGENE ALTERATION

Besides the conspicuous red and brown staining of rock in the mineralized area, the vicinity of the ore zone is also characterized by a minor amount of canary-yellow at the surface. The red and brown colors are the result of the oxidation of pyrite to limonitic minerals. The yellow is the result of the oxidation of molybdenite to molybdite. The oxidation of pyrite and molybdenite has not gone to great depths, nor has it been complete even at the surface. In the more open fissures both sulphides may be altered to considerable depths, but in the more massive veins both pyrite and molybdenite are present within a few inches of the surface. The reasons for the relatively shallow oxidation are probably both chemical and physical.

The outcrop of the deposit is largely at altitudes of 11,500 to 13,000 feet, and at the higher elevations the temperature, a short distance below the surface, remains below the freezing point of water for a large part if not for all the year. No exact data on local rock temperature at different depths are available, but in the Climax mine and in numerous others at corresponding altitudes ice crystals form on the walls of workings, evidently collecting moisture from the air. This low temperature has prevented a free downward movement of surface solutions during glacial and postglacial time, but in preglacial and interglacial time[29], conditions were favorable for extensive oxidation. As the deposit lies on and near the axis of the glaciated Tenmile Valley, a considerable quantity of oxidized ore may have been removed from the deposit by glaciation. This removal, together with the unfavorable conditions for oxidation in postglacial time, probably accounts for the shallowness of the present oxidized zone.

The chemical behavior of molybdenite in oxidation has not been much studied and is not well known. Under the conditions that prevail in the Climax deposit, however, the molybdenum seems to have been in large part oxidized to the higher oxide MoO_3, which combined with ferric oxide from the oxidation of pyrite to form molybdite. This com-

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[29] U. S. Geol. Survey Prof. Paper 148, pp. 271-272, 1927.

pound seems to be only slightly soluble under existing conditions, and there is little evidence of movement or concentration of the molybdenum. So far as has been determined there is no indication of the formation of secondary molybdenite and, therefore, no indication of sulphide enrichment of molybdenum.

ORIGIN

Most of the great number of deposits of molybdenite that have been described are closely associated with intrusive rocks, and have been generally regarded as genetically related to the igneous rocks. The association ranges from pegmatite dikes, in which molybdenite is regarded as a primary mineral, through high-temperature veins to intermediate-temperature veins. Molybdenum is apparently also present in deposits formed at relatively low temperature, as some of the lead deposits on oxidation yield abundant lead molybdate. The primary mineral from which the molybdenum was derived in the lead deposits has usually not been determined.

The minerals associated with the molybdenite at Climax give no very definite evidence as to the temperature of formation. Pyrite, the most abundant metallic mineral, is formed through a long range, and sphalerite and chalcopyrite are also formed through rather long ranges of temperature. Among the nonmetallic minerals quartz, the most abundant mineral, and orthoclase, sericite, and fluorite are minerals of long range. Topaz is perhaps indicative of moderately high temperature, but taken alone it would hardly give any clear indication of the conditions under which the deposit was formed.

The general kind of rock alteration associated with the molybdenum deposit is rather closely similar to that of some of the disseminated copper deposits, notably the deposits at Ely, Nev.,[30] and Bingham, Utah[31]. The similarity is especially notable in the presence of abundant secondary ortho-

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[30] Spencer, A. C., The geology and ore deposits of Ely, Nev.: U. S. Geol. Survey Prof. Paper 96, p. 56, 1917.

[31] Butler, B. S., Loughlin, G. F., Heikes, V. C., and others, The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, p. 166, 1920.

clase. The fact that both of these copper deposits contain minor amounts of molybdenite is another indication of similar conditions of formation. Spencer considers that the Ely deposits have formed at temperatures between 200° and 350°, or in the general range of the mesothermal deposits as defined by Lindgren. The Bingham disseminated deposits were doubtless formed under similar conditions. Buddington[32] has described deposits at Shakan, Alaska, which are similar to the deposits at Climax in the abundance of secondary orthoclase or adularia, but differ in the presence of other sulphides in considerable abundance and in a later stage of zeolitic mineralization. As to the conditions of formation Buddington concludes:

> The minerals of the adularia period appear to follow the pegmatite stage and to be best grouped, following Lindgren's classification, as of hypothermal origin. In so far as the sulphide minerals themselves are concerned, they might belong to either hypothermal or mesothermal veins; but since, with the exception of pyrite, they follow for the most part the adularia period and are succeeded by the zeolites, it would seem they are best grouped as belonging to the mesothermal period, and the minerals of the zeolite period as formed in the epithermal stage.

The similarity of the Climax deposits to these cited would seem to justify the assumption that the deposits were formed under conditions represented by the transitional parts of the hypothermal and mesothermal zones.

A deposit of molybdenum in the Valley of Ten Thousand Smokes, Alaska[33], is of particular interest, as the conditions of formation are better known. This deposit of "molybdenum blue" ($Mo_3O_8.xH_2O$) occurs in and around a steam vent which has a temperature of 264° centigrade and contains calcium sulphate and ammonium and ferric chloride and sulphate combinations. Fluorine was also present. This combination of molybdenum with oxygen rather than with sulphur, even though hydrogen sulphide was abundant in the area, is striking. Zies states that "molybdenum blue is quite easily formed when a solution of an alkaline molybdate is treated with a reducing agent such as hydrogen sulphide." He further

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[32] Buddington, A. F., Molybdenite deposit at Shakan, Alaska: Econ. Geology, vol. 25, pp. 197-200, 1930.

[33] Zies, E. S., The Valley of Ten Thousand Smokes: Nat. Geog. Soc., Katmai ser., vol. 1, No. 4, 1929.

states, "If it (molybdenum blue) is exposed for a considerable period to hydrogen sulphide, however, an insoluble sulphide of molybdenum will eventually be formed."

This fumarolic occurrence suggests that molybdenum is not carried as the sulphide, but in some more highly oxidized form as a fluoride or chloride, and that when the temperature becomes sufficiently low for the formation of hydrogen sulphide in the solutions the molybdenum is either deposited as, or eventually reduced to the insoluble molybdenum sulphide.

The genetic associations of the copper deposits of Ely and Bingham and the molybdenum deposits of Alaska with bodies of intrusive rock are much more evident than those of the deposit at Climax, but the mineralogy of the Climax deposit and the associated rock alteration are so similar to those of the other deposits that they also strongly suggest such a relation. The mineralized Tertiary dikes in the Climax district were probably intruded shortly before the period of mineralization, but their association with the ore is not sufficiently close to point to them as sources of mineralization. In its general pipelike or stocklike character the deposit is also similar to the numerous other deposits. The O. K. mine, in the Beaver Lake district, Utah[34], is a good example of such a pipelike body with a siliceous core surrounded by less completely replaced rock containing ore minerals, including molybdenite. The Cactus mine, in the San Francisco district[35], is a similar pipelike deposit on a larger scale in which the rock shows strong brecciation and replacement. The disseminated copper deposits of Bingham, Utah, and Ely, Nev., are much larger breccia stocks, in which there has been strong replacement of the rocks and mineralization.

There are numerous breccia chimney or stock deposits in Colorado that have physical similarities to the Climax deposit, but contain different metals. Some such deposits are the Patch, in the Central City district; the Bassick, in the

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[34] Butler, B. S., Loughlin, G. F., Heikes, V. C., and others, Ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, p. 517, 1920.

[35] Idem, p. 517.

Querida district; and numerous pipe or stock deposits of somewhat similar character in the Red Mountain section of the San Juan region.

The origin of deposits of this type is as yet somewhat uncertain. In the earlier descriptions of such deposits it seems to have been generally regarded that the brecciation was due to movement of the rock or to volcanic activity, and that the mineralizing solutions found the breccia zone an easy passageway and replaced the breccia in whole or in part. Recently Locke[36] has suggested that in the early stages of mineralization there was solution of the rock with the production of open cavities. The rock around such openings caved much as a mine stope caves, and the caved area enlarged in the fashion of a shrinkage stope till the chimneys or stocks were produced. In the later stages of mineralization deposition exceeded solution, and the rock fragments were partly replaced and cemented by vein minerals, which filled or partly filled the spaces between fragments.

In the Climax area there has undoubtedly been a good deal of fissuring of the pre-Cambrian rocks, as is evident from their highly fissured character outside the mineralized area. There has also been shearing in some of the Tertiary dikes, and such shear zones are the most highly mineralized. Mineralization occurred in rocks that were much broken, but it is not evident that they were more broken than in some other parts of the pre-Cambrian granite, and it is not clear why one particular area was mineralized and others not.

ZONAL DISTRIBUTION OF MINERALIZATION

In many mining districts a zonal arrangement of the minerals and metals has been recognized. Certain metals and minerals that are abundant near the center of the mineralized area give place upward or outward to others. There is no clear evidence of such zoning in the Climax district except in the zones in the deposit itself. There are, to be sure, a few veins containing zinc and lead in the surrounding

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[36] Locke, Augustus, The formation of certain ore bodies by mineralization stoping: Econ. Geology, vol. 21, pp. 431-453, 1926.

area, but no evidence has been found to indicate that they are directly related to the molybdenum deposit. This absence of other metals associated with the molybdenum, with the exception of iron, a little zinc and copper, and a very little tungsten, is rather surprising, and the reason for it is not clear, though there are numerous molybdenum deposits in which pyrite is the only other metallic mineral.

From the similarity to other deposits that are known to be associated with intrusive bodies it may be inferred that the Climax deposit is genetically associated, not with the exposed dikes, but with a larger though still concealed intrusive body whose apex had approached sufficiently near to the surface for the gases liberated from it to escape through the fractured rock. For some reason that is not apparent the escape started where the present deposit is located and, once started, continued to drain the gases from the crystallizing stock. These escaping gases effected the alteration of the rock and deposited the molybdenite. If there was a zoning in a deposit formed in such a "blow hole" the zoning would probably be mainly in a vertical direction, and the erosion surface at any given time would show but one zone. This may be the reason why molybdenite is the only commercial metal found in this deposit. As the molybdenite deposit itself is the strongest evidence of the presence of an unexposed stock, the argument presented above will be differently appraised by different readers, according to their views regarding the association of ore deposits with intrusive stocks.