Some General Principles
Useful in Exploration for Tungsten

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I. INTRODUCTION

The element tungsten was first isolated by Oxland, in 1847. It was not until 1857, with the patenting by Oxland of the first iron-tungsten alloy, that the metal came into any appreciable use. In 1860 Muschet discovered that by adding tungsten to steel an alloy could be prepared which would harden without quenching (28), and in 1898 Taylor and White of the Bethlehem Steel Company discovered the process for making a tungsten steel which would hold a cutting edge at red heat. From this time on, with the additional stimulation afforded in 1907 by the development of the tungsten filament for incandescent lamps, the tungsten industry has rapidly grown in importance (12). The recent war has revealed tungsten to be one of the most important, if not the most important, strategic material.

Besides its use in high speed steels, tungsten, because of its remarkable properties, viz. the highest melting point and the highest tensile strength of all metals, the extreme hardness of its carbides, valuable chemical, electrical and alloying properties, is finding a rapidly expanding field of employment in radio tubes, x-rays, glass, catalysts, and dyes. There is no doubt that if production could be increased sufficiently and the price lowered enough, this versatile metal could do much more to accelerate the development of our civilization.

The tungsten industry is still in its infancy. The major obstacle to its expansion has been the scarcity of the metal. However, there are good reasons for believing that tungsten is in reality not as scarce as is commonly thought. It exists in the earth's crust in about the same proportion as zinc (2). As it is one of the "newer" metals, little more than a curiosity before the present century, we may assume that many deposits exist that have so far not been reported.

We may expect that with the opening of South America, China and India to industrialization, the hunt for tungsten will be greatly accelerated. It is the purpose of this paper to draw from the material available on known deposits some generalizations that may be useful in this search. It is not intended as a general survey of all known occurrences, nor as a detailed description of the exploration methods employed, such as the ultra-violet light, mass spectroscope, etc. It does not contain a description of the mineralogy of tungsten nor does it cover many points of academic interest which have so far been of no economic use.

II. GENERAL DISTRIBUTION OF TUNGSTEN

A. Geographic

Tungsten ores are widely scattered over the earth. Many countries show a very minor and sporadic production. Four metallogenic provinces, however, heavily dominate tungsten production accounting for 89.1% of the world's supply from 1913 to 1937. These are; the Sino-Malaysian province with 62.6%, the North American Cordilleran province with 10.8%, the Andean province with 9.9%, and the Iberian-Cornwall province with 6.7%. Australia and Japan-Korea follow with 3.3% and 3.5% respectively. The remaining 3.8% is divided among twenty other widely scattered producers.

It may be significant that none of the important metallogenic provinces is situated in the interior of a continent, and that all of them, with the exception of the Sino-Malaysian province, border on oceans. An explanation is offered by Chung Yu Wang (1924). He suggests that these areas, which lie in the unstable meeting places between the rising continental cordilleras and the sinking ocean basins, were intruded by magmas under great pressure having their origin in the abyssal depths beneath the ocean basins. The Sino-Malaysian province does not support this line of reasoning; it seems more related to the arcuate chains of southeastern Asia (8).

B. Regional

Within the major metallogenic provinces the tungsten deposits are not scattered heterogeneously, but show definite alinement in belts paralleling the major directions of folding.

In the North American Cordillera, which has been intensively searched for tungsten, three major belts of distribution have been well established (see page 7). Deposits within these belts are not alined in an unbroken chain. Lava covered regions impose considerable gaps, and even in areas of igneous intrusion apparently favorable for the deposition of tungsten, gaps of considerable size occur. Localities in the Sierras of California and in Nevada are surprisingly numerous and well alined. Only an occasional locality of minor importance is found outside these belts. They are described in detail by Kerr (21).

In China, in the Nanling region, source of almost all China's tungsten, the deposits show evidence of a similar distribution in belts, although this region has probably been far less thoroughly searched. Geologically the region is characterized by zones of intense and complexly folded mountains, by wide-spread late Mesozic granite intrusion, and by rich high temperature metallic deposits containing tungsten, tin and some bismuth and molybdenum. In general these mountains follow the axes of different anticlinoria, along which granite intrusions are now exposed. The tungsten deposits are closely associated with these intrusions. They are not scattered but in the main are restricted to the broad cores of the major anticlinal zones (20).

In Malaya no reference has been made to a belt like distribution of the known deposits which seems to parallel the trends of the folded mountains with their granite cores. J. B. Scrivenor (1928) states that the position of the tungsten localities does not suggest an orderly arrangement of the tungsten ores. As for example, they do not become any more productive to the north nearer the Tavoy deposits of Burma (26). This may indicate not only that the Malaysian deposits are not just an offshoot of the deposits of Burma, but that the two may be part of a large belt of distribution which may extend well into central Borneo.

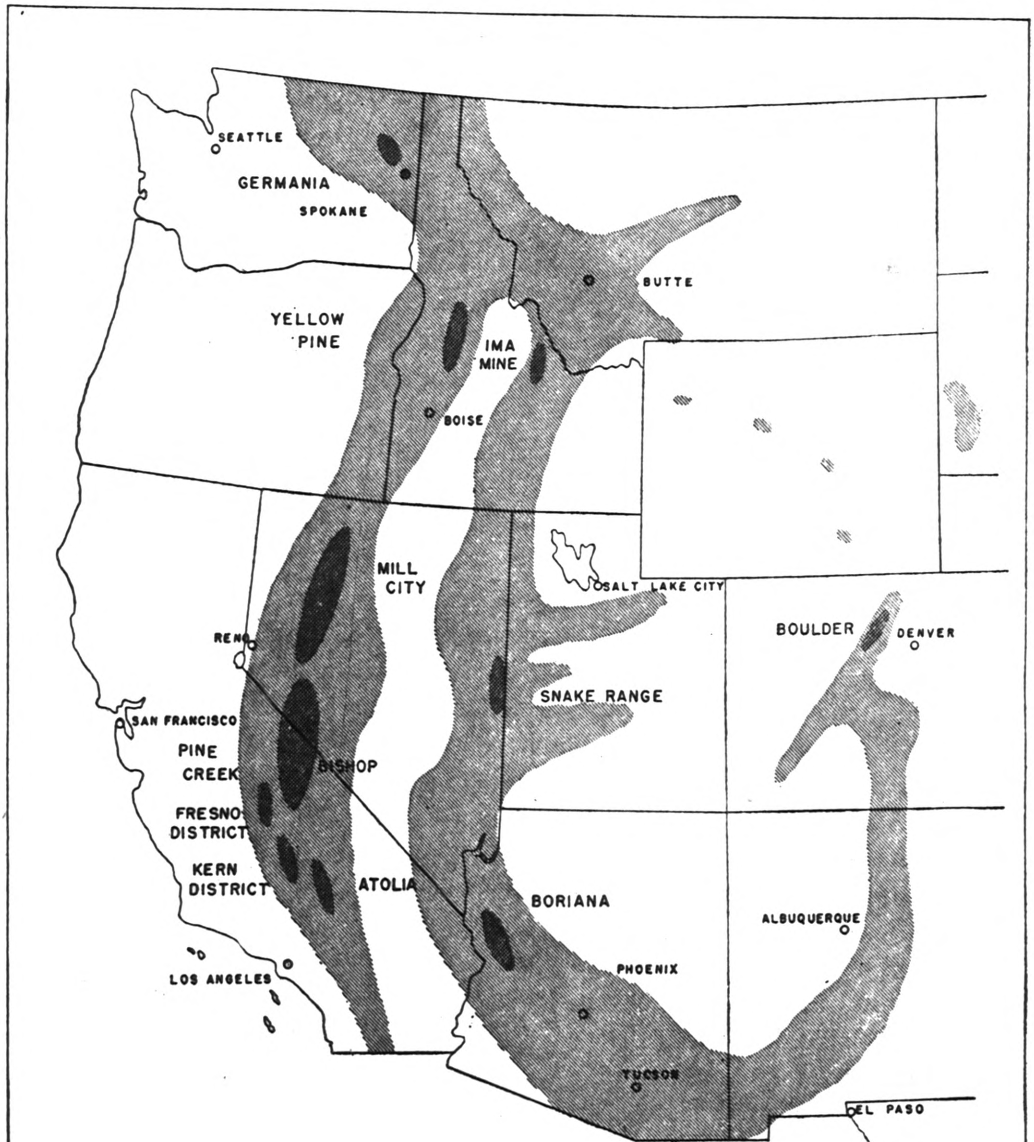
C. Relation to Source Magma

1. General Composition

The tungsten which ultimately reaches pegmatites, veins, replacement, and other types of deposits is derived from a predominantly granitic type of magma. Granite and granodiorite are the most common rock types of the intrusives associated with tungsten deposits, although monzonite and quartz monzonite are not uncommon. Diorite and syenite are reported in close proximity to certain ore deposits, but their genetic connection to the ores is in doubt (21).

2. Tungsten Content

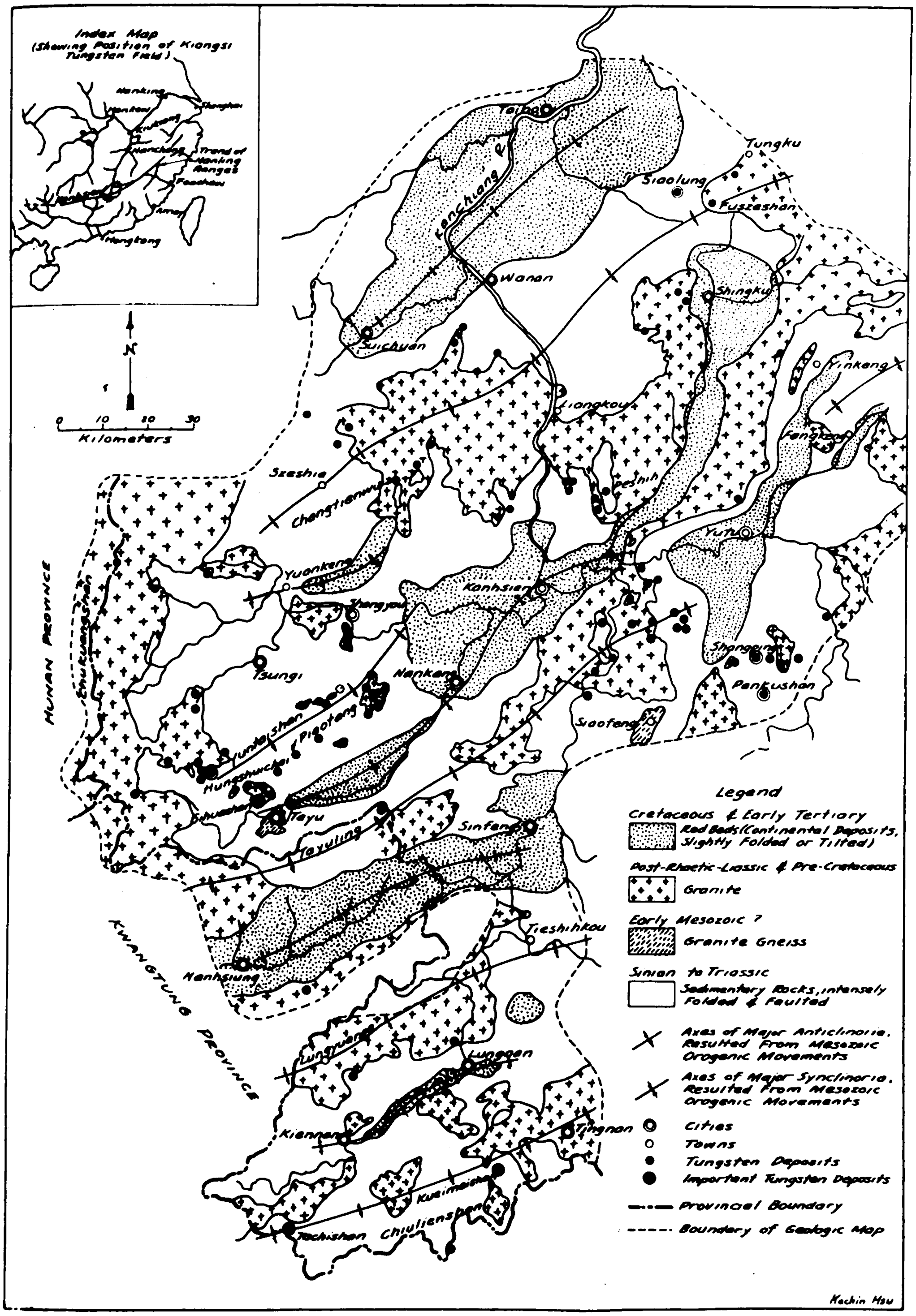
Magmas vary considerably in tungsten content. The distribution of tungsten deposits over the western United States indicates that the Cordilleran igneous sources must have had a comparatively large tungsten content. The same is true of the granitic areas of southern China, Burma, Malaya, and Bolivia. However the distribution of the tungsten in the intrusive bodies originating from these source magmas indicates a remarkable degree of localization of the tungsten. Though scattered specks of scheelite have been found in numerous places in aplites, no true disseminated deposits of tungsten are known. The Whetstone Mountains occurence near Benson, Arizona, described as a disseminated deposit by Hess (1933) (14), has been shown by Wilson (1941) (33) to be an irregular concentration of end stage material, hence more in the nature of a segregation. The selective distribution of tungsten in dikes is also remarkable. In spectrographic work by Bray on the Tertiary dike rocks of the Front Range, Colorado, the only dike of the six dikes analysed that showed any trace of tungsten was one directly related genetically to tungsten ore deposits. It is also worth noting that the only other dike also related to ore deposits, while it showed no trace of tungsten, showed a unique similarity to the one mentioned here in other minor elements, particularly in nickel, cobalt, and chromium (3). This spectrographic tracing of minor elements, though still in the experimental stage, may prove a very useful tool in the search for tungsten.



Tungsten-bearing zones in the western States

More productive regions are indicated in darker shade. Important districts are shown by name.

From " Tungsten Mineralization in the United States ",
P.F. Kerr , Geol. Soc. of Am. Memoir 15,
(1946).



Map of Kiangsi Tungsten Field.

From <u>Tungsten</u> by Ching Kuo Li,
Reinhold Pub. Co, New York,
(1943).

III. TUNGSTEN DEPOSITS

Temperature of Formation	Zones of Formation	Subzones	Forms		Examples
atmospheric	surface		eluvial*		placer deposit Atolia, California
50° C-200° C	epithermal		quartz veins		huebnerite veins Tonopah, Nevada and Cripple Creek, Colorado
200° C-300° C	mesothermal		quartz veins	replacement depos.	Boulder County,** Colorado, and Kiangsi, China
300° C-500° C	hypothermal	lower limit	quartz veins		Kiangsi, China Bolivia Portugal Australia
		upper limit	quartz veins		Malaya Burma Kiangsi, China
500° C-800° C	pyrometasomatic		contact metamorphic deposits		scheelite deposits in California and Utah
575° C-1000°C	orthotectic	lower limit	pegmatoid deposits		pegmatites in Burma, China, and United States
		upper limit	segregation deposits		granite at Mawchi, Burma

Table of Tungsten Deposits taken from Kuo Ching Li and Chung Yu Wang, Tungsten, Reinhold Co., New York City, 1943.

*Ought to include hot-springs deposits, example deposits at Golconda, Nevada.

**Now considered epithermal. A better example would be the mesothermal huebnerite veins in Lemni County, Idaho.

A. Pyrometasomatic Replacement Deposits

1. General Considerations

a. Distribution

According to Frank Hess, "Few tactite tungsten deposits (contact metamorphic deposits, ed.) are known outside the United States, though they are found on King Island between Tasmania and Australia, in Mexico and Korea," (15). The conditions responsible for contact deposits of tungsten represent a restricted phase of those prevailing for contact deposits generally. The intrusive must be of the acid granitic type described in the previous section, and the intruded country rock must be highly calcareous, (limestone or dolomite, pure or impure).

b. Chemical Behavior

There seem to be no examples of the ability of tungsten to replace anything but highly calcareous rocks. A striking example of this selectiveness is demonstrated in the Yangtaishan tungsten zone of southern Kiangsi. Here are found numerous examples of the replacement of granite and aplite dikes by a peculiar mica rich greisen. The replacement is quite extensive, and the greisen is rich enough in cassiterite to justify its being mined as a tin ore. But the cassiterite is the only ore mineral in the greisen. The wolframite is strictly limited to the associated veins. Evidently there is a remarkable difference in behavior of tin and tungsten in replacement processes (7).

It is therefore not surprising that contact metamorphic deposits are extremely rare in southern China and Burma, since the invaded country rocks are almost exclusively non-calcareous pre-Cambrian and pre-Devonian schists, sandstones, phylites, etc. In Bolivia the country rock is chiefly metamorphosed quartzite.

c. Stages of Formation

It is convenient to divide the formation of a contact metamorphic tungsten deposit into five separate stages: the original limestone, marmorization, initial metamorphism, advanced replacement, and regressive effects. All these stages are not universally present however. In the vicinity of some deposits granite may be found in direct intrusive contact with limestone, without metamorphic effect.

The initial composition of the invaded limestone may vary widely without materially effecting the ultimate product of metamorphism. Where the forces producing the metamorphism are weak, alteration may follow certain bedding planes, such as an oölitic bed, or it may follow streaks of impurities.

In the process of marmorization a blue or grey limestone is changed to white. Analysis indicates a proportionate increase in the magnesium and silica. Marble zones are erratic in their distribution; although frequently found near the intrusive, they may occur at considerable distances, and localization of the marble at the contact is not necessarily expectable.

Initial metamorphism is characterized by pale garnet, fiberous wollastonite, pale vesuvianite, and the rest of the minerals belonging to the "pale zone" of Hess and Larsen (15). Initial metamorphism appears to be low in tungsten content. Traces are found, and often nuclei of more advanced metamorphic minerals yielding a few grains of scheelite are found. Zones of initial and advanced metamorphism may be too mixed to map, but much unnecessary exploration could be avoided if this distinction were kept in mind.

In the zones of advanced metamorphism, darker contact silicates predominate, and the limestone is more completely altered to a garnet rock, commonly rich in quartz and epidote. In some deposits tungsten is found in contact rocks rich in magnetite, andradite, plagioclase and hedenbergite. These rocks are more properly termed "skarn" in preference to the more common "tactite".

Regressive effects in contact tungsten deposits take the form of late, widespread quartz impregnation. The major replacement stage is frequently responsible for considerable volume change. Where this volume change is negative, shrinkage fissures are produced at right angles to the stratification. The shrinkage fissures are filled by this late quartz. These later solutions are generally barren of additional tungsten. They may be inaugurated by the deposition of a little pyrite, pyrrhotite, chalcopyrite and sphalerite, but the later sulfides with lower melting points are more abundant in the tungsten bearing quartz veins.

2. Prospecting Considerations

a. Distribution of the Tactite

Three major factors influence the distribution of tactite; proximity to the intrusive contact, variations in the chemical composition and permeability of the original limestone, and structural control.

(1). Proximity to Contact

Tactite usually borders directly on the contact of the limestone and the intrusive. However, there are many exceptions. Wilson, in his report on the Darwin Hills District, states that the tactites are not always confined to the immediate environs of the exposed stock, nor is there any consistency in the areal pattern of the depth of the recrystallized shear zones of silicate rocks away from the stock.

(2). Variations in the Permeability and Chemical Composition of the Original Limestone

As stated in the general description of alteration, a tungsten bearing tactite may be formed from a pure limestone just as completely as it may from an impure one. In most districts, if there is any preference, the impure limestone is altered rather than the pure limestone. Deposits in Beaver County, Utah offer an excellent example. A pure, white limestone shows little or no replacement, even at the intrusive contact, but a grey, impure limestone is extensively altered. Tungsten mineralization in the grey limestone stops abruptly at the contact with the white limestone (17). On the other hand, in the Darwin Hills district, it is the purer limestone which gets the preference (34). The relative importance of permeability is not fully understood, but no doubt the more permeable limestones are more extensively altered.

(3). Structural Control

The dip of the limestone beds at the intrusive contact frequently exerts considerable influence on the size and distribution of tactite. The deposits of the southern Sonora District, Mexico (31), and those in Beaver County, Utah (17) are greatly influenced by this type of structural control. It is evident that within these regions the mineralizing solutions traveled up very close to the intrusive contact, and out along the bedding planes of the limestone. The largest and deepest tactites are found where the beds dip into the contact at an acute angle. Where the beds are parallel to the contact, or dip away from it, no tactites are found.

There is a marked relation between the distribution of tactite and the fracture system in some areas. In the Darwin Hills, for example, tactites are prominent where both large and small elements of the fracture system transect purer limestone (34).

b. Distribution of Ore within Tactites

(1). General

In many deposits, as in the Nightingale District, Nevada (27), the scheelite is well disseminated throughout with only a minor amount of localization in small quartz veins or cracks. Hence, in reports on such deposits the distribution of the ore is not distinguished from the distribution of the tactite.

Scheelite frequently occurs in pockety lenticular zones within the tactite, generally parallel to the walls of the tactite. Ore zones must be relatively near the intrusive contact, but chances of finding ore are not in direct ratio to the nearness. In Lower California, Mexico (10) some deposits have the ore zone on the marble side of the tactite, others have ore on the igneous side, while still others have ore zones completely within the tactite. There is no constant relationship between the width of the tactites and the width of the ore bodies they contain. In the southern Sonora District areas where tongues of granite have penetrated the limestone for some distance from the main contact are especially favorable for ore (31). Fries and Schmitter report that in Lower California prospecting is best on and near contacts between the quartz diorite and moderately large beds of metamorphic rock. Small roof pendants, even if they contain good ore, can hardly be expected to produce considerable tonnages. Neither can small limestone beds (10).

(2). Structural Control

Channels of ascent of the ore bearing solutions are of two types; those formed by post-tactite faulting, and those along the contact of the tactite and the igneous injection, or the contact of the tactite and impervious bed, such as a schist.

In the scheelite deposits of northeastern Brazil, the country rock at the contact is schist. The limestone beds lie at some distance from the contact and are interbedded with schist. The ore is localized at the contacts of the limestone and schist, where apparently the solutions were offered freer passage (18).

The formation of tactite tends to seal up the pre-existing fractures and prohibit their use as channels by the later ore depositing solutions. In Beaver County, Utah broad zones of breccia in strongly metamorphosed, dark limestone are found to be completely barren. The metamorphism was post-brecciation (17).

But post-tactite fracturing which opens up new channels for the ore solutions is not uncommon. In the Darwin Hills District scheelite ore bodies are formed at structural clusters where elements of the fracture system transect variable combinations of bedding plane slips, brecciated beds, and purer beds of altered limestone. A given mineralized cross fissure will localize shoots of ore only when metal deposition is facilitated by entry into one of these prepared horizons. Thus the relative permeability of a bed structure defines the ore reservoir. Economically, in this district, fractures of the northeast tension group are of most importance as broad guides to ore distribution. Northwest tear lines are not entirely free of mineralization, but are of no economic importance.

In the Serra Nevada deposits near Bishop, California, the absence of scheelite and other ore minerals in many of the tactite bodies indicates that the channels were sealed before the tungsten and sulfide solutions reached them. Continued shearing of the brittle earlier minerals, among which garnet predominates, helped keep passageways open until final mineralization. In some deposits post-mineral faulting continued the same general shearing, but in other, where post-mineral faulting is absent, there is no existing proof that shearing occured prior to the deposition of scheelite (23).

(3). Guide Minerals

In some deposits certain minerals may be so closely associated with the scheelite that they may prove useful as guides in locating ore. In the Old Hickory Mine in Beaver County, Utah, scheelite is generally found to be more abundant in beds rich in magnetite. In northeastern Brazil scheelite is closely associated with epidote, garnet and quartz. These three minerals are considered guide minerals for tungsten in the district. Though high grade quartz-scheelite-garnet ores often occur, the epidote-quartz-scheelite ore is generally more productive and the highest grade tungsten accumulations seem to favor this association.

B. Quartz Vein Deposits

1. General Considerations

Most of the tungsten deposits of the world are of the quartz vein variety. They vary all the way from the late pegmatite type to the epithermal type. The hypothermal type is by far the most important.

a. Distribution of Tungsten

As a general rule we may take the commonly dome shaped contact of the granitic intrusive as an ideal surface of reference which divides the tungsten lodes vertically into two groups of about equal value. Almost all tungsten veins, whether mostly within the granite or mostly within the country rock, can be traced to the contact. While numerically more tungsten bearing veins are found within the associated intrusives, the veins in the sedimentary rocks are generally richer.

b. Paragenesis

(1). Hypothermal Deposits (7)

In hypothermal veins wolframite and molybdenite are considered early vein minerals. In general wolframite crystalizes later than tourmaline and zinnwaldite, but earlier than quartz, orthoclase, scheelite, and all sulfides except molybdenite. Wolframite is commonly penetrated or replaced by scheelite, pyrite, pyrrhotite, arsenopyrite, bismuthinite, chalcopyrite and other sulfides. Although replacement by scheelite is common, most scheelite in wolframite bearing veins is believed to be primary. Scheelite is sometimes found deposited in vugs upon chlorite.

Massive quartz, which constitutes 90% to 97% of the volume of ordinary tungsten veins, crystallizes later than tourmaline, zinnwaldite, topaz, orthoclase, beryl, molybdenite, wolframite, cassiterite, bismuthinite, and native bismuth, overlaps the crystallization periods of fluorite, arsenopyrite, pyrrhotite, magnetite and some pyrite, and is earlier than chalopyrite, pyrite, sphalerite, galena, tetrahedrite, stannite, sericite, chlorite and calcite.

There is convincing evidence that the advanced pneumatolytic metamorphism and replacement, (greisenization)is a phase slightly earlier than, and different in nature from, the introduction of the ultra-siliceous solutions which deposit the common wolframite quartz veins.

A third stage of mineralization is frequently observed to follow the deposition of the wolframite, cassiterite, scheelite, pyrite, molybdenite and bismuth. The minerals of this later stage include sericite, chlorite, chalcopyrite, pyrite, galena, sphalerite, tetrahedrite, and stannite. Sericite is the most common.

Because of its economic importance, the relationship between wolframite and sacciterite deserves particular attention. William R. Jones (19) maintains that cassiterite was deposited at a higher temperature and before the wolframite. J. Morrow Campbell (6) maintains that cassiterite was deposited later than the wolframite. J. Coggin Brown (4) and A. M. Heron (13) support the contention that the wolframite is the elder mineral. However, there is no doubt that cassiterite is present in relatively larger quantities in veins traversing granite than in those which lie in sedimentary rocks, nor is there any doubt that the opposite is true of wolframite. Thus if wolframite is the older mineral some additional factor besides temperature is involved.

(2). Mesothermal Deposits

Mesothermal tungsten veins are much less common than either hypothermal or epithermal veins. In this type of deposit tungsten is also regarded as an early mineral. The mineralogy of these veins is apt to be complex and the paragenetic relationships obscured. The mineralogy of the huebnerite veins of the Blue Wing District of Lemhi County, Idaho, one of the outstanding examples of a mesothermal tungsten deposit, has been described by Umpleby (30). The most striking feature brought out by a study of these ores is the absence of a definite sequence in the formation of the constituent minerals. Only one period of mineralization is recorded. In some places the huebnerite occurs with distinct crystal outlines, indicating that it was first to form. In other places it is so intimately intergrown with spalerite that it must be contemporaneous. The two are frequently in contact with, and bear the same relation to, the inclosing quartz. In places sphalerite includes pyrite, molybdenite and tetrahedrite. Elsewhere pyrite includes the last two and probably also chalcopyrite. Galena seems contemporaneous with sphalerite. The tungsten in this deposit, which may be somewhat exceptional because of its complexity, is intimately associated with the zinc.

(3). Epithermal Deposits

Tungsten in epithermal veins appears to be a late deposit. It is frequently associated with the tellurides which are generally deposited slightly later. In his report on the ferberite veins of the Magnolia District, Colorado, Wilkerson (32) gives the following sequence of mineralization: quartz; quartz and hematite; quartz; quartz, pyrite, marcasite, and sphalerite; fluorite (?); calcite (?); quartz, pyrite, alunite, and ferberite; tellurides and native gold; ferberite; and last quartz, ferberite and pyrite.

c. Mineralization in Tungsten Veins

Of the thirty or more tungsten bearing minerals, only scheelite and those of the ferberite-hübnerite series, chiefly wolframite, are important ore minerals of tungsten. According to Hess and Schaller (16) it is probable that in the presence of both iron and calcium, scheelite is the tungsten mineral most likely to form. Thus it is almost the only mineral of tungsten in tactite deposits. Where calcium is subordinate, some member of the wolframite group is to be expected though practically all wolframite quartz veins contain minor amounts of scheelite. But large occurrences of scheelite without a trace of the wolframite group are common. According to Ahlfeld (1a) ferberite and huebnerite, the extremes of the series, seem to be the dominant minerals of tungsten in deposits classified as mesothermal and epithermal. Wolframite is the usual dominant mineral in hypothermal vein deposits.

2. Prospecting Considerations

a. Structural Control

Tungsten bearing veins seem to be subject to all the structural controls in the formation of traps, etc. that influence the localization of ores in most other types of metalliferous veins. The solutions may be blocked by an impervious layer, as they were by a diorite sill at the Red Rose Mine in British Columbia (29). The distribution of ore may be closely related to the distance of the veins from the related intrusive, as at Lemhi County, Utah. In this area, valuable ore shoots are confined to the quartzite within a few hundred feet of the granite contact where the ore shoots are confined to the larger parts of the veins, the grade of ore increasing in proportion to the width of the veins (5).

Hypothermal tungsten veins show two interesting types of distribution; regions in which the tungsten veins are clustered into relatively small, well defined areas, within which all the veins are mineralized, and generally converge downwards, and broad regions, such as southern Kiangsi, in which the tungsten bearing veins are widely distributed, but show a marked degree of parallelism throughout.

The first type is well illustrated by the tungsten deposits of Burma. According to Campbell (6) the majority of the tungsten deposits occur in small patches, the length of which is sometimes equalled by the width, neither dimension over 2000 feet. The series of veins within the circumscribed areas are invariably mineralized, and little wolframite is found outside these areas. An extraordinary number of these deposits occur on hill tops. This suggests the silicification accompanying mineralization may have made the mineralized areas more resistant to erosion than the surrounding country rock, so that topography may serve as a guide in location of ore. These deposits are estimated to be within 800 feet of the igneous contact below. The ore does not persist for more than 300 feet down. The thermal gradient is relatively high. Comparing this to the low thermal gradient of the Morro Velho gold mine of Brazil, in which the ore persists to an unusual depth of more than 6400 feet, and in which the thermal gradient is very low, Campbell suggests that the thermal gradient should be used as a guide to the persistance of ore at depth. The tungsten deposit of Isla de Pinos, Cuba (25) is a similar group of converging veins, and the deposits of Bolivia offer a third example. However the Bolivian deposits, such as that at Chicote, in which 72 veins and veinlets bearing tungsten occur in an area of four square kilometers, do not show such marked convergence. Here the veins strike in any direction and dip at any angle. The ore persists to a depth of over 1300 meters.

The second type of distribution, that of the southern Kiangsi region, has been partially described in the first section of this paper under distribution. In this area all the tungsten bearing veins have steep dips. Within each locality the veins dip in the same direction at nearly the same angle hence are parallel.

Within the area as a whole the tungsten bearing veins show a remarkable regularity in their strikes and dips. The diagram below illustrates the regularity of the strikes of tungsten bearing veins (20).

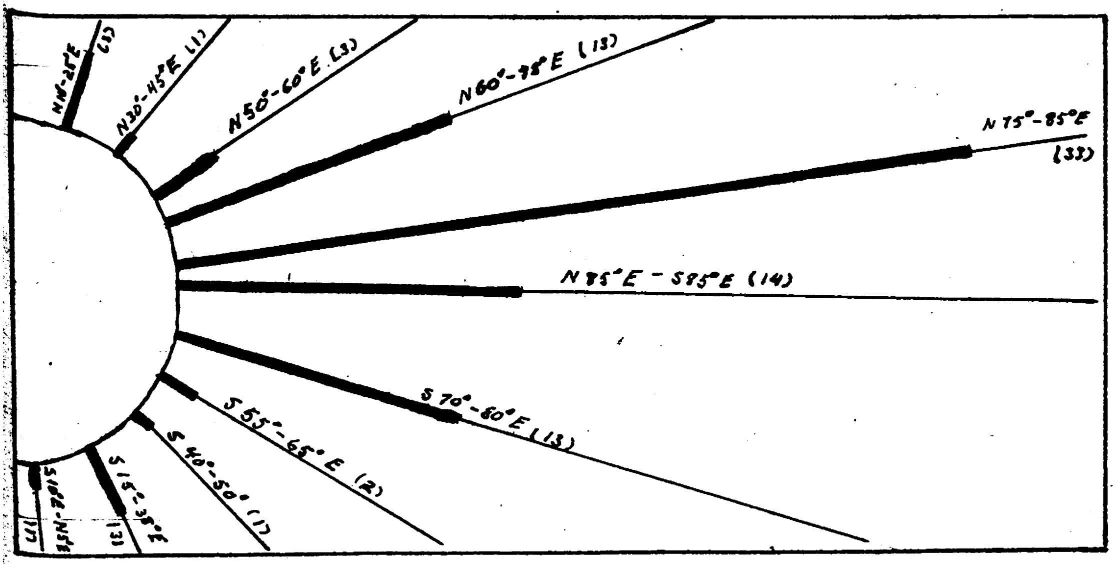


Diagram showing the prevalent strikes of the tungsten veins of southern Kiangsi. Longer rays represent the more common strikes. Numbers in parenthesis represent the number of localities.

taken from "The Tungsten Deposits of Southern Kiangsi, China", by Ke-Chin Hsu, Econ. Geol., vol. 36, p. 431-474, (1943).

It is also worth noting that within this region the sedimentary cover is frequently an impervious phyllite, and it is common to find considerable enrichment at the contact, due to the impounding of the tungsten bearing solutions.

b. Alteration

In some areas the alteration of the wall rock surrounding tungsten bearing veins offers useful guides in the locating of ore deposits. The alteration accompanying the ferberite veins of Boulder County, Colorado, supplies the pre-eminent example. It has been described in detail by Lovering (24). A narrow zone of sericitic alteration encases the ferberite veins, but gives way abruptly to a wider outer envelope of argillized rock. As a vein is approached, the country rock becomes bleached and soft, but adjacent to the vein its appearance changes remarkably. The bleached chalky aspect is lost, giving way to rock of much more normal appearance. The general effect is that of a layer of fresh granite separating the vein from a wide zone of strongly altered granite, which in turn grades outward into fresh rock. Under the microscope, the apparently fresh rock close to the vein is found to be strongly sericitized, and slightly silicified, carrying some carbonate. The argillized envelope may be divided into three sub-zones; an outer sub-zone where the bleached rock grades into the fresh, and in which the chief alteration minerals are allophane, montmorillonite (?), hydrous mica, and sericite; an intermediate sub-zone, in which beidellite is abundant; and an inner sub-zone of intende alteration containing much dickite. Minerals of zones closer to the vein generally replace those of zones further away. This zonal alteration is also defined by the type and degree of alteration of the ilmenite in which the country rock is relatively rich. This ilmenite shows four zones of different alteration which, going from the fresh country rock toward the vein, may be described as follows: first zone, slightly altered to leucoxene; second zone, slightly altered to hematite and leucoxene; third zone, strongly altered to hematite and leucoxene; and fourth zone, closet to the vein, altered to pyrite, magnetite (?), titanite and leucoxene.

The zones of alteration described above are associated with all the veins of the district, and a few locally productive veins lie in almost unaltered rock. The alteration is useful only as a guide in outlining the general area of hydrothermal activity, and the degree of alteration is a measure of the intensity of this activity which makes it useful in determining which areas are most likely to yield ore.

In the Boriana District of Arizona, the wolframite-scheelite veins are found penetrating a country rock of phyllite and slate. The phyllite close to the richer parts of the veins is softer and more sericitized (17a).

C. Pegmatite Deposits

1. General Considerations

Tungsten minerals are found in pegmatites, but not in abundance. The studies of pegmatites by Landes (22) are largely negative from the standpoint of tungsten deposition. Tungsten minerals in pegmatite dikes belong to the later phase of pegmatitic alteration. The stage of tungsten deposition is closely related to the period at which pegmatites grade into high temperature quartz veins. The close relationship of pegmatites and aplites is a common feature of tin and tungsten occurrences. However, according to Kerr (21), field relationships suggest that the pegmatite or aplite may have marked the channel of the tungsten in solution rather than its final resting place. The role of pegmatites and aplites is probably much more important in the migration and accumulation of tungsten than the few pegmatitic occurrences of the element would suggest.

2. Prospecting Considerations

Aside from the well known criteria which distinguish complex ore bearing pegmatites, in general, from the simple, barren variety, not much can be said about guides to finding tungsten in this type of deposit. Complex pegmatites within an area known to contain tungsten deposits formed at high temperatures, such as hypothermal veins or tactites, ought to be examined for tungsten minerals. Pegmatite dikes may be more resistant to erosion than the surrounding country rock, and may stand out as ridges, as they do in the southern Sonora District (31). Pegmatites with a low over all tungsten content may have their tungsten minerals concentrated in large pure masses so that they are economically workable. The deposits at Oreana, Nevada are of this type and contain large masses of pure scheelite. The tungsten here occurs not only in pegmatite dikes cutting a metadiorite intrusive but also in lense like pegmatitic masses lying on the inclined contact between the metadiorite and the limestone below. These masses show a marked alinement suggesting that they followed channels. These channels do not intersect any of the pegmatite dikes, as far as is known, but it is suggested that if such an intersection were found it would probably be a very favorable site for ore (21a).

D. Secondary Enrichment Deposits

Tungsten does not form secondary enrichment deposits in the ordinary sense of the term, since the tungsten minerals are relatively insoluble, and when they do dissolve the tungsten rapidly hydrolyzes to form insoluble compounds, and its downward migration is halted (16). But Campbell discusses stock-work deposits in Burma which have weathered in situ to the extent that they can be profitably worked by ground sluicing. In a sense these could be considered a secondary enrichment since the ore before weathering was too hard and too low grade to be workable and could be considered a protore (6).

E. Eluvial Deposits

Tungsten minerals are brittle and relatively soft. They are easily reduced to very small particals and in this form are easily dissolved and washed away. Debris from strata very rich in tungsten veins in Burma contains virtually no tungsten after having been transported only a few miles. But a great proportion of the world's tungsten production to date has come from talus and slope wash deposits confined to the vicinity of deposits in situ. There are no true alluvial tungsten deposits, though some deposits such as the placer deposits at Atolia, California have been interpreted as residual desert deposits. The alluvium of the Atolia region is low in tungsten, but its gold content has made it profitable to work with tungsten as a by-product (21). For prospecting, it is obviously advisable to examine the stream beds and slope wash of known tungsten deposits, and it is equally obvious that the drainage systems of streams carrying tungsten ought to be carefully searched for tungsten deposits in situ.

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F. Hot-springs Deposits

There are two types of hot-springs deposits; distributed veinlets underlying an area of spring deposition, and outflow lenses of spring deposit accumulation. The later type, as illustrated by the deposits at Golcanda, Nevada (21b) will probably prove to be the most important, although very few such occurrences of tungsten have so far been recorded. Tungsten in these deposits is colloidal and is associated with colloidal manganese or iron (wad or limonite).

The colloidal condition of the tungsten has so far been a major obstable to its economic development. It is not amenable to physical methods of separation. The tungsten content of ore required for the chemical methods now employed must be double what would be required for gravity separation.

At Golonda a number of deposits several acres in area have been found, the only surface indication of which was the iron stained soil in spots around the margins of broad rounded mound-like hills.

G. Segregation Deposits

A deposit worked at Mawchi, Burma, sometimes erroneously referred to as a disseminated deposit, is the only known example of an economically workable segregation deposit of tungsten (7). It consists of scattered pockets of cassiterite, wolframite, tourmaline and completely kaolinized feldspars. These pockets may be regarded as irregular concentrations of final magmatic liquid, therefore as segregation deposits. Their formation has been described by J. A. Dunn (9). Similar occurrences are found on Robinet Ridge, Boriana, Arizona, and in the Whetstone Mountains near Benson, Arizona, but these are too lean to be workable.

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