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Abstracts - Base Erosion Model
Details of Northward Drift
May 1975

LARAMIDE PLATE TECTONICS AND PORPHYRY COPPER DEPOSITS
OF THE AMERICAN SOUTHWEST

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May 1975

Most, if not all, of us attending this symposium have often pondered the uniqueness of the Late Cretaceous-Tertiary boundary of the western United States and responded to questions concerning how, why, when, in what way, and, in particular, WHERE was good olde Mother Nature unique during Laramide time and exactly how deep must one drill. Thousands upon thousands of company reports, manuscripts, maps, sketches, etc. have concerned most aspects of the LARAMIDE, and, since offered the opportunity this spring, I might as well add still another dimension by attempting a Global Tectonic approach to the problem.

Many fundamentals of the plate tectonic model which I wish to develop are summarized on Figures 1a, 1b, and 1c. Figure 1a depicts many of the more critical geologic details of the North American plate after 100 million years of W- to WNW-directed drift away from the mid-Atlantic Ridge (Coney, 1972). The mottled pattern shows the areal distribution of the Late Cretaceous seaway as it appeared at circa 76 m.y.B.P. (Gill and Cobban, 1966). At 75-80 m.y.B.P. quiescent sedimentation dominated most of the seaway and large volumes of black shale and mudstone accumulated, as mirrored by the Upper Mancos, Lewis, Kirkland, Pierre, and Bearpaw Shales. Beyond the western strandline, however, immense prisms consisting of continental fanglomerate and conglomerate of the Overton, Price River, and Evanston Formations accumulated along the active front of the Sevier Thrust Belt (Cobban and Reeside, 1952; Spieker, 1949; and Armstrong, 1968). But this protracted style of Late Cretaceous marine-continental deposition, as well as many other pre-Laramide patterns, terminated or changed drastically prior to or during Laramide time. Many of the more apparent changes are shown on the 65 m.y. plate tectonic reconstruction of Figure 1b.

By 65 m.y.B.P. the shallow epeiric sea, which bathed the western interior since Early Cretaceous, abruptly retreated to the Gulf Plains, leaving in its wake a systematic progression of off-lapping strandlines flanked interiorly by coal-bearing marshlands, flood plains strewn with carcasses of Triceratops and Trachydon, and patterns of tectonism, plutonism-volcanism, and sedimentation unlike any experienced previously or since in western North America. The dominant feature of the Southwest and Rocky Mountain Region during latest Cretaceous and Paleocene time was the presence of a composite system of N-to NW-trending mountain ranges which extended from Mexico to Canada. Each individual mountain uplift became a source area from which conglomerate, fanglomerate, and finer grained fluvial detritus were shed into small flanking intermontane basins such as the Hanna, Bighorn, Denver, San Juan, and Caballona. By mid-Paleocene time the total structural relief between any given differentially subsided basin and uplifted mountain block often exceeded 20,000 feet; yet paleogeographic studies demonstrate that the ranges were eroded about as rapidly as they were uplifted and at no time did lofty heights exist for long periods (Love, 1960; and Van Houten, 1961). In contrast then with the intense localized stratigraphic and structural telescoping so characteristic of the Sevier, Idaho-Wyoming, and Montana Thrust Belts of pre-Laramide age, Laramide mountain building was dispersed across a major epeirogenic warp composed of numerous subdued local uplifts reminiscent of those envisioned by King (1958) and Roberts (1968).

Synchronous with the initiation of Laramide epeirogenesis throughout the Central and Southern Rocky Mountains, plutonism-volcanism likewise swept rapidly eastward to the present Rocky Mountain Front. Figures 2a and 2b summarize the chemical affinity of Laramide igneous rocks from Arizona. Similar plots are reproduced by coeval igneous rocks from Colorado and New Mexico although they are, in general, more alkali-rich. Employing the suite index classification (Rittmann, 1962) and the alkali-lime index (Peacock, 1931), most fresh Laramide igneous rocks from the American Southwest are demonstrably medium calc-alkaline (Rittmann) or calc-alkalic to alkali-calcic (Peacock). Near identical petrochemical trends are shown by averages of the main plutonic facies of the Mesozoic batholiths of California (Figure 2a) as well as the rhyolite-andesite formations of Peru and Chile (Figures 2a and 2b). These data clearly demonstrate that volcanic and plutonic rocks of the Southwest have chemical affinities common to petrotectonic assemblages found in Andean-like intra-continental and mature island arcs of the circum-Pacific. Moreover, studies concerned with the spatial and temporal distribution of Hidalgo, Silver Bell, and Cat Mountain calc-alkaline volcanic rocks and their coeval sub-volcanic equivalents show that these arc-like magmas first surfaced throughout the Southwest at circa 75 m.y.B.P. (Figure 1b) with porphyry copper alteration-mineralization following shortly thereafter.

Assuming that Laramide plutonism of the Southwest is indeed arc-related, one can predict the depth (h) to the paleo-Benioff zone following arguments presented by Dickinson and Hatherton, 1967; Hatherton and Dickinson, 1969; and Dickinson, 1970. In these papers the authors demonstrate that the K_2O level in erupted lava from active arc volcanoes increases somewhat systematically with depth to the inclined seismic zone. Similar conclusions were reached by Ninkovich and Hayes (1972) following their synthesis of all Indo-Pacific arcs. Figure 3 summarizes the K_2O-SiO_2-h curves for the Andean-arc as given by Dickinson (1970), and the Indo-Pacific arcs analyzed by Ninkovich and Hayes (1972). The 100 fresh Laramide analyses plotted on Figure 3 suggest that the depth to the Laramide Benioff zone below Arizona was between 150 to 250 km. Wedding these petrochemical data with the plate tectonic reconstruction, absolute plate positions and motions derived in Figure 1b, one can construct with some confidence a generalized plate tectonic model for early Laramide time (75 to 65 m.y.B.P.) as shown on Figure 4. The proposed working model predicts a very shallow dipping Laramide Benioff zone (20° or less) and that this shallow to sub-horizontal attitude caused calc-alkaline magma generation to become protracted over a much wider zone and indeed became displaced inboard from the Sierran volcano-plutonic orogen by as much as 800 km (Colorado Porphyry Belt and Tyrone-Santa Rita-Hillsboro Porphyry Belt).

Persistent waxing and waning of intra-arc plutonism and volcanism within the expanded epeirogenic welt mechanically weakened the crust, terminated compressional tectonics (so characteristic of the back-arc and foreland settings of the Sevier Belt), and initiated bi-directional ($ENE\pm 20^\circ$ and $NNW\pm 20^\circ$) extensional tectonics accompanied by subordinate wrench tectonics along strands of the Texas zone.

It was within this regional and plate tectonic framework that polycyclic, water-saturated sub-volcano plutons repeatedly experienced the requisite physical and chemical conditions conducive to the localization and preservation of porphyry copper alteration-mineralization in the American Southwest.

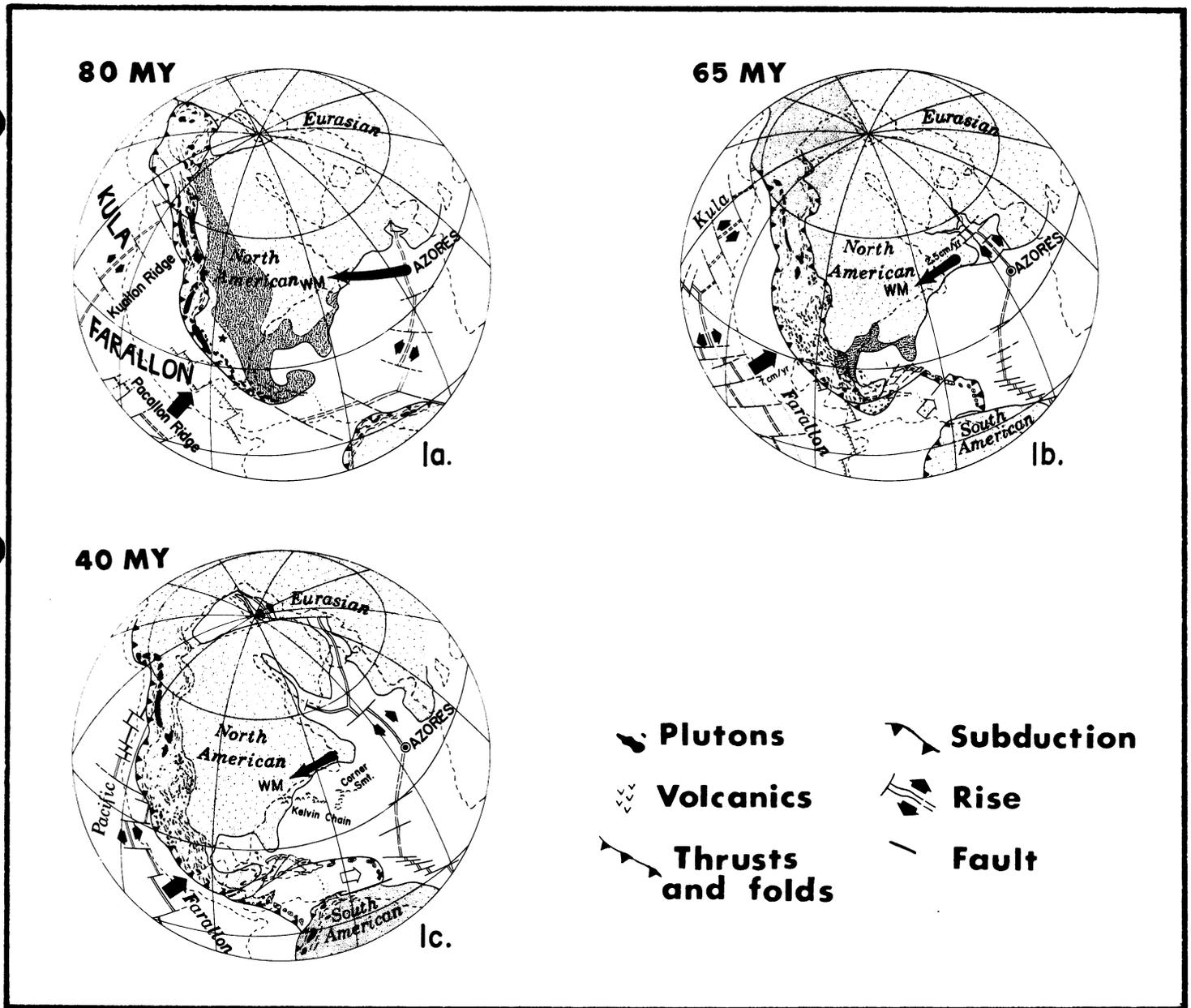
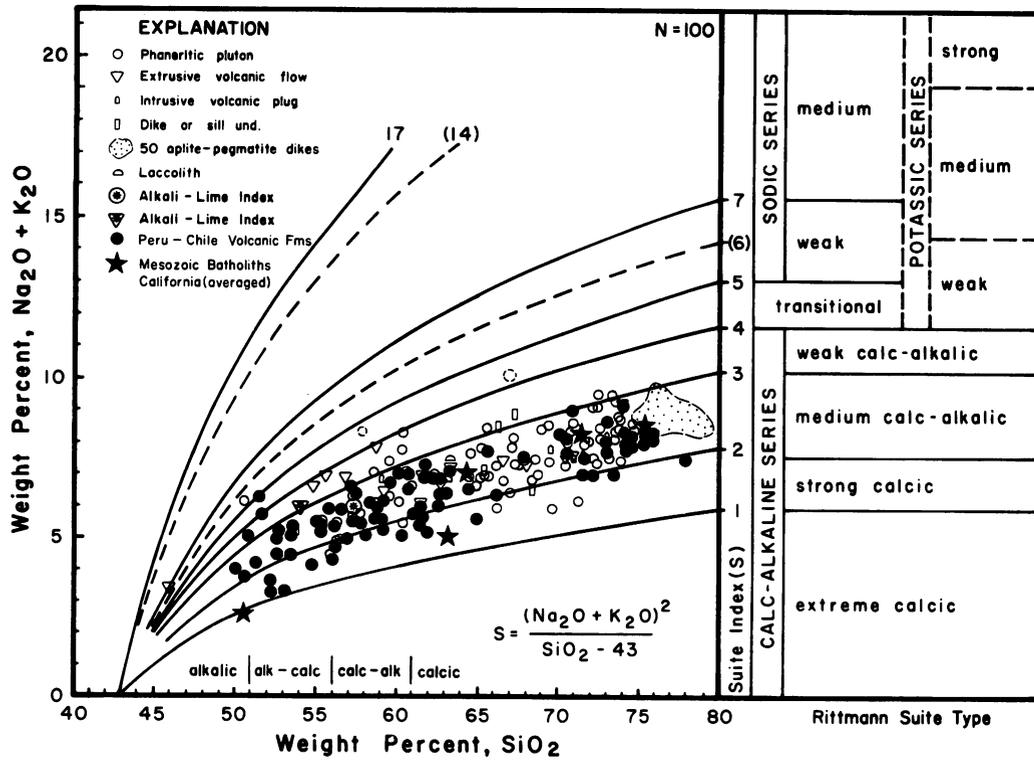
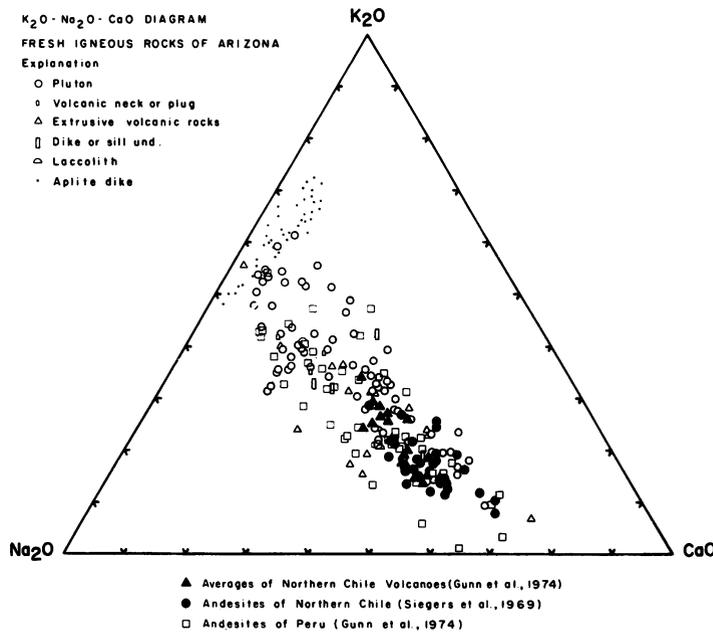


Figure 1. Plate tectonic reconstructions showing absolute configurations at 80 m.y. (A), 65 m.y. (B), and 40 m.y. (C). Absolute position of plates is relative to present coordinates, with light dashed lines showing the present position of continents. Heavy black arrows represent the assumed absolute motion vectors for each construction. Tectogenetic development, absolute position, and motion vectors for North America are modified after Coney (1972, 1973). Length and direction of absolute motion vectors for the North American plate summaries drift from 180 to 80 m.y. (A) and from 80 to 40 m.y. (B and C) where the position of the White Mountain magma series (WM) is at the tip of each arrow and assumes that this series overlaid the Azores hotspot at 180 m.y. (Morgan, 1971). Distribution of plate boundaries, movement plan, and tectogenesis of the Caribbean are modified from Malfait and Dinkelman (1972). Reconstructions of Late Mesozoic and Tertiary spreading patterns in the Pacific Ocean are derived from magnetic isochron plots given by Larson and Chase (1972) and assume the poles of rotation proposed by Clague and Jarrard (1973) for the Pacific plate and a 42 m.y. age for the Hawaiian-Emperor bend.

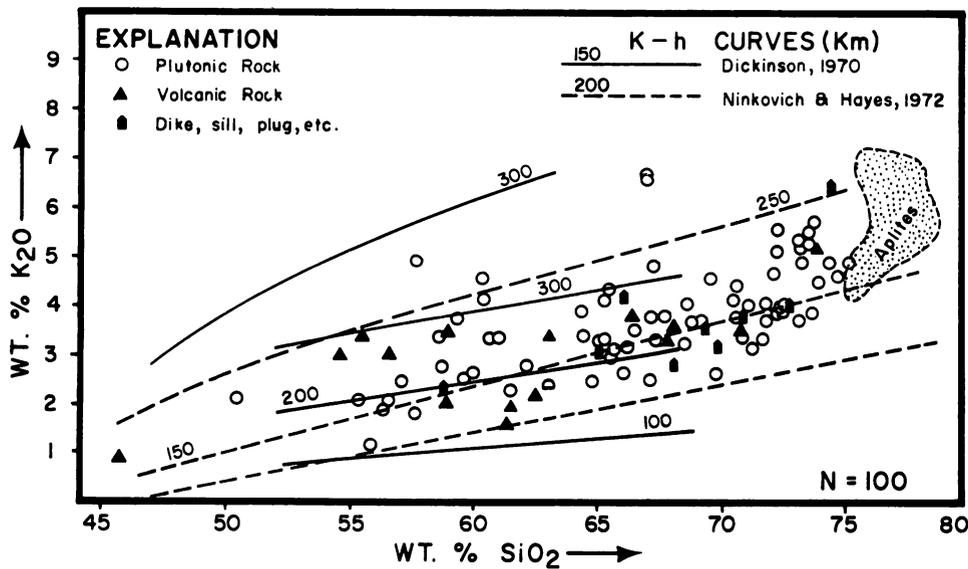


2a.

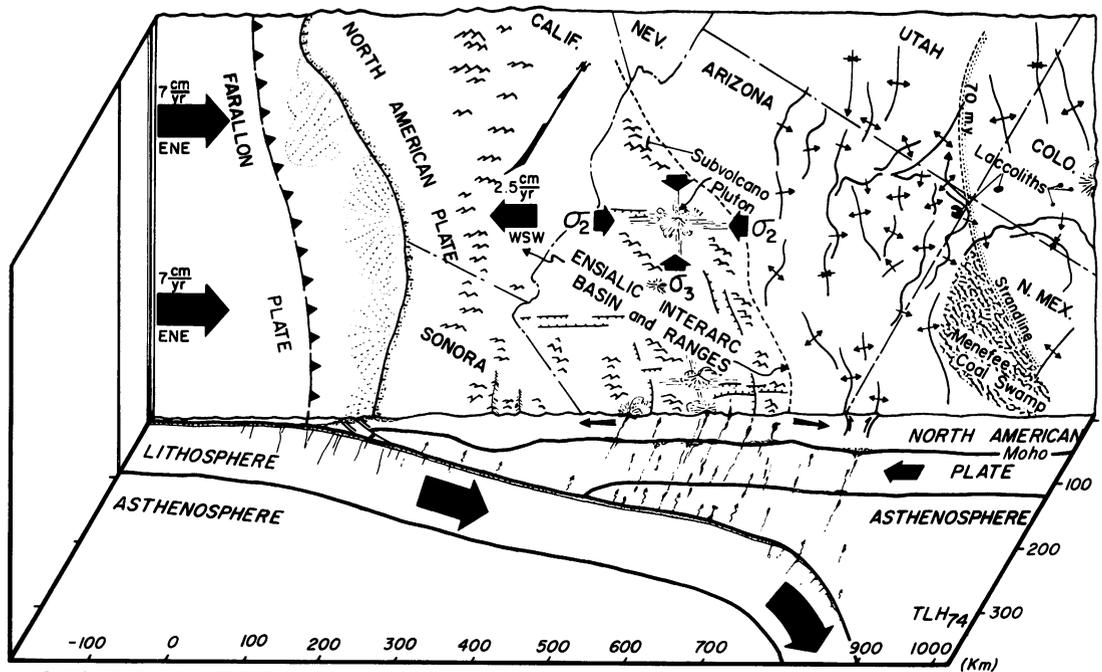


2b.

Figure 2. $K_2O + Na_2O - SiO_2$ and $K_2O-Na_2O-SiO_2$ variation diagrams for 100 fresh Laramide igneous rocks from Arizona. Igneous rock classifications (Fig. 2a) follow the suite index (Rittmann, 1962) and the alkali-lime index (Peacock, 1931). Analyses of the Chile-Peru andesite-rhyolite formations plotted in Fig. 2a are from Pichler and Zeil (1969).



3.



4.

Figure 3. K-h-SiO₂ plot of 100 fresh Laramide igneous rocks from Arizona. Depths to Benioff zone (h) adapted from data published by Dickinson (1969) and Ninkovich and Hayes (1973).

Figure 4. Generalized paleotectonic reconstruction of the American Southwest from 65-75 m.y.B.P. Dark, heavy arrows on the Farallon and North American plates are absolute motion vectors derived in Fig. 1b. Suggested regional tectonic stress field after Rehrig and Heidrick (1972) and Heidrick (1974). Paleoenvironments are modified from McGookey et al. (1972).

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THOMAS W. MITCHEM

SCIENTIFIC COMMUNICATIONS

**Pre-Ore Environment of Southwestern North
American Porphyry Copper Deposits**

SPENCER R. TITLEY,
U.S.A.



✓ COPPER MINING AND ARIZONA LAND USE PLANNING A GEOLOGIST SPEAKS

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Professor of Geosciences
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Ed. Note: This is the second article in a series on the factors influencing land use planning decision making.

INTRODUCTION

Copper deposits of Southern Arizona constitute a nearly unique resource on this planet. There are few other known locations where the forces and processes of nature combined to form such a concentration of metal in such a restricted region. The great number of discoveries on the Island of Luzon during the past ten years suggest that a small part of the Philippines are similarly endowed and, although of a different origin, similar concentrations of copper are known in the Democratic Republic of the Congo and in Zambia in south-central Africa. Also, other large deposits of the type found in southern Arizona occur in the western hemisphere, but nowhere are these deposits found in the known abundance and concentration as in this part of the American southwest.

In deciding the best use of the gradually vanishing undeveloped land in the United States, many problems are

being created by expanding population and man's requirement for a quality environment. Not the least of these requirements is the requirement for the preservation of certain areas in their natural state. Curiously, concern for the future of mineral resources has not appeared to be a factor in many of these decisions. In Arizona, the problems of land use involve another variable which must be considered: the presence of large bodies of ore. The professional voice of the exploration geologist seems to have been strangely muted while the debate on these decisions continues. Although the debate continues concerning the level of atmospheric contamination acceptable in extracting and processing copper, and heated words are being exchanged between various interest groups about land and mineral law reform in state and national capitals, the knowledgeable citizen hears or reads little, if any, strictly geological information in reports of these debates. He is generally presented statistics of economics and production, and the occasional sweeping generalization that copper deposits occur in the ground and must be mined to extract the metal.

The problems of contamination resulting from processing and extraction are rightfully those of the present, and their consideration is long overdue.

Solutions, however, must be in terms which recognize the uniqueness of the known and potential copper occurring in this region. Equally important are the problems of land use and land acquisition. Many known and certainly some as yet undiscovered copper ore bodies exist in southern Arizona; these *must* be considered when land use decisions are being made and before the "system goes critical". Geologic understanding and the role of the professional geologist must no longer be ignored if wise policy is to be made. It should be the duty of the interested policymaker, the lawmaker, and his constituents to acquire, if not an understanding, at least an appreciation of the occurrence and distribution of certain natural resources in Arizona, the United States, the Western Hemisphere, and the world simply because world mineral economics and technology are becoming increasingly important in political decisions. Arizona cannot isolate herself from these broader aspects of mineral resource occurrence and use. The decisions and plans which must be made must recognize that a major resource exists which is not only State, but national in scope, and that copper, as well as other metals, occurs only in certain regions and often to the exclusion of other metals.

Continued on page 2

A NOTE FROM THE DIRECTOR:

DEPARTMENT HEAD NAMED

It is my pleasure to announce the appointment of Dr. Thomas J. O'Neil as Head, Department of Mining and Geological Engineering, College of Mines, The University of Arizona.

Dr. O'Neil, who is a specialist in the field of mineral economics, has been a graduate student and full-time faculty member of the Department of Mining and Geological Engineering since 1968. Prior to coming to The University of Arizona, Dr. O'Neil received a B.S. degree in mining engineering from Lehigh University, Bethlehem, Pennsylvania, and an M.S. degree in mining engineering from Pennsylvania State University, University Park, Pennsylvania. He has been a development engineer for Ingersoll-Rand Company, Rock Drill Division, and an industrial engineer for Kennecott Copper Corporation, Utah Copper Division.

Dr. O'Neil has been an active participant in professional society and College activities. He is currently the national secretary of the Mining and Exploration Division of the American Institute of Mining, Metallurgical and Petroleum Engineers, and a registered Professional Mining Engineer in the State of Arizona.



Dr. Thomas J. O'Neil, recently appointed Head, Department of Mining and Geological Engineering.

GEOLOGIST SPEAKS *Continued*METALLOGENIC PROVINCES
AND COPPER DEPOSITS

Most metals which man extracts occur in abundance in discrete (well defined) regions termed *Metallogenic Provinces*. Several metals may occur together in deposits in one region or province (*polymetallic provinces*), or provinces may contain only one metal. The copper deposits of southern Arizona compose a polymetallic province because they also contain as by-products molybdenum, zinc, and some gold and silver. For hundreds or thousands of years man has recognized the discrete nature of the occurrence of metals. However, it has been only during the past decade with the increased number of discoveries that the discrete nature of many provinces has been revealed, and that geological, geophysical, and geochemical data have provided what geologists now consider a firm basis for beginning to understand where and why discrete provinces might occur.

Historically, the recognition of a metallogenic province has had lasting political and economic implications. We are now concerned with the present and future importance of copper in Arizona. Curiously, this region indirectly figured in a major political decision based on concepts of metallogenics nearly 200 years ago. A belief propounded by the Greeks that gold resulted from the interaction of the sun's rays with certain types of fluids in the earth was propagated into the late part of the second millenia. With this belief, Spain concentrated her efforts at conquests in the New World to those regions where the sun's rays were strongest. After several hundred years of fruitless search based on this concept, Spain relinquished all territorial rights in the western hemisphere north of the Gulf of California in the treaty of 1790. (Godwin as cited by Adams, 1938, p. 283). Hopefully, our understanding of the processes of natural concentration of metals has advanced during the past 180 years. Hopefully, also, our growing understanding will aid in the development of policies which will further the clean, intelligent, and wise extraction of those metals which occur in this region, long ago mistakenly ignored by Spain.

There are more than thirty presently known copper deposits in southeastern Arizona and adjoining parts of Mexico and New Mexico. Of these, only ten were being mined in 1953; the remaining 21 deposits represent discoveries or rediscoveries made since then (see Table 1). All but four occur in southeastern Arizona. Not all of these are presently

Producing Prior to 1953

Ajo
Bisbee
Castle Dome
Cananea
Chino (Santa Rita)
Copper Cities
Inspiration - Miami
Magma
Morenci
Silver Bell
Lag. (10).

Production Since 1953

Christmas
Esperanza
Mission
Pima
Sierrita
San Manuel
Twin Buttes
(7)

Table 1
MAJOR COPPER BODIES IN CONTIGUOUS
SOUTHEASTERN ARIZONA, NEW MEXICO, AND SONORA

Discoveries and Developments

Copper Creek
Helvetia
La Caridad
Lake Shore
Kalamazoo
Poston Butte (Florence)
Red Mountain
Rosemont
Sacaton
Safford (KCC)
Safford (P.D.)
Morenci (Metcalf)
Tyrone
Vekoi
(14)

Producers in northwestern Arizona
(Not Shown on Map)

Mineral Park
Bagdad
(2)
Total 33

being mined or developed, but it seems certain that most have the potential for ultimate development and extraction. It takes only a simple arithmetic operation to appreciate the fact that since 1953 the rate of discovery in this region has been more than one per year, a record of discovery unparalleled in any other region of comparable size. The fact that these discoveries have been and continue to be made in this small part of the southwest attests to the unusual geologic quality of this region.

Exploration continues in this part of the North American continent because a large number of deposits occur in this region and thus the probability for discovery is certainly higher than in most other parts of the continent, and indeed, in most other parts of the world. The copper bodies which are being sought and which have been found belong for the most part to a distinct genetic type of deposit termed "porphyry copper". Although differing to varying degrees in the details of their geology, most of these deposits are broadly similar to each other in the way they came into being, in the nature in which the rocks containing copper have been modified, and in the amount of copper which they contain. They are correctly termed large, low-grade copper deposits. Despite their "low-grade", however, they represent very anomalous amounts of copper when the earth as a whole is considered.

The amount of copper in the deposits of Arizona is variable but averages between 0.4% and 0.6% (8 to 12 pounds

of copper per ton of rock). The processes which act in and below the earth's crust produced this concentration. Parts of some deposits in Arizona have been upgraded to smaller volumes of around 1% copper or 20 pounds of copper per ton of rock by processes which have acted at the surface of the earth in the geologic past by dissolving and re-precipitating this lower grade copper. It is noteworthy that much of this copper has been mined in the past several decades and extraction of copper is now, in large part, that of the lower ore grades. Although of lower grade, the copper in these deposits is still present in amounts of from 8 to 12 pounds per ton of rock. This represents the end product of a natural upgrading of copper from 0.02 pounds per ton in the deep rocks of the earth to 12 pounds per ton in a copper deposit—an enrichment of 600 times the amount of copper present in the deep rocks below the crust! Clearly, unusual processes must have acted to bring this about, and although it is beyond the scope of this article to discuss modern arguments and thoughts about those processes in any detail, it is undeniably true that it has happened, *and only in special places on earth*. Southern Arizona is one such place.

One important aspect of this amount of copper in the rocks of Arizona deposits deserves further comment. This amount of copper, 0.4-0.6%, is the result of a complex sequence of geologic events. Nature has exceeded this level of concentration in only a few copper

bodies. Consequently, man has to work with rocks containing this small amount of copper. There is no way to upgrade or increase the amount of copper in these rocks, and we certainly cannot wait the millions of years necessary on the off chance that nature would upgrade it further. It should go without saying that the more copper in a rock, the more valuable it becomes, and those who search for and extract copper would desire nothing better than to find and produce copper from rocks of higher metal content. The fact that copper can be profitably produced from rocks of such low grade is basically a reflection of the necessity to do so but is also testimonial to the quality of man's technology and his imagination in devising low-cost extractive techniques.

Figure 1 shows the location of all operating large copper mines in southeastern Arizona and adjoining parts of New Mexico and the State of Sonora, Mexico. In addition, the map shows other known bodies of copper mineralization of this region that are either prospects where the amount of copper contained can be economically extracted or copper bodies presently undergoing development. Several characteristics of this map deserve comment.

First, the distribution of these mines and mineralized bodies is not erratic. They occur as features of a broad arcuate belt as illustrated in Figure 2. This belt starts near Nacozari, Sonora, and extends from there northwestward into Maricopa County, where it turns eastward, extending across Arizona into southwestern New Mexico. This belt and the copper deposits within and closely adjacent to it ignore county, state, and international boundaries. That more deposits occur in Arizona than in Mexico or New Mexico within the belt may simply reflect the lack of thoroughness with which those adjoining regions have been explored. We do not yet know if copper bodies of the sort which occur in the arcuate belt occur in any great quantity outside of or within the area enclosed by the belt in southern Arizona and adjoining regions, but the possibility is real.

Second, it is noteworthy that the known ore deposits occur as separate bodies of copper mineralization; that is, the bodies are isolated. There is no indication from geology as it is presently known and understood that there is any continuous mineralization by copper in economic quantities in this belt. It is significant that in many instances the copper deposits apparently occur in clusters. Such clustering is known in the Sierrita Mountains southwest of Tucson, where at least four separate bodies occur in a restricted area. Other clusters occur



Fig. 1. Map showing principal copper mines, development, and prospects in the Southwestern Copper Province.

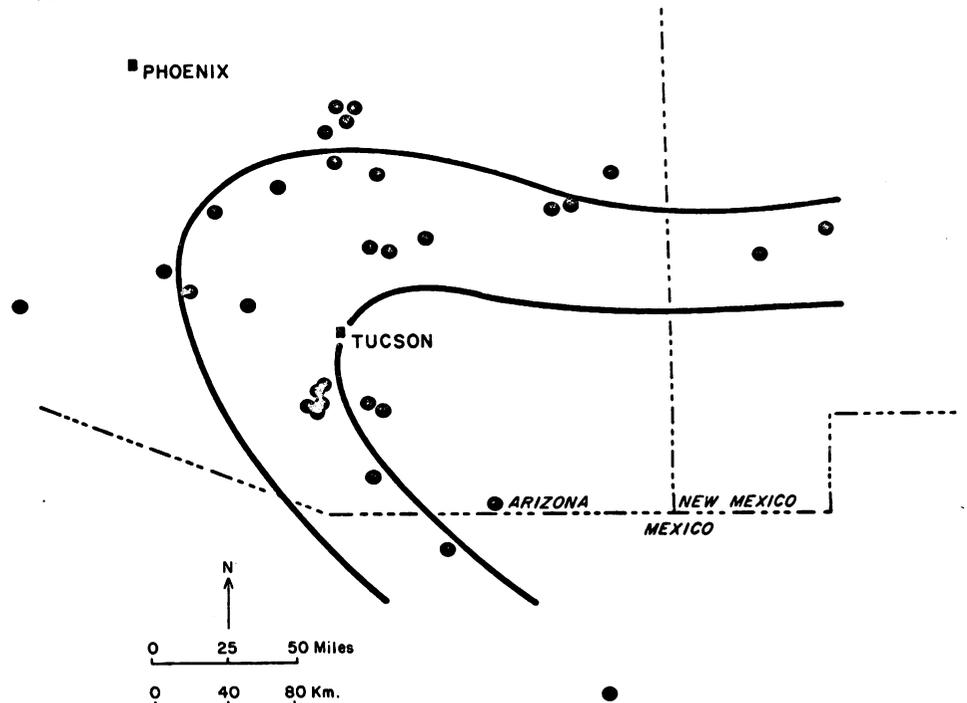


Fig. 2. Provisional geologic boundaries of the southwestern copper deposits.

in the Globe-Miami area, and there is strong suggestion of clustering in the San Manuel-Copper Creek region, as well as in the group of deposits near Safford. Exploration is far from complete in and around many of the deposits of the region, but when it has been completed, it is likely that presently known bodies in many parts of the belt will be revealed to have been parts of a cluster of copper ore bodies. Reasons for the clustering are not known, but it is an important aspect of our knowledge of the nature of

occurrence of copper bodies not only in this region but others as well.

Third, the ore deposits shown on the map reflect, with only one possible exception, the position of *old* mining districts. This in itself is a potentially valuable tool in land zoning decisions. Up to this time all the copper bodies except for the one at Sacaton reflect the results of thorough and sometimes deep exploration of some areas where mineralization was already

Continued on page 5

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GEOLOGIST SPEAKS *Continued*

known. The fact that one was found at Sacaton, apparently unrelated to previously recognized mineralization, however, is a fair portent of the future course of exploration and discovery of copper bodies in the arcuate belt. In some instances, old mining districts hold a high probability of having a deeply buried "heart" of copper ore somewhere near them, *but* there is also a high probability of discovery within the arcuate belt of copper deposits which have not yet revealed their presence in any way now recognizable.

Fourth, the arcuate belt of porphyry copper deposits is a belt of deposits of only one age and one type. Not included in this belt are copper deposits of other ages such as those at Bisbee, Ithaca Peak, near Kingman, and Bagdad. These deposits, together with a host of smaller base and precious metal deposits, occur within and near the area of the belt. Thus, the position of the belt as now defined should not be construed as the final outline of the position of known porphyry copper deposits. As discoveries increase in other parts of the region, it may be possible to better define the factors controlling the location of other porphyry copper deposits in the areas adjoining the arcuate belt. The arcuate belt *is* an area in which the probability of discovering additional copper deposits of one age and type is very high. The areas adjoining the belt still manifest a good probability of at least some as yet undiscovered copper bodies occurring because of the presence within the area surrounded by the belt of Bisbee, and the presence of Ajo, Ithaca Peak, and Bagdad outside of it.

Finally, most of the copper deposits of southeastern Arizona occur in a region that once was the shallow shelf of an ancient sedimentary basin, although we cannot say for certain why they should be there, or if indeed there is any direct relationship. The basin, which extended through what is now most of Cochise County and into Sonora and Chihuahua Mexico, is no longer recognizable as such

Continued on page 8

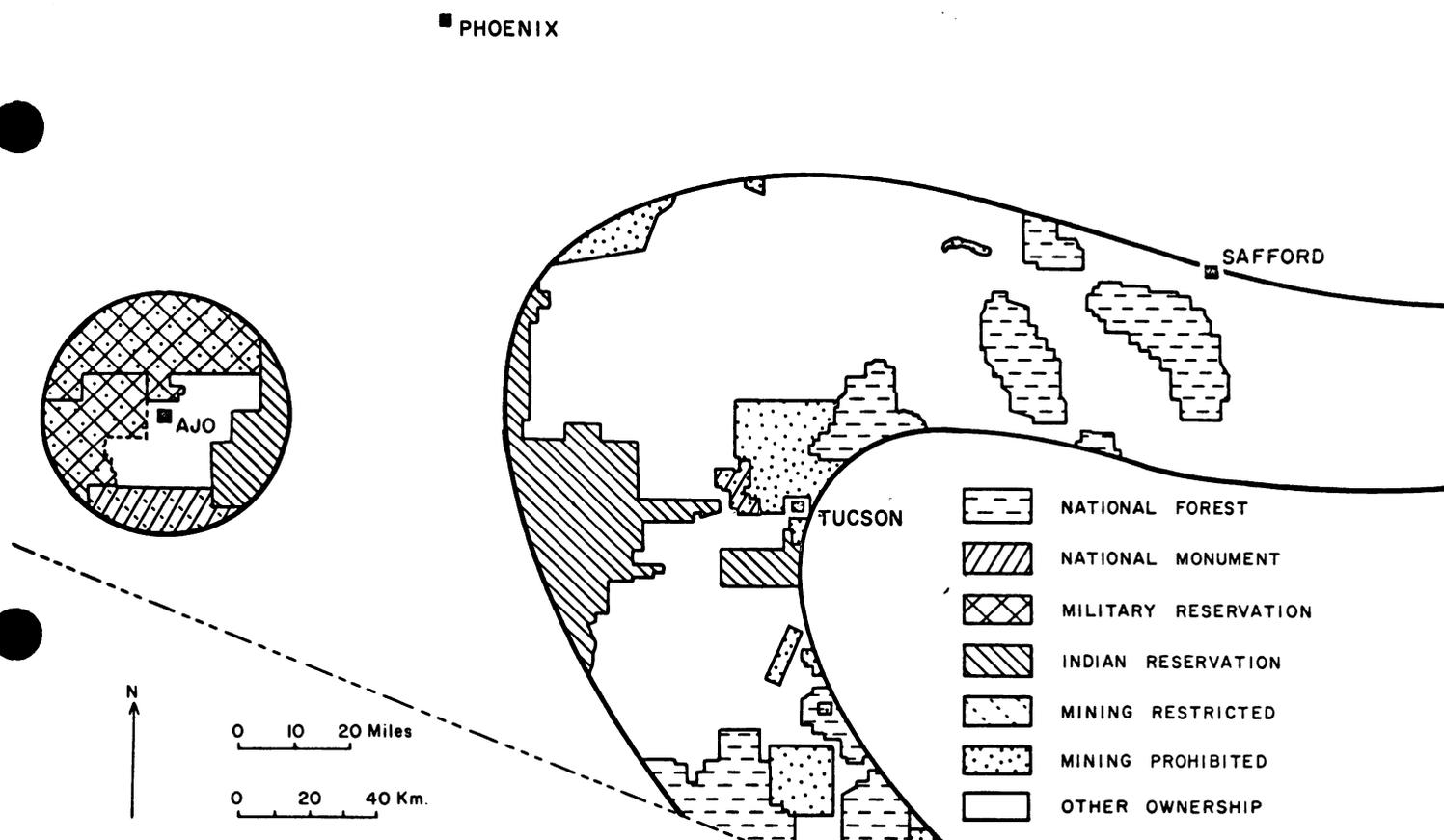


Fig. 3. Land ownership status within the Southwestern Copper Province and in the vicinity of Ajo (modified from land status map in Reference 2).

GEOLOGIST SPEAKS *Continued*

but is interpreted with a high degree of certainty from the distribution and thickness of rocks which formed in it. At about the end of the age of dinosaurs, the basin edge was the site of the evolution of a great number of volcanos. It was by these volcanic processes, which lasted about 15 million years, with their buried chambers of copper-bearing molten rock serving as a source, that nature formed the copper deposits of southern Arizona. Evidence for this is rather good—we can see the volcanic rocks near and about many of the deposits of southeastern Arizona, we can determine that they are of about the correct age to be related to the copper deposits, and in many places they contain copper mineralization. Where we see clusters of copper deposits, we are probably seeing the now-cooled granitic rock hearts of a cluster of ancient, long-gone volcanos.

Therefore, the arcuate belt containing the copper deposits can not only be drawn simply by including most of the known deposits of this region in the complete absence of geological knowledge, but also, it can be described in terms of lines grossly identifiable with rocks whose geologic importance is recognized.

LAND STATUS

The preceding discussion has been a summary of much geologic thought by many who have studied these deposits for a long time. There is not total agreement on certain concepts of genesis or formation of the deposits, but there is general concurrence that a large number of deposits occur here. Intense exploration underway here now attests to the general belief that more exist than have been found. There is a region in southeastern Arizona where, in comparison with most other regions on earth, the probability of finding copper deposits is very high. This fact leads to a consideration of the distribution of various types of land and land ownership in Southern Arizona.

Figure 3 is a base map outlining those areas with differing regulations governing mining. The gross outline of the arcuate belt of copper deposits in southeastern Arizona has been superimposed. As can be observed, the land types within the belt include virtually all types of lands set aside or recognized for some special purpose. Indian reservations, national forests, areas of definite mining prohibition, game and special ranges, and national monuments as well as a variety of public and privately held lands

compose the varied ownership, and reflect the diverse nature of regulations governing or prohibiting land acquisition for mining purposes. The small scale of the map precludes showing a great amount of detail but this information may be gained from a study of the larger scale state publications (2). What is significant about this map and its superimposed geologic information is the great diversity of ways in which land is already designated for purposes other than extraction of mineral resources in a region now recognized as having an unusual and unique potential for copper mineralization.

SUMMARY

Regarding land status and potential ultimate use in southern Arizona, in my opinion the following comments and questions merit more than passing consideration *now*, in the early 1970's.

This nation, bounteously endowed with mineral resources and mineral wealth, seems always to have taken them for granted. So long as land was plentiful in the West, there seemed no reason to consider them otherwise. With few exceptions, when designating the status

Continued on page 10

YEAR 2000 *Continued*

required to meet the challenge ahead of us in meeting the needs of "The Second America". Our young people have a challenge which has been unequalled in history . . . the challenge of assuring a quality life for every American while preserving our environment and our natural resources. For, if the solutions to the problems we have been discussing are to be found, they must be found during the working life of these young men and women.

GEOLOGIST SPEAKS *Continued*

of lands, their characteristic as specifically mineral-bearing or of high mineral potential has received little attention. With no intent to suggest that any special formal status be given southern Arizona and her known and potential copper resources, can we perhaps now at least recognize that there exists here a unique planetary resource? And cannot this recognition be "factored" into future decisions regarding all sorts of land use planning?

There has been an indifference towards the way the land has been spoiled in not only the extraction of mineral resources but sometimes the search for them. This indifference has resulted from our mineral wealth and the immense land in which to search for them. Public pressure and the recognition of some sort of problem have led to steps to improve this situation. We need only look to the future of the development of additional copper in this region, however, to gain some idea of the immense nature of the potential and continuing problems that extraction and processing will bring to the State.

It is perhaps a major understatement to say that the problems posed by the present and potential incompatibility of extraction and processing on one hand, and urban growth and maintenance of environmental quality on the other, are challenging. They are like no others known on earth at this time. It is fair to say, however, that the first steps towards their solution will come from an awareness of their existence on the part of the citizenry, state policymakers, and industry.

Do we not now, then, have a two-fold obligation, first, to recognize the value to Arizona and to the nation of the unique copper resource that is Arizona's and, second, to recognize the need *now* for

imaginative planning for development of that resource with a minimum of environmental and esthetical impact? Problems are solved by cooperation. They cannot be solved by completely ignoring their existence, or by ignoring them until they have reached a point where their solution is attended by emotion and a lack of cooperation rather than reason.

Primarily, should we not now be considering the potential impact of sharply increasing demands on copper by present and developing technologically-oriented nations and its influence on Arizona copper during the next two decades or longer? Should it not now be possible to begin considering the problem in its entirety rather than the piecemeal fashion which is now and has been the pattern of the past? Is it not time to begin to consider the potential overall problems and take the first steps toward some wise policies and decisions?

Shouldn't we *now* become aware of the potential impact of the ultimate development and exploitation of most of the copper bodies known today over the next 15 years, and the continuing impact of the discovery and development of bodies not yet known? Are we undertaking any research now on the best ways to minimize this impact? Not to my knowledge.

Long range problems exist which we cannot yet even define. But for the present, could we not ask some specific questions? For example, should we not now be planning for the eventuality of development of copper bodies where the arcuate belt crosses the Tucson-Phoenix corridor? Already discoveries encroach upon the path of planned urbanization.

Is it too soon to consider the possibility of a "consolidated" smelting center in Arizona, developed and built by the producers of copper well away from areas of potential urbanization where, through present and developing techniques of low-pollution level processing, Arizona can ultimately derive the economic benefits from the processing of copper and its associated metals?

With a view toward maintenance of the esthetical qualities of the region and lowered extractive costs for ores, should we not now begin to recognize the advantages of certain methods of mining by underground breakage of certain types of orebodies and subsequent leaching of copper—or even extraction of copper by

methods as yet unknown? And should we not be seeking the counsel of ground-water hydrologists on this problem. And is it not time for the federal government to become aware of the fact that major research and "breakthroughs" in extractive processes, not only for copper but for other resources as well, are sorely needed in the national good?

Should we not now adopt an extremely cautious attitude in acts which modify land status in this region through either zoning or withdrawal for some special purpose which result in restrictions and prohibitions on exploration and ultimate development of any mineral-bearing or untested lands in these mineralized regions of Arizona? And should not this same caution apply to other parts of the United States where we can identify metallogenic provinces of the other metals and minerals necessary to our well being?

On an international basis, should we not be considering these same problems with our neighbors to the south in Mexico? Prevailing southeasterly winds do not portend well for the Tucson or Phoenix region in the likely event more copper is discovered and processed in the arcuate belt south of the international border. We must again remember the Metallogenic Provinces are not aware of county, state, or national boundaries.

Finally, is it not time for far-seeing leaders to begin evolving far-seeing plans to accommodate the total resources of this region? There are few places on earth at this time where the juxtaposition of so many potentially incompatible activities have the potential for mismanagement and conflict. Given the proper education, the proper cooperation, and the ability to evolve the proper policies *before* the problems become critical, Arizona may be able to have her cake and eat it too!

REFERENCES:

- (1) Adams, F.D., 1938, BIRTH AND DEVELOPMENT OF THE GEOLOGICAL SCIENCES: Dover, New York.
- (2) OWNERSHIP AND ADMINISTRATION OF PUBLIC LANDS IN ARIZONA, 1971, Arizona, 1971; Arizona Department of Economic Planning and Development, Phoenix.

KAISER
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COMPANY

RECEIVED
AUG 7 1972

TUCSON
KAISER EXPLORATION & MINING CO.

August 4, 1972

J. E. K.

AUG 7 1972

Mr. J. David Lowell
5215 N. Oracle
Tucson, Arizona 85704

Subject: Comments on the Oxidation of
Disseminated Copper Deposits

Dear Dave:

Your invitation to comment on the speculation that disseminated copper deposits are characteristically more deeply oxidized in the ore zone than the peripheral pyritic zone led to a rash of generalizations that I will now try to sort out.

I concur that pyrite is commonly present near surface in peripheral zones, and I confess that it has seemed so commonplace that I had given it little thought. Furthermore, I have formed many of my opinions from work with supergene enriched deposits, and these may require revision. The problem relates to the relative rate of sulfide decomposition, or the rate of formation of reagents, including oxygenated and acidic solutions, and their rate and effectiveness of percolation. Both the amount and strength of the solutions are relevant, but it is assumed that at least some solution reaches comparable depths in both zones and continues to the water table which may be well below the base of apparent oxidation. Therefore, the solutions become ineffective at depth, and some process of "depletion" or "accomodation" is at play.

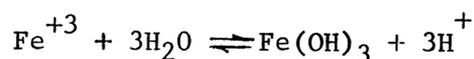
Effect of Host Rock. I had accepted that differential rock reactivity and permeability, or perhaps better stated as alteration and fracturing, were sufficient reasons for the stated effect. The neutralization effect of rock silicates has rarely be treated quantitatively, but in simple tests silicates such as albite and orthoclase will reduce the acidity of dilute solutions 10-1000 times. This effect would be expected with montmorillonite, also, but it is minor with kaolinite and probably sericite. It is

reflected in the prevalence of films of manganese and copper oxide, which precipitate by neutralization, in the peripheral zone.

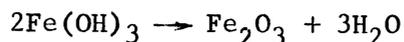
The admonition to "don't look for porphyry copper deposits at the top of the mountain" has less merit with primary or volcanic-associated deposits than with enriched deposits, but they are commonly in low relief where erosional conditions are moderately stable. This suggests a reduction in competency which has been considered to result from alteration, and the more competent peripheral zone may rise above the central deposit. (Interior relief may also be present when a potassic core is exposed.) However, the relative relief may be argued to result from differential supergene effects and reflect the result rather the cause of differential oxidation.

Effect of Sulfide Minerals. When you asked for a chemical explanation relating to the difference in initial sulfide content, I suggested that a quantitative expression would be impossible and that I believed this effect would be overshadowed by the effects of the host rock. I am still of this belief, but I have found in my old experimental work some chemical basis for more accelerated leaching of pyrite-chalcopyrite mixtures than of pyrite only. In a column leaching experiment, in which distilled water was percolated through a mixture of crushed sulfides and quartz, the rate of leaching of chalcopyrite was proportional to the amount of pyrite present, and the acidity of the solution was greater for mixtures in which pyrite exceeded chalcopyrite than for only pyrite. This effect is not present in solutions derived from mixtures of pyrite and molybdenite.

The ratio of ferrous to ferric iron in solutions derived from pure pyrite was markedly greater than that from samples containing chalcopyrite, and it is concluded that the acidity is influenced more by hydrolysis of ferric iron than by the presence of free sulfuric acid. This hydrolysis will occur with ferric ions even in moderately strong acidic solutions,

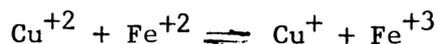


and the iron hydroxide may peptizes to irreversibly form hematite.



Cupric ions will also hydrolyze in more basic solutions, but this effect is relatively minor in solutions containing iron.

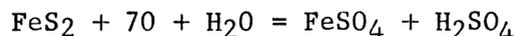
The proportion of ferric iron present is influenced by the presence of copper ions,



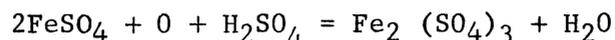
and this reaction proceeds because of the continued removal of ferric ions due to hydrolysis and precipitation. This is the reaction on which a large part of capping theory is based, i.e.,

the transport of iron is retarded in cupric solutions by the accelerated oxidation and precipitation of ferrous iron. (This reaction has a very low equilibrium constant, i.e. it tends to move to the left until the products on the right have a very low concentration. However, the ferric ions are removed from solution by precipitation, and the cuprous ions are unstable unless complexed in aqueous solution and may form cuprite or disproportionate to cupric ions and native copper; the latter may subsequently redissolve.)

The probable reaction for the decomposition of pyrite results in both ferrous sulfate and sulfuric acid,



Oxidation of the ferrous sulfate by aeration consumes half of the acid first formed,



but this is a lethargic reaction in acid solutions, as attested by experimentation in the use of splash towers, aeration sprays, and bacteria to oxidize ferrous iron in recirculated solutions from cement copper plants. (In an equilibrium system, shredded cans would react to reduce all ferric ions to ferrous ions before any metallic copper would be precipitated; therefore metallic copper is unstable in association with solutions containing ferric ions, and it is generally restricted to near the base of the oxidized zone in disseminated copper deposits.)

The oxidation of ferrous ions by cupric ions and the resulting hydrolysis of the ferric ions formed increases the acidity (hydrogen ion content) 50 percent more than that produced by simple decomposition of pyrite. That this is probably a factor in natural systems is based chiefly on empirical evidence that ferrous ions are only slowly affected by oxygenated solutions. Furthermore, these reactions are related to finite decomposition and percolation rates rather than "geologic time", and the solutions will leave the system after a fairly short time if not reacted. Ferric oxides do precipitate in the pyritic zone, of course, and some oxidation therefore occurs. However, the rate of formation or reaction may be retarded, but the unifying effect of possible equilibrium must be considered. In the test cited, the acidity of the solutions from mixed sulfides was less than that of solutions from pyrite only when the weight of pyrite in the pyrite-chalcocopyrite mixture was less than half that of the pyrite sample. The general belief that pyrite produces comparatively more acidic solutions was not, under the test conditions, demonstrated to be true when compared with the solutions produced from mixtures of pyrite and chalcocopyrite.

Mineral Solubilities. The absolute solubility of minerals in a natural system is elusive, but the relative solubility (or decomposition) of the principal sulfides in disseminated copper deposits

seems well demonstrated by experimentation and observation as sphalerite (covellite, chalcocite), chalcopyrite, pyrite, and molybdenite. Although we are considering oxidation reactions rather than strict solubility, all of the minerals form a common anion and would comply with the mass action restriction in an equilibrium system; i.e. a less soluble mineral would be immune from attack until the more soluble minerals were depleted (or converted). This is only imperfectly achieved, chiefly because of the relative isolation of many minerals, but the general pattern exists and reasons for exceptions are commonly evident as due to large mass or enclosure in gangue such as quartz or chlorite. The result is early depletion of copper sulfides in the upper weathering zone, but some relict pyrite and molybdenite may persist for a long period. I would speculate that the decomposition of chalcopyrite in advance of pyrite extends for only tens of feet (but this should be a variable and I am now reaching back into memory). Relict pyrite may give an appearance of greater vertical extent, but I define the oxidized zone as where oxidation has been prevalent (more than half but including almost all sulfides in veinlets) but sometimes a indefinite boundary exists and a transition zone must be recognized. Furthermore, this chemical boundary is often defined in practice on the basis of milling characteristics.

Subjectivity of Observations. Pyritic halos or their capping are more commonly better exposed, fairly quickly recognized, or may have a comfortable simplicity, and they sometimes receive more visual attention than the potential ore zone. The greater retention of pyrite may be in part only due to its greater abundance, and my recollection is of both fairly large veinlets and also of truly disseminated pyrite well enclosed in fairly fresh rock. This search may require some effort with the hammer because of the more massive character of the rock, but the inner well-fractured rock also requires effort to break beyond the myriad of healed fractures that are now, of course, oxidized veinlets, or willpower to look beyond the more significant features of core. This is, of course, a comment of surface evidence rather than depth of oxidation, but I am stressing that isolated retention of pyrite may be unduly weighted because of greater visibility in peripheral zones, or it may even be quantitatively different without giving reason to invoke an unusual explanation other than rock or mineral inhomogeneity.

Effect of Equilibrium. The role of the water table in oxidation-enrichment processes has been clouded by theoretical chemical arguments, but observation suggests that it is the ultimate boundary between the oxide-sulfide zones. To define this boundary by oxidation-reduction potential, or Eh, is chemically correct but of little practical help, for its depth is more related to hydrology and the Eh of natural systems is generally inferred by the products rather than the solution. (At the theoretical oxidation boundary for a porphyry copper system, $Eh=0$ at pH 4.6. This is pH variable, and the zero value has no special significance. The solutions from the leaching tests cited were $Eh = +0.46$ to $+0.63$ and were strongly influenced by the ferric-ferrous ratio. The pyrite vs 3:1 pyrite-

chalcopyrite solutions had ferrous-ferric ratios of 12.3 and 3.7 (and decreased with increased amounts of chalcopyrite), and the redox potentials of the solution were $E_h = +0.55$ and $+0.61$. Thus, it can be generalized that the solution from the pyrite-chalcopyrite mixture were more oxidized, but a quantitative expression of the solution character would be tedious and only approximate.

If the water table is the ultimate boundary (and its effect is due only to the greater mass of ground water relative to percolation water), a uniform depth of oxidation modified only by the water table gradient may eventually be achieved. As a practical matter, however, oxidation as here considered must be absent beyond the sulfide deposit, and some gradient is probable in the outermost zone. Accelerated central leaching might induce both lateral seepage and exaggerated erosional relief, and these effects could enhance an oxidation gradient toward the central area.

The preceding comments are chain-of-thought in character, and you may use them in any way you wish. I will mail them immediately, however, to avoid further delay, but I hope you will invite reconsideration, clarification, or some background references if you feel those steps may be useful to you.

Sincerely,



Joseph J. Durek
Senior Geologist, North America

JJD:la

cc: John E. Kinnison

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

November 22, 1966

*For Cu
General Geol*
937
J. E. K.

NOV 32 1966

TO: J. H. COURTRIGHT

FROM: B. N. WATSON

High Cu/Fe Ratios Related to
Potassic Alteration --- Its
Significance to Exploration

The copper prospect high on the southeastern side of the Whetstone Mountains recently brought to the attention of the Company by Messrs. Devere and Von Fay is, at first glance, a rather unique occurrence. The principal mineralized zone - several thousand feet long by several hundred feet wide and large enough to be considered for open cut mining - contains a system of parallel chalcopryite veinlets in a fresh-appearing quartz monzonite porphyry. The pyrite content of the zone seems to be very low. This occurrence, however, may point the way to some new concepts in the exploration for copper in Arizona.

Thin sections cut for petrographic analysis from three Whetstone specimens show only weak sericitization of twinned plagioclase and similarly weak kaolinization of orthoclase. The principal alteration effect is that of recrystallization and coarsening of the porphyry matrix which is primarily quartz and orthoclase. Chewed-up patches of chlorite exist side by side with fresh biotite suggesting a hydrothermal biotitization. Chemical additions to the porphyry seem to be limited to potassium, silicon, sulfur, copper and possibly some iron. The potassium occurs as growths of K-feldspar along the chalcopryite veinlets, and indeed a couple of other of the Whetstone hand specimens show megascopically pink selvages along chalcopryite veinlets.

Just such an association between high Cu/Fe ratios and potassic alteration is emphasized by S. C. Creasey in his article on hydrothermal alteration included within the volume on Geology of the Porphyry Copper Deposits, Southwestern North America. Mr. Creasey states that "Chalcopryite is the only widespread hypogene copper mineral in the potassic alteration. At Agb, Bagdad and San Manuel the copper content in the potassic alteration is ore grade without the benefit of secondary enrichment." (p. 61.) Discussing San Manuel he notes that the "argillized rock forms the outer pyritic zone; it is north and south of the K-enriched rock (potassic alteration) which includes the ore..." (p. 71) and concludes that probably "the copper accompanied the fluids responsible for the potassic alteration rather than the argillic." (p. 72.) Mr. Creasey summarizes: "Copper metallization accompanies argillic, quartz-sericite, and the potassic alterations, but the content of hypogene copper seems to be significantly higher in the potassic alteration than in the other two types.... In the San Manuel deposit, the amount of pyrite in the ore zone (potassic alteration) is several times lower than in the zone of argillic alteration. This fact

and the fact that the thick zones of secondary enrichment occur in those deposits where the copper metallization is associated with argillic or quartz-sericite alterations suggest that a basic difference in pyrite-chalcopyrite ratio exists." (p. 73.)

At Silver Bell a substantial tonnage of new ore has been drilled out west of Oxide pit beneath what must be classically considered very poor capping. Resident geologist James Briscoe has noted the high chalcopyrite/pyrite ratio in the protore rock here and has told me that considerable addition of K-feldspar is seen in the monzonite porphyry related to this Oxide pit west extension. He does not remember, however, any signs of K-feldspar addition to the relatively fresh alaskite which comprises the major portion of host rock. This alaskite is a phaneritic, potassium-rich rock in the first place, and any additions of K-feldspar are liable to be seen only microscopically as rims around relict K-feldspar and albite.

The Company's Whetstone Mountains prospect would appear to demonstrate that a commercial-sized zone evincing copper-bearing potassic alteration can exist independent of the argillic and quartz-sericite alterations. The consequence is significant: Without substantial amounts of pyrite there will be very little acid created for leaching and the classic rich porphyry copper cappings will not form. Furthermore, since potassic metasomatism does not tend to break down the altered rock, the host rock will appear megascopically fresh and will not give off the deep red-to-purplish hues so often used as a guide in aerial reconnaissance.

The questions then arise: How many Whetstone-type prospects have been passed over for lack of good capping and megascopic alteration? How many such prospects have gone undetected from the air for lack of the "right color" or signs of argillic and/or quartz-sericite alteration? Careful study of the Whetstone prospect might give the Company some exploration leads to a relatively unrecognized type of copper occurrence in the Southwest - if such occurrences exist on an economic scale. If the Whetstone Mountains exemplify the type of environment for such copper-bearing K-enriched deposits, then the Chiricahuas, Huachucas, Grahams, Baboquivaris, and others could be good hunting grounds.


BARRY N. WATSON *BNW*

BNW/kw

cc: WESaegart
SVonFay
BJDevere
JEKinnison ✓

Pocul - ^{Supergene} Clay Alt

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

March 15, 1965

FILE MEMORANDUM

SACATON GEOLOGY

Dr. G. M. Schwartz visited recently in Tucson, and I discussed an alteration feature I have noted in the Sacaton deposit, whereupon he suggested the probable mineral in question—one of the clay group.

Briefly, I have seen in thin-sections in the primary sulphide zone that the feldspars have been replaced completely by a very fine-grained aggregate of a mineral possessing the general characteristics of Kaolinite. Sericite, quartz, orthoclase, and biotite are also present as alteration products. The Kaolinized feldspars were further identified precisely by John W. Anthony (University of Arizona) using x-ray diffraction patterns.

Superposed upon these alteration products, in both the leached capping and chalcocite zones, is a mineral too fine-grained to be identified in thin-section, but its brownish color in plain light and its weak birefringence under crossed nicols suggest it to be a clay mineral aggregate. Dr. Schwartz said this description of appearance and occurrence to be exceedingly suggestive of allophane, which he has identified at San Manuel and also from other deposits. The identification must be made with very high-power microscopes with "oil-immersed" objective lenses. X-ray patterns are not diagnostic apparently because the mineral is nearly amorphous.

The probability, then, is that the supergene clay at Sacaton is allophane, and perhaps this will prove to be a mineral of common occurrence in the supergene and capping zones of porphyry copper deposits.

JOHN E. KINNISON 

JEK/jak

cc: JHCourtright

File copy: Route to all geologists

Lynchburg

Tactite

by
Spencer T. Tolley

STRUCTURAL AND MINERALOGICAL CONTROL OF ORE
IN THE LYNCHBURG MINE, SOCORRO CO., N. M.

INTRODUCTION

The Lynchburg Mine, owned by The New Jersey Zinc Company and operated during the last decade by C. S. Eganer and Co., is located in the Magdalena Mining District of Socorro County, New Mexico.

The Magdalena Mining District has been described in some detail by C. W. Knight and A. H. Koschmann in U.S.G.S. Professional Paper 200. This paper describes some of the early development work in and the basic geologic setting of the Lynchburg Mine which is located in the south end of the District. However, development work done in the mine since the publication of that paper has opened a considerable amount of underground area and has permitted further study of geologic features of this portion of the District. Perhaps the most significant details noted are those which involve the control of ore deposition in the Lynchburg orebody.

Controls of ore in the mine are for the most part classical and include stratigraphic favorability, faulting and, to an undetermined extent, folding. The most interesting aspect of control is the effect which the silicate minerals, developed early in the alteration process, have had on the subsequent localization of specific ore minerals. Detailed geologic mapping of the structure and the silicate alteration has established a relationship between ore and gangue minerals which persists throughout the stoped area.

Geologic Setting

The Magdalena Mining District is located in the northern end of the Magdalena Mountains of west central New Mexico. The mountains, which consist of a series of fault blocks, have a rough north-south trend and are situated at the southern edge of the Colorado Plateau. The major faulting in the District is of northerly strike and has resulted in the development

of a mountain range with a Precambrian core and top, flanked to the west by longitudinal down-dropped blocks capped by Paleozoic sedimentary rocks, and to the east by blocks of the Precambrian complex which have been largely stripped of their sedimentary cover.

The greatest amount of ore mined in the District has been taken from orebodies in the sedimentary rocks which flank the west side of the range. These orebodies have been developed primarily within the Kelly limestone (Mississippian) at its intersection with longitudinal or transverse faults, or at the limestone contacts adjoining monzonite and granite intrusions.

Orebodies around the intrusives are typical of the pyrometamorphic type as is evidenced by their location with respect to the intrusions and by the characteristic silicate minerals which constitute the principal gangue. The silicate minerals which have been developed are two predominant types of garnet (andradite and grossularite), two prevailing pyroxenes (diopside and hedenbergite), and various amphiboles, clays, and chlorite minerals. Magnetite is abundant near the intrusions where it forms massive bodies, but less abundant in the ores where it is generally finely disseminated. Hematite is widespread and of less restricted distribution with respect to intrusions than is magnetite. The ore minerals mined in the District have been sphalerite and galena with their oxidized products and lesser amounts of chalcopyrite. Pyrite is present in most of the ores near the intrusive masses but is not important as a constituent of the orebodies which are at some distance from the intrusions.

The Lynchburg Mine is located at the southern end of the District, near one of the major longitudinal faults. Surface exposures in the area of the mine and in the greater portion of the south end of the District are restricted to upper Paleozoic rocks and post Paleozoic volcanic rocks. Very little geologic knowledge regarding the location of the ore shoots has been obtained from surface geology although some of the conditions are well understood.

below the surface.

The orebody is typical in most respects of the other orebodies in the District except for the lack of any known igneous intrusion. On the basis of intense silicate alteration which is present in association with the Linchburg ores, Loughlin and Koschmann (1942) have postulated that an igneous body underlies the southern end of the District.

GENERAL FEATURES OF THE ORE SHOOTS

The major ore shoots in the Linchburg Mine which make up the main orebody occur in the Kelly limestone and are discontinuous, elongate features of nearly equidimensional cross-sectional size. The orebody itself has a nearly north-south strike and is continuous over a known distance of some 1600 feet. The ore shoots which comprise the orebody are high grade masses of ore associated with faults or fractures and strike generally north or northwest. They are separated from each other by intervening areas of mineralized ground of lesser value. The effects of stratigraphy are pronounced in their influence upon the shape of the various ore shoots. Bedding replacement has taken place along faults or fractures and, as a result, tabular bodies of ore which conform to the sedimentary structures persist for considerable distances away from the major feeders.

Although each ore shoot will vary slightly in mineral composition and assay, the orebody can be considered to contain sphalerite with subordinate galena, some chalcopyrite and, very rarely, pyrite. Gangue minerals are most commonly the various silicate, oxide, and carbonate minerals.

Stratigraphic Control

The first recorded deposition upon the Precambrian basement is Mississippian and is represented by some 125 feet of crinoidal limestone. This sequence of rocks, the Kelly formation, represents the most favorable ore carrier. It has been separated into four units for the purpose of description and definition of stratigraphic control. The base of the formation consists of

a horizon of sandy, arkosic or quartzitic limestone, averaging 6 feet in thickness. Above it are 50 feet of crinoidal limestones which are only locally important as ore-bearing beds. The "Silver Pipe" horizon caps the lower crystalline beds and is a persistent stratigraphic marker throughout the District. A dense, lithographic bed some 8 feet in thickness, the "Silver Pipe" is seldom ever replaced by ore minerals. Lying above the Silver Pipe and making up the remaining portion of the Kelly section is a sequence of coarsely crystalline limestones in which the greatest amount of sulfide minerals found to date have been deposited.

The most favorable portion of this upper crystalline section is a span of limestone beds about 35 feet thick which bottoms approximately 10 feet above the Silver Pipe beds. Minor amounts of ore have been mined from beds below the Silver Pipe, particularly near fractures, but the extent and persistence of ore in these portions of the section has been unimportant.

Structural Control

Faulting. Faults in the Linchburg Mine can be separated into two broad classes. The first class includes those faults which have had apparently little or no effect upon direct control of ore within the orebody itself, but may have had considerable influence as major conduits along which the ore fluids passed. The other group of fractures or faults are those which have apparently served as feeding and controlling structures within the orebody itself. The classes appear to be genetically related.

To the first class of faults, belong the major longitudinal faults in the District, one of which is the Linchburg Fault, associated with the Linchburg orebody. This fault constitutes a major break which has dropped the sedimentary horizons some 500 feet vertically, to their present position in the Linchburg Mine.

To the second class of faults, belong two sets of easterly dipping faults and fractures. These breaks dip toward the Linchburg Fault and

strike north and northwest. The principal controlling faults are the northwesterly-striking breaks which cut across the orebody at a slight angle, and have apparently controlled the location of most of the high grade ore shoots. The high grade ore adjacent to the Linchburg Fault has been localized by the north trending fault set.

Folding. The sedimentary beds are gently folded perpendicular to the strike of the main ore zone. The most conspicuous feature is the presence of a large, gentle anticline, which over the length of the mineralized zone raises the marker horizons 80 feet. Each limb has minor attendant folds and the plunge of all is gently westward.

The relationship of folds to ore deposition is obscure. The location of the highest grade ore within the ore shoots, however, has been along the crests of the minor folds where they have been intersected by the north and northwesterly-striking faults. Further, the only location in the mine in which any extensive ore has been found beneath the Silver Pipe horizon is in an area at the north end of the orebody where a sharp syncline has been developed along the limb of the principal fold. Although the beds below the Silver Pipe have been passively explored, there are no other such occurrences of ore except locally in horizons immediately adjoining the Linchburg Fault zone. It seems possible to speculate from this that development of zones of low compression in the downwarped portions of the fold may have taken place in the horizons below the Silver Pipe with similar development of low compression areas as in the beds above it in the anticlinal areas. Aside from speculation as to cause, however, the apparent relationship of folds to the ore shoots requires some consideration in the concept of ore control.

Mineralogy

The minerals which have been developed in the Linchburg orebody are typical of those found in most pyrometascmatic deposits and include suites of silicate minerals, sulfide minerals and oxide minerals. Erosion has not

been extensive enough to develop any more than minor amounts of secondary minerals, which are found at depth, mainly along faults.

The following relationships appear to be persistent with respect to paragenesis. Silicate minerals developed early in the alteration process and were overlapped to some extent and followed by extensive deposition of hematite and, locally, magnetite. Sulfide minerals were deposited last and replace silicate minerals. During the time of deposition of sulfides, some recrystallization of silicates may have taken place. Detailed work on the chemical nature of the minerals is presently in progress, hence only the megascopic and microscopic relationships and inferences can be given at this time except as otherwise noted.

Sulfides. Four sulfide minerals comprise in excess of 99% of the hypogene ore minerals present. In order of decreasing abundance, these are sphalerite, galena, chalcopyrite and pyrite.

Sphalerite ranges in color from a dark, presumably high iron variety to an amber to almost honey yellow type that is assumed to represent a variety of lower iron content. All gradations of color are present but the darkest and lightest varieties are to be found at the eastern and western extremes respectively of the ore shoots. The dark variety is most commonly found next to the fault zones and the features which are presumed to represent the channelways of the ore-bearing fluid. The light colored types are found somewhat removed from such features. Most commonly, sphalerite replaces the garnets present in the gangue assemblage and more rarely, the pyroxene minerals.

Galena is present, usually in association with the sphalerite, but invariably associated with pyroxene minerals. From the standpoint of spatial relationship to feeding structure, the galena is generally to be found some distance away. The exception to this relationship may be found in the few scattered shows in the orebody where galena is in abundance along feeding

structures that have been characterized by adjacent alteration of the host rock to epidote. However, where the epidotization ends, galena becomes less abundant.

Chalcopyrite is found in practically all of the ores in close association with sphalerite. Locally, it occurs abundantly enough to be considered ore. Its spatial relationship to feeding structure is inconsistent and it appears to be more closely related to sphalerite deposition than it does to any proximity of structure.

Pyrite, although noted as one of the four sulfides is lacking in most of the Linchburg ores. Where found, it usually lies along the edges of the ore shoots and is most commonly seen in the areas of silicification and marbelization.

Silicates. Garnet is the most abundant silicate mineral present and is represented by two varieties. Andradite is the earliest formed and is found close to the major faults. Grossularite, apparently formed later in the process of silication, is less common but is found primarily at the fringe of the main garnet zones. The garnets form a conspicuous zone of mineralization adjoining structure, but also persist away from the feeding structures beyond the zone composed mainly of the garnet, and are present in silicate zones in which other minerals are the predominant alteration feature.

Pyroxenes are present primarily in an area outside of the garnet zone where they are the most abundant of the silicate minerals present. Two pyroxene types have been positively identified, diopside and hedenbergite, and a third is problematical. Little pyroxene is present in the main garnetized zone adjoining the structures, but beyond the garnet areas it is abundant.

Epidote is very localized in its occurrence but where found, occurs almost to the exclusion of other silicate minerals. It forms no persistent zone but rather, as noted previously, it is related to structures at only widely separated localities.

Local areas of amphibole are present, associated usually with the pyroxene from which they appear to be derived. Distribution is erratic and no zonal relationships appear to be persistent. The identity of the amphibole has not yet been positively established but it may be cummingtonite.

Silica is present throughout the orebody, usually found adjoining feeding structures and locally at the outer fringes of the silicated areas. Pyrite is sometimes present as a replacement in the silica zone but generally occurs as isolated crystalline masses of small size.

Oxides. The oxides of iron are the only oxides present in appreciable quantities. Massive magnetite occurs in only two closely related areas near the center of the known limits of the orebody. However, it may be found in small amounts in most of the more intensely sulfidized zones in the orebody.

Hematite is abundant and widespread throughout the orebody. It is least abundant in the areas of intense garnetization but is widespread in the areas of pyroxenes and in the marbelized zones which fringe the orebodies. In such zones it is finely disseminated and occurs uniformly distributed.

Zones

Careful attention to the details of mineralogy in the mapping of the orebody has revealed a persistent nature to the habits of occurrence of the various silicate and sulfide minerals with respect to certain faults or feeding structures. The zones have been assigned numbers to indicate associations of ore minerals with silicates and, in most respects, it is believed that such zoning represents an "intensity" of silicate and sulfide alteration.

Zone 1. This is the zone of intense silicification which adjoins major faults. It is seldom of commercial importance although, locally it may be replaced by very slight amounts of sphalerite and galena. It seldom exceeds a known 10 feet in width but is found through most of the stratigraphic thickness of the Kelly formation along most of the length of the Lynchburg

Fault zone. This is the only example in the group of zones in which there is some doubt as to the expression of intensity. The origin of the silica is not clear; the problem of whether it represents material which has migrated through the major fault zones under high physical conditions, or is a late low temperature feature has not been resolved.

Zone 2. This zone is characterized by a mixture of the two garnet types present in the silicate assemblage. In this zone garnet occurs with the complete exclusion of any other minerals excepting minor quartz and very rare calcite. The zone is not always present along the Linchburg and associated faults, but appears to be more widely distributed than does Zone 1. Its width is variable, ranging from a few feet up to 20 feet or more - most commonly it is about 15 feet wide. Commercial mineralization in this zone consists of the dark sphalerite most of which occurs on the outer fringe of the zone and not adjoining the faults.

Zone 3. The gangue mineral assemblage in this zone consists primarily of light garnet, pyroxene (diopside) and hematite. Minor amounts of calcite and quartz are present. The relative quantities of the various minerals present vary across the zone with a higher ratio of pyroxene to garnet at the Zone 2 contact than is to be found at the inner border of the zone. At this outer edge of the zone, however, the presence of garnet in the pyroxene assemblage is sufficient to classify the rock type as belonging to Zone 3. Sulfide mineralization in this zone is primarily galena-sphalerite with sphalerite predominating at the Zone 2 border and galena becoming increasingly abundant as the outer margin of Zone 3 is approached.

Zone 4. Alteration minerals are primarily diopside and hematite which have been replaced by galena and, rarely, sphalerite. Most of the disseminated chalcopyrite mentioned earlier occurs with the sphalerite which is found in the outer areas of Zone 3, the preceding zone, and the inner areas of Zone 4. Zones 3 and 4 have the widest horizontal extent and have accounted

for the largest tonnages of lead-zinc ore mined although not the highest grade.

Zone 5. This zone is characterized by a hematized limestone with only minor isolated amounts of the pyroxene minerals. It occupies a narrow strip at the outer edge of Zone 4 and gives way rather imperceptibly to Zone 6 (marble) and the unaltered limestones containing fine disseminations of the sulfide minerals.

Significance of the Zones

The most immediate importance of the mapping of the silicate zones has been the establishment of criteria whereby the various structures which controlled ore deposition can be recognized. The presence of a high intensity zone of silicate alteration in the barren walls of a stope has generally indicated a northwesterly striking break that has been productive for considerable distances beyond the main western limit of ore.

The zones established are of academic interest from the standpoint of the study of the influences surrounding ore deposition. Further work is now in progress on this aspect of the problem, but the field observations have indicated a definite replacement favorability of certain sulfide minerals for particular silicate minerals. This favorability may possibly be shown in part to represent a thermal gradient controlled by the location of certain faults. However, of most importance, the mineralization in Zones 3 and 4 appears to be the result of chemical favorability rather than the existence of thermal gradients set up at the time of the ore-forming process.

Finally, the recognition of the various zones has indicated a definite relationship between the ore deposits and controlling or feeding structure. The ore deposit can be considered to be pyrometamorphic in all aspects except for the lack of an igneous body. The so-called "contact effects" of alteration are not confined to the immediate area of an intrusion but have spread out along faulted ground wherever the openings were available for transfer of material. A careful search for structural effects seems warranted in further study of these deposit types.

ACKNOWLEDGEMENT

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New Jersey Zinc Company.

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Paper 200.

S. R. Titley

December 2, 1957

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Por Cu Misc 68

J. H. C. JAN 24 1965

Rock Type
Sample Number
Location
Mineral

Rock Type Sample Number Location Mineral	K ₂ O x 10 ⁻¹⁰ moles/gram	⁴⁰ Ar/ ³⁹ K x 10 ⁻³	⁴⁰ Ar atoms %	Apparent Age in m.y.	Reference
Phlogopite-molybdenite rock 1, 2 RM-4-64 La Colorada Ore Body 30° 58.9' N., 110° 17.6' W., Cananea, Sonora, Mexico phlogopite	7.70	3.50	29.7	58.5 ± 2.1	This work
quartz diorite ² PEB-39-60 Torreson-Cananea Road 30° 57.78' N., 110° 34.73' W., Sonora, Mexico biotite	6.91	4.02	22.5	67.2 ± 2.2	Damon et. al. 1964
quartz diorite ² RM-7-63 Patagonia Mountains 31° 23.2' N., 110° 43.1' W., Santa Cruz Co., Ariz. biotite	6.26	3.83	17.3	63.9 ± 2.0	this work
granodiorite ² RM-6-63 Santa Rita Mountains 31° 42.9' N., 110° 52.5' W., Santa Cruz Co., Ariz. biotite	7.13	4.07	18.3	67.9 ± 2.1	This work

$K^{40} = 1.21 \times 10^{-4} \text{ g/gram K}$
 $\lambda_{\beta} = 4.76 \times 10^{-10} \text{ yr.}^{-1}$
 $\lambda_{\alpha} = 0.569 \times 10^{-10} \text{ yr.}^{-1}$

Constants used to calculate results from the Univ. of Arizona Lab.

1. contains copper sulfides
2. on Cananea - Kingman zone

quartz monzonite RM-3-64 Acacanda Co. Property Twin Buttes Area 31° 55' N., 111° 02' W., Pima Co., Ariz. biotite	7.69	7.41	3.19	28.7	53.5 ± 1.9	this work
phlogopite-garnetite rock ^{1,2} RM-1-62 Esperanza Pit, Dival Corp. Twin Buttes Area 31° 52.0' N., 111° 07.7' W., Pima Co. Ariz. phlogopite	8.37	9.46	3.75	19.1	62.6 ± 2.0	Meuser, 1965, in prep.
muscovite-quartz veinlet ^{1,2} RM-3-62 Esperanza Pit, Dival Corp. Twin Buttes Area 31° 52.0' N., 111° 07.7' W., Pima Co. Arizona muscovite	7.74	8.47	3.62	10.8	60.6 ± 1.8	" "
granodiorite ² PED-8-62 Twin Buttes Area 31° 53.95' N., 111° 06.95' W., Pima Co. Ariz. biotite	7.71	8.17	3.51	9.4	58.7 ± 1.8	Damon, et al. 1964

(3)
Mauger, 1965,
in prep

51.0 ± 2.7

7.1

2.96

8.25

8.99

albite-muscovite-quartz-
pogonite²
RM-9-63

Twin Buttes Quad

31° 59.1'N,

111° 07.8'W

Pima Co., Arizona

muscovite

²

granodiorite

PEB-11-63

Tucson Mountains

32° 17.67'N,

111° 09.77'W,

Pima Co., Ariz.

biotite

72.9 ± 2.2

12.0

4.46

8.78

6.66

Bikerman and
Damon, 1965,
in press

²

granophyre

PEB-12-63

Tucson Mountains

32° 17.63'N,

111° 09.77'W,

Pima Co., Ariz.

biotite

75.1 ± 2.2

5.3

4.51

9.63

7.08

" " "

²

granite

PEB-3-64

Tucson Mountains

32° 16.57'N,

111° 12.37'W,

Pima Co., Ariz.

biotite

71.4 ± 3.3 ave.

34.6

27.8

4.08

4.49

6.36

6.99

5.16

5.16₅

Bikerman and
Damon 1965
in prep

²

granodiorite

PEB-10-64

Cocoraque Butte,

Rogkrugs Mountains

32° 13.10'N, 111° 20.62'W,

Pima Co., Ariz.

biotite

68.6 ± 2.2

19.2

4.11

9.12

7.34₅

Bikerman, 1965
in prep

Mauger, et. al
1965

64.6 ± 2.5

28.8

3.87

7.31

6.26

blackite
2

FED-22-59
Silver Bell District
32° 24.82'N., 111° 33.10'W.,
Pima Co., Ariz.
biotite

67.1 ± 2.7

35.3

4.02

6.72

5.54

quartz monzonite
2

FED-21-59
Silver Bell District
32° 23.87'N., 111° 31.77'W.,
Pima Co., Ariz.
biotite

65.5 ± 2.0

19.7

3.92

8.15

6.88

quartz monzonite
1,2

FED-3-63
Silver Bell District
El Tirol Pit
32° 25.67'N., 111° 32.22'W.,
Pima Co., Ariz.
biotite

65.9 ± 6.6

66.5

3.95

9.07

7.61₅

quartz monzonite
2

FED-20-64
Slate Mountains
32° 32.6'N., 111° 53.2'W.,
Pinal Co. Ariz.
biotite

70.9 ± 2.3

21.9

4.25

8.82

6.87₅

quartz monzonite
1,2

FED-17-64
Bagdad Copper Co. open pit
Bagdad,

Yavapai Co., Ariz.
34° 35.0'N., 113° 12.5'W.,
biotite

This work

This work

Quartz monzonite ^{1,2} Pit-5-65 Mineral Park Pit Laval Corp., Kingman, Ariz. 35° 22.70'N., 114° 08.55'W., Mohave Co.	7.70	9.96	4.29	29.2	71.5 ± 2.6	This work
phlogopite						
quartz monzonite ¹ Pit-4-64 Lone Star District	3.41 ₅					
Graham Co., Arizona plagioclase and sericite						
quartz-orthoclase-biotite ¹ pegmatite, NM-2-62 New Cornelia Pit Ajo, Arizona 32° 21.52'N., 112° 52.00'W., Pima Co.	5.97 ₅	6.61	3.77	28.6	63.1 ± 2.2	Damon, et.al., 1964
biotite						
Schultze Granite Globe-Miami District	7.32	7.77	3.41	not listed	58	Creasey and Kistler, 1962
Gila Co., Ariz. biotite						

Schulze Granite PED-5-59 2 miles west of Miami, Arizona on U.S. Highway 60-70. 33° 23.00'N., 111° 54.17'W., Gila Co. biotite	7.01 ₅	7.31	3.45	19.7	57.8 ± 1.8	Demon, et.al. 1964
Lost Gulch Quartz Monzonite ¹ Miami District	7.24	8.36	3.7	not listed	62	Greasey and Kistler
Gila Co., Ariz. biotite						
Granite Mountain Porphyry ¹ Ray District, Pinal Co., Ariz. biotite	6.86	7.96	3.72	not listed	63	" " "
quartz diorite porphyry Christmas District	6.49	7.39	3.66	" "	62	" " "
Gila Co., Ariz. biotite						
quartz monzonite ¹ Chino, New Mexico 32° 47.5'N., 108° 04.2'W., biotite	6.77	7.76	3.76	" "	63	Schwartz, 1959
biotite-augite monzonite porphyry Bingham stock Bingham, Utah 40° 31.17'N., 112° 07.00'W., biotite	5.67	5.00	2.90	24	49 +7 -2	Armstrong, 1963**

¹ Argon analysis by neutron activation

J. E. K.

MAY 24 1968

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

May 14, 1968

TO: J.H. Courtright

FROM: J.E. Kinnison

LEACHED CAPPING,
COPPER RETAINED
IN LIMONITE.

The interpretation of leached outcrops over porphyry copper deposits is aimed at distinguishing those which indicate better copper values, usually chalcocite, from those which indicate relatively lean sulphides. The capping reflects the oxidation of sulphides at a former, higher level, and a proper interpretation of limonite thus produced is critical to proper evaluation. The recognition and application of maroon "relief limonite" has been most successful in accomplishing this. Certain difficulties have occasionally arisen. There are three circumstances under which the analyses and mapping of the leached capping can be misleading. These are: 1) Limonite of the dark variety, which appears to be derived from chalcocite, has in a few instances been found to be derived from very lean copper sulphides or from pyrite alone. 2) The typical "live limonite" does not develop, and instead brown or yellow limonite which usually indicates high pyrite content is in fact developed from copper sulphides. 3) Capping studies may bog down when limonites are ambiguous in one way or another, and cannot be interpreted.

Beginning in 1960, at Black Water, I became interested in the copper content retained within the limonite. Since then I have had other limonites analyzed on a visual spectograph as opportunity permitted. The results of these data point to certain conclusions, although the background for them is not as complete as I would like. Mr. James Sell has suggested that I set these data and conclusions into a memorandum so that, even though they are incomplete, they might be utilized in the Mexican exploration program.

It is well known that a capping consisting of strongly altered rock and limonite, and leached of any visible copper minerals, derived from a chalcocite zone, will assay from .03 to .05% copper on the average. While it is not known what mineral is responsible for this value in copper, it is conceded that the values lie within the limonites and not within the rock. As an example, "typical" live limonite at Bagdad has been analyzed by the U. S. Geological Survey and found to contain about 1% copper. My conclusions, from data in the attachment, indicate the following:

Limonite derived from copper sulphides will retain within the limonite a measurable quantity of copper, whereas limonite derived

from very lean or pyritic sulphides will not contain a measurable quantity of copper.

In those samples I have so far tested, the above conclusions have been confirmed regardless of the color of indigenous limonite. Therefore, it is probable that limonite which appears to be "live", but has been derived from pyritic material, will show no copper. Also, limonite which appears to be derived from pyritic material, if it has in fact been derived from copper sulphides, will contain a measurable amount of copper. Finally, limonite whose interpretation is in question might be resolved by direct measurement of the copper content within the limonite.

The analyses which I have so far made have been done qualitatively with the visual spectrograph, but presumably any other sensitive method of measuring copper content would work. The standard microchemical test using potassium-thio-cyanate may be sufficiently sensitive. In practice, a sample consisting of limonite alone, about the amount that can be held on the tip of a knife blade, is required for the spectrograph. If limonites are scratched out and placed in a vial in the field it is naturally best to have more than the minimum--a large "pinch", or roughly half a gram would be ample.

Determination of copper retained in limonite should not be compared with bulk geochemical sampling. It has an entirely different object. It furnishes a direct correlation of copper with the types of limonite present (is the limonite "live" or not?) -- and that is, of course, the main feature that is being depicted on a leached out-crop map.

If a simple microchemical test is found to be effective, this could be made in a nearby camp and results be immediately available.


John E. Kinnison

cc: JDSell, w/attach.
WESaegart " "

JEK:lab

SPECTROGRAPH RESULTS
ATTACHMENT FOR MEMORANDUM

The following data are abstracted from my notes, and are characteristic of results so far obtained.

Blackwater, Arizona

1. Altered schist with black silicious limonite with a red streak. Considered "Live limonite" when mapped in 1960. Later found to overlie pyrite (Bear Creek drilling, 1963).

Visual Spectrograph:

Cu-None. Four samples tested.

2. Altered granite with abundant maroon, pulverent, "Live limonite". Narrow zone south side of "East Butte". Sulphides here were not determined by drilling.

Visual Spectrograph:

Cu-Moderate. Less than Silver Bell
"Live limonite" run as a standard.

Silver Bell, Arizona

Typical "live limonite" in alaskite or porphyry.

Visual Spectrograph:

Cu-Strong easily identified lines. I
have used this as standard of comparison
for tests on other limonites.

Michiquillay, Peru

1. Capping from ridge over very low-grade pyritic area, Black, silicious limonite with Brown-orange streak. Considered probably to be "live".

Visual Spectrograph:

Cu-Trace. Very weak lines, burn out
quickly.

2. Capping over ore at DDH-N17. Brown limonite with orange to yellow-orange streak. Does not look like "live limonite", and would be interpreted as pyritic capping.

Visual Spectrograph:

Cu-Strong. Like Silver Bell "standard".

3. Outcrop over ore at K-21. Strong sericite, low total sulphides indicated. Limonite is yellow and brown with a yellow

streak. Looks like pyritic limonite.

Visual Spectrograph:

Cu-Negative-Questionable. The
limonite is sparse and hard to
scratch out enough for a good
test.

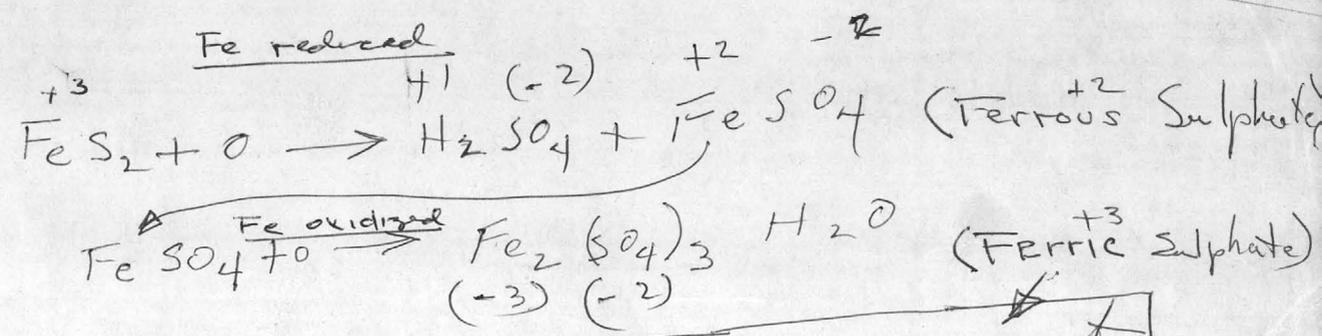
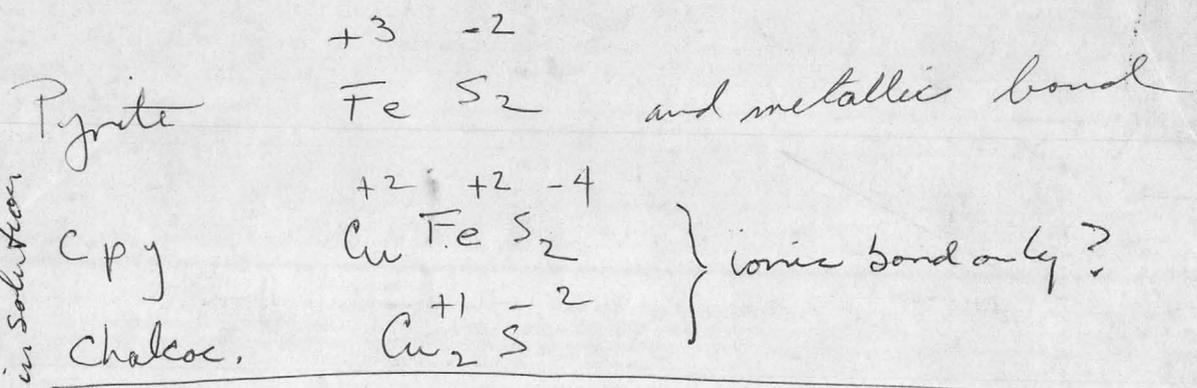
Chiracahua Mountains, Arizona

Prospect. Limonite, yellow and brown with orange and yellow
streak, as dissinations in strongly sericitized granite. In-
terpreted to overlie pyrite only. (Pyrite found locally at
the surface.) No "live limonite" present.

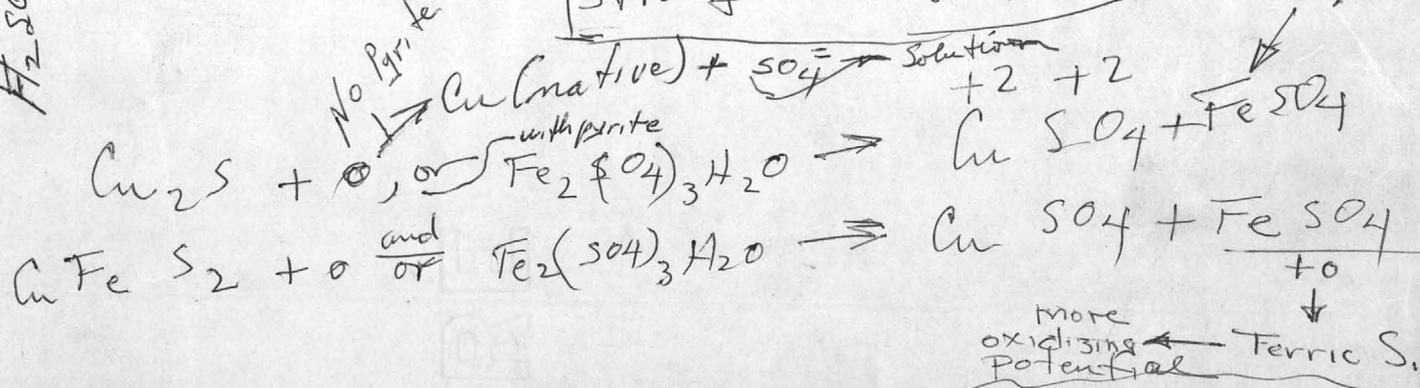
Visual Spectrograph:

Cu-None

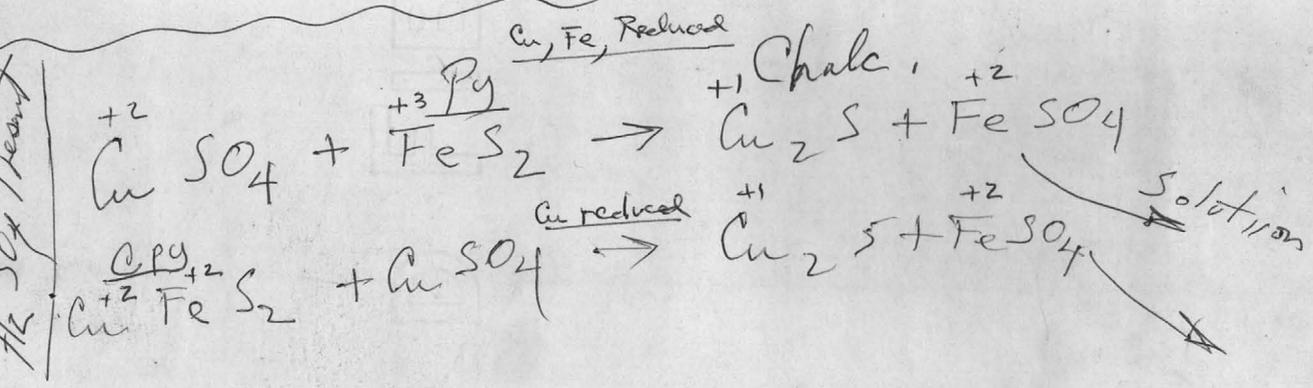
Leaching (Oxidizing zone)
 Fe & Cu leached, clay formed
 $H_2SO_4, Fe_2(SO_4)_3, H_2O$, present in solution



Strong oxidizing agent



Secondary Chalcocite
 Supergene Chalc. zone
 H_2SO_4 Present



Fe leached
 Supergene clay formed

"oxide zone" Cu and Fe Sulphates
 $\rightarrow FeSO_4$

"Supergene" zone, Fe Sulphate $\rightarrow FeSO_4$

Normally referred to as reducing zone.
 Is this really oxidizing zone?

AGS talk, Oxidation environment of
porphyry coppers. See Durek

Re: Gratton & Murdoch, Transac AIME 1914
"The sulph. ores of copper"

They state the "direct ox. of $C_c \rightarrow Nat Cu + C_c$

→ in intimate association"

or is this Durek's quote?

Anyway — Durek replied to this
that "Favorable conditions for this
reaction are rare in nature".

THE FORMATION OF OXIDIZED COPPER MINERALS
IN DISSEMINATED COPPER DEPOSITS

J. E. K.
DEC 14 1965

J. J. Durek

Chemical Environment During Weathering

Present Evidence. An oxidizing ore deposit appears to be one of the simplest of natural chemical systems, where reactions occur near the surface at normal temperatures in water solutions. But the inherent variabilities of superimposed igneous, hydrothermal, and supergene processes, and the relative openness of the system in terms of air and water have forced an acceptance of qualitative generalizations.

The copper and iron sulfate systems have been determined for elevated temperatures, and the combined system has been partially determined (Posnjak, 1929). Much of the theoretical support for relationships determined empirically during early capping studies was developed from these system studies. They indicate that, at 50°C, cupric oxide and the basic sulfates may form in solutions containing greater than 97 percent water when the CuO concentration is larger than SO₃, and that chalcantite forms in solutions containing less than 80 percent water when CuO is equal to or less than the SO₃ in the system. Only goethite, of the common stable iron minerals, is present in the aqueous iron sulfate system, and no field occurs for hematite or, of course, jarosite. By extrapolation, only goethite is shown to form in solutions containing from 96 percent water to almost infinite dilution when the ratio of SO₃ to Fe₂O₃ is less than approximately 3 to 1; no precipitate forms when the SO₃ exceeds this ratio.

Within these limits it is necessary to speculate about the probable limitations in its range. However, an environmental restriction based on modern climate is not warranted since marked climatic changes have occurred in the Southwest during historical time and major changes may be inferred to have occurred during the formation of the enriched orebodies.

It is certain that no single homogeneous solution prevailed, and two kinds of solutions probably existed. More concentrated acidic solutions were associated with the decomposing sulfides, and relatively mild solutions formed chrysocolla and the acid soluble tenorite or copper carbonates. Except for the common confinement of native copper and cuprite to the lower part of the capping, there are no major transitions within the capping and in its basic features, especially the iron minerals, probably persisted as formed.

Acidity. The leaching solutions began as rain water, which is about pH 6 when in equilibrium with atmospheric carbon dioxide at the present time. The acidity was only slightly changed during percolation through the relatively stable capping, but when the oxygenated solutions encountered sulfides they become acidic through the formation of sulfuric acid and by cation hydrolysis. Ferric iron readily hydrolyzes and a conspicuous precipitate forms when the pH is greater than 2.5; ferrous iron remains in solution in similar concentrations to pH 5. Of course, both of these ions

will remain in solution at a higher pH in concentrations equal to the solubility of their oxides or hydrated oxides, and a large amount of iron could be eventually transported in weakly acidic solutions within the geologic time involved. A pH of 2-2½ is readily achieved in moderately concentrated iron solutions such as mine water where the pH is depressed by hydrolysis of iron as rapidly as ferrous iron oxidizes until an equilibrium is reached or the iron is depleted.

Copper also hydrolyzes in aqueous solutions, and the precipitation of tenorite lowers the pH until the solution is in equilibrium with the hydroxide. The amount of copper in solution above pH 6.0 is negligible, and this is often cited as the highest pH at which copper will remain in solution. In the absence of strong complexing agents cuprous ions are not stable in aqueous solutions.

Jarosite is very abundant in capping and is relatively insoluble in acid. It is synthesized at elevated temperatures in very acidic solutions of about pH 1, but its association with hematite makes it doubtful that this acidity was achieved during weathering.

Silicate reactions offer few quantitative clues, although a large amount of kaolinite is formed from feldspar by the acid solutions. The often observed alteration of biotite or chlorite to illite is achieved in dilute sulfuric acid of pH 0.5, but lack of knowledge of reaction rates, as with the synthesis of jarosite, makes an application doubtful.

The highest probable basicity is controlled by the calcite equilibrium and may be achieved locally. When neutralization occurs in solutions containing calcium, it proceeds only to pH 8, where precipitated calcite is in equilibrium with dissolved CO₂. In more basic solutions the precipitation of calcite causes ionization of carbonic acid, and the acidity is increased by the release of hydrogen ions until equilibrium is again achieved. In sulfate solutions, gypsum may precipitate before equilibrium is achieved, and the equilibrium pH is increased.

The range in acidity of leaching solutions is probably pH 2-8. Greater acidity may occur in pyritic veins where solution flow is restricted or in film reactions during evaporation where the solution may not even be aqueous in nature. The synthesis of jarosite or the alteration of chlorite require solutions having a pH of 1 or less to cause reactions observable within hours or weeks, but no evidence exists that this condition is present in nature.

Copper Concentration. During the decomposition of a sulfide ore, the copper in solution is restricted only by the precipitation of basic or normal sulfates. In sulfide leaching experiments, the copper retained in solution is between 10⁻³ and 10⁻⁷ mole per liter. Solutions passed through pyrite-chalcocite samples are in equilibrium with brochantite, but solutions from pyrite-chalcopyrite samples are more acidic and chalcantite forms when evaporation occurs.

When copper sulfate solutions are evaporated, the metal concentration may become very large before chalcantite is formed. Because of the free sulfuric acid and iron sulfates in the solution, the maximum copper concentration should be less than 1.4 moles per liter, which is that derived from the solubility of chalcantite. During industrial leaching of sulfide dumps and in mine sumps, the copper in solution is generally less than 0.1 mole per liter, but these solutions are not saturated. When chalcantite is redissolved, solution concentrations equal to its solubility may occur, especially where circulation is impeded.

Sulfate Concentration. The dissolved sulfur readily forms sulfate in the presence of oxygen, and bivalent sulfur is rare in mine waters. Mine sump water may contain 0.7 mole per liter sulfate, and concentrations of 2 moles per liter probably occur in evaporating solutions where chalcantite is forming. The range of sulfate in ground water draining several copper deposits has been reported to be 10^{-1} to 10^{-3} mole per liter (Emmons, 1917), but many of the samples were from non-oxidizing zones and the larger concentrations are more characteristic of solutions associated with decomposing sulfides. In sulfide leaching experiments, the largest sulfate concentrations are 10^{-2} to 10^{-4} mole per liter.

Carbon Dioxide Concentration. The carbon dioxide present in ground water is derived from the atmosphere or by solution of carbonate minerals. A concentration greater than predicted by gas equilibrium has been attributed to organic action or decay, selective adsorption on soil particles, reduced ventilation, or loss by diffusion in water saturated sediments (Adams, 1937).

The maximum CO_2 dissolved in water at 25°C in equilibrium with the atmosphere is 10^{-5} mole per liter (Harned, 1943). This is reduced approximately 3.4 percent per 1,000-foot rise in elevation and 1.7 percent per degree rise in temperature. Solubility is also reduced in the presence of dissolved salts, and the absorption coefficient is nearly linear to the salt concentration but varies little from one salt to another (Johnson, 1915).

When acid solutions react with limestone near the surface, the effective partial pressure of CO_2 approaches one atmosphere and the equilibrium solubility of CO_2 will increase to $10^{-1.5}$ mole per liter.

In surface waters, carbonate is usually not present in appreciable quantities but bicarbonate occurs in concentrations of 200-400 ppm in limestone areas to less than 50 ppm in waters that drain areas of relatively insoluble igneous rocks. In waters from 42 mines in non-calcareous rocks, carbonate was present in concentrations of 13-240 ppm, but in a single sample exceeded 1,500 ppm (Emmons, 1917).

It must be noted that variations in the CO_2 content of the atmosphere have probably occurred during the oxidation of these copper deposits. An increase probably occurred during the period of Tertiary volcanism, and a decrease occurred during the Pleistocene epoch when solubility increased in the cooler oceans. The present contributions from domestic and industrial fuels is

also creating an imbalance.

Chemical Stability of Oxidized Copper Minerals

Introduction. During the past decade a major effort has been made to apply thermodynamic and chemical data to theoretical studies of geologic processes. Because most data are determined for a temperature of 25°C and atmospheric pressure, it is chiefly in the study of surficial processes, such as weathering or sedimentation, that these data may be applied even semi-quantitatively.

A calculation of mineral stabilities was made by Garrels (1954) for the formation of copper oxides and sulfides in solutions derived from the oxidation and leaching of a sulfide deposit. The only assumption necessary was the sulfur concentration of the solution. For the model calculation 0.1 mole per liter was used, and the activity of the various ions could then be defined for any selected oxidation potential and acidity.

Mineral stabilities are defined by oxidation potential only when valence changes are relevant. Reduced phases are negligible in the near-surface zone of oxidized capping, and only cuprite may be of local importance. It is possible, therefore, to discuss capping minerals simply in terms of relative solubilities.

Effect of Temperature. The standard temperature at which thermochemical measurements are made (25°C or 77°F) is higher than the mean annual temperature of much of the world. This discrepancy is commonly discounted but is significant if the exclusion of a mineral stability field is expected.

At lower temperatures the brochantite field expands into the normal tenorite field and the chalcantite field expands to replace the antlerite field. It is approximated that the antlerite field is absent below 18°C (66°F), and the chalcantite and brochantite fields are greatly expanded.

At standard temperature and pressure neither malachite nor azurite will form in solutions in equilibrium with the atmosphere, and azurite will not form even in solutions saturated with CO₂. Qualitative experiments suggest that azurite may form by dehydration, and temperature changes are probably a major factor.

The solubility of malachite and azurite decrease with increasing temperature, in contrast with the other oxidized copper minerals, and their formation is therefore enhanced in warmer environments. It is probable that azurite forms only at temperatures above 25°C or where CO₂ is present in the atmosphere in greater than normal abundance.

Occurrence of the Oxidized Copper Minerals

Calculated Stability Fields. Calculated mineral stability diagrams

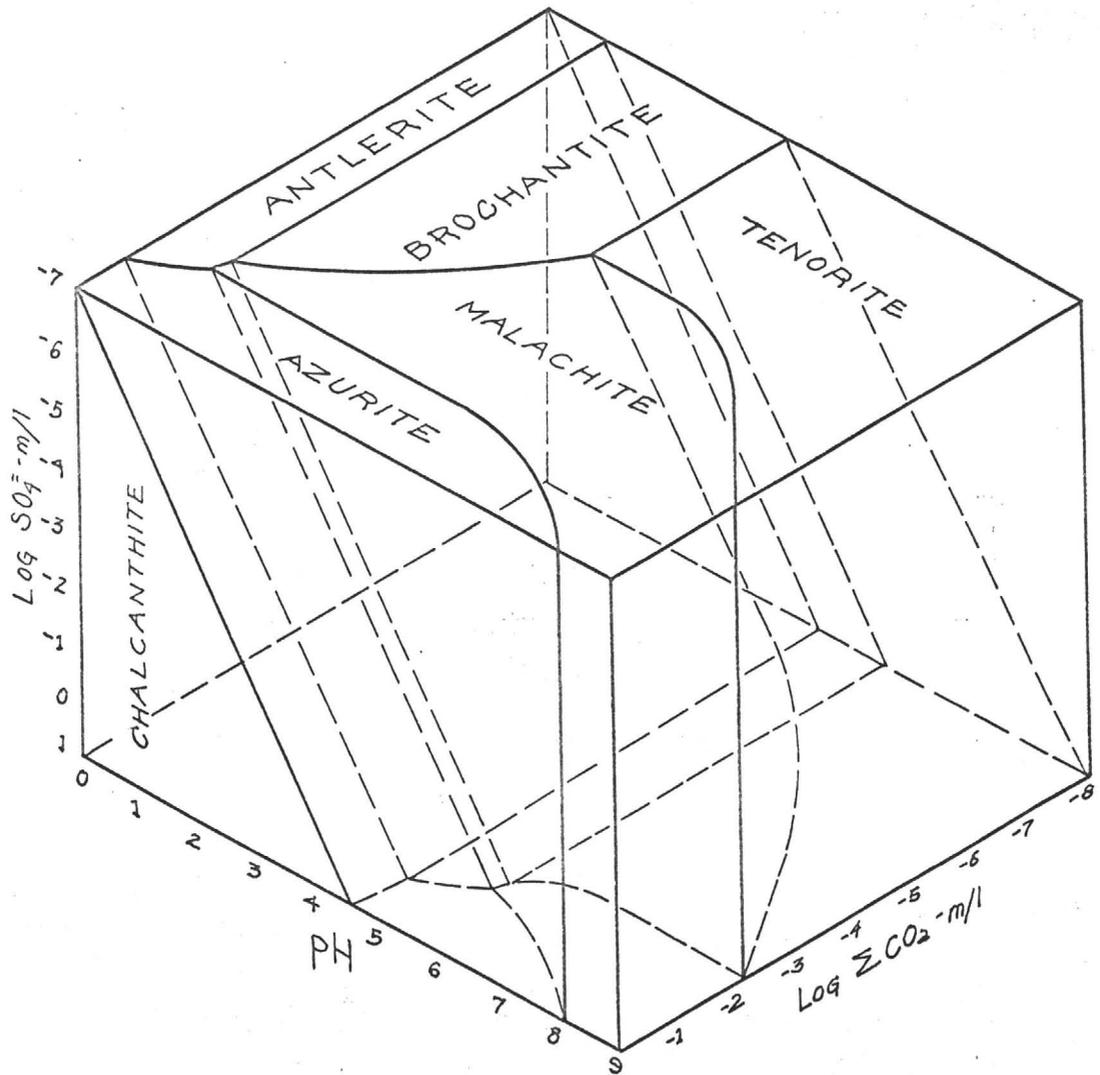


FIG. 28. COMBINED
STABILITY FIELDS OF OXIDIZED COPPER MINERALS
at 25°C.

FIG. 25
 STABILITY FIELDS OF OXIDIZED COPPER MINERALS
 at 25°C

Contours indicate Cu^{+} activity

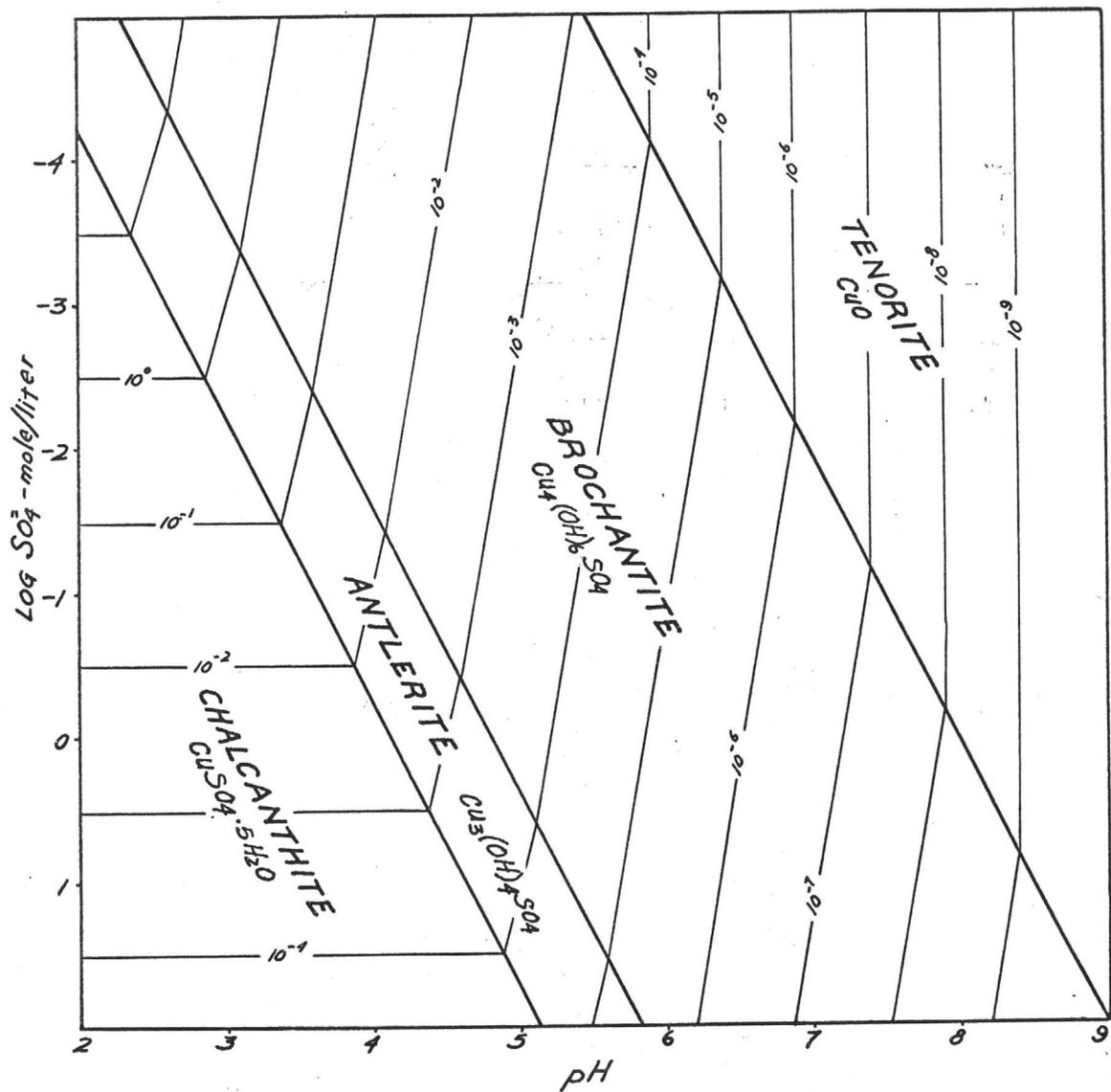


FIG. 26
APPROXIMATE STABILITY FIELDS OF OXIDIZED COPPER
MINERALS at 18°C

ANTLERITE IS UNSTABLE BELOW THIS TEMPERATURE

Contours indicate Cu^{++} activity

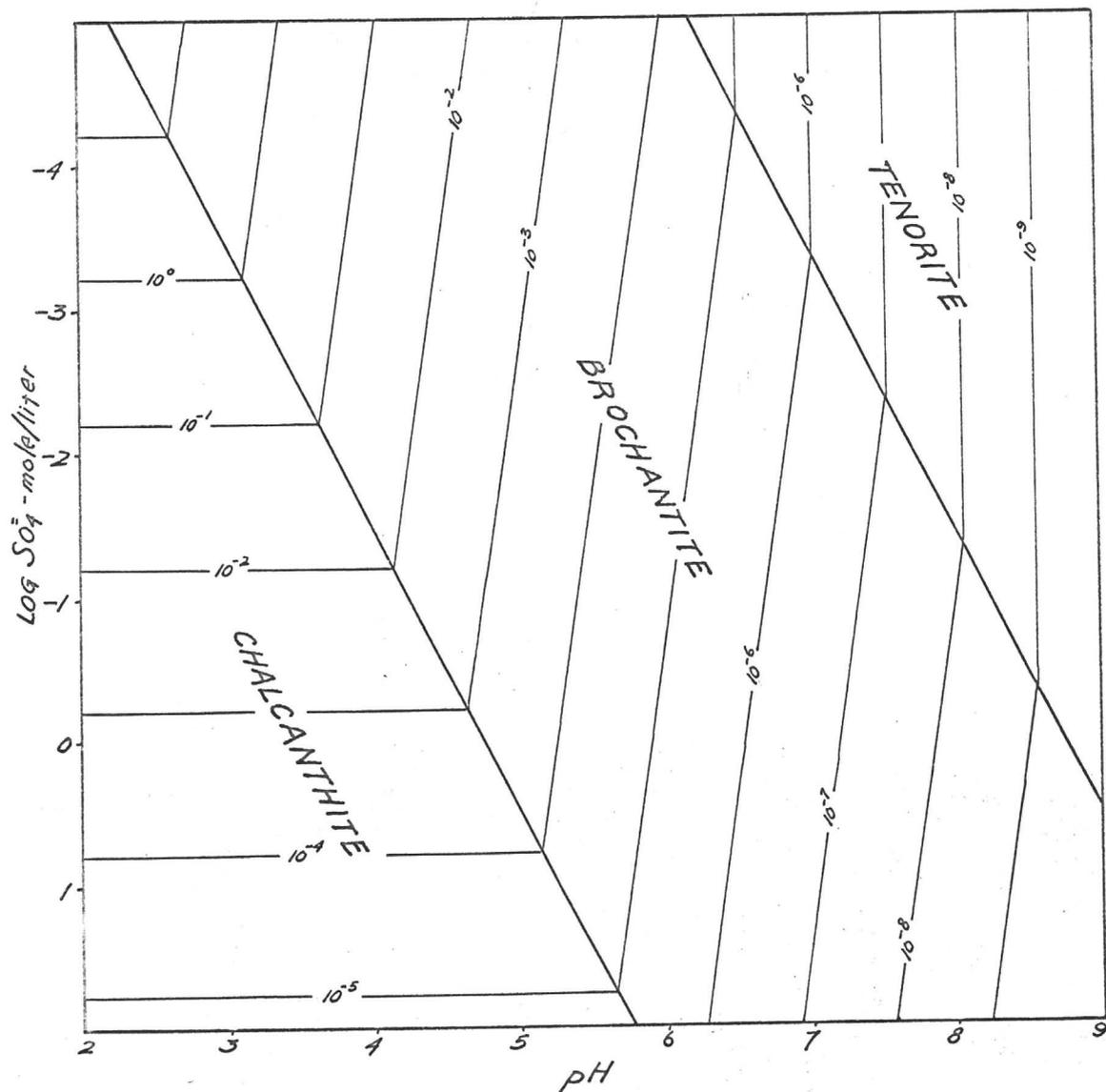


FIG. 27. STABILITY FIELDS OF THE COPPER CARBONATES
IN NON-SULFATE SOLUTIONS AT 25°C

Contours indicate Cu^{++} activity

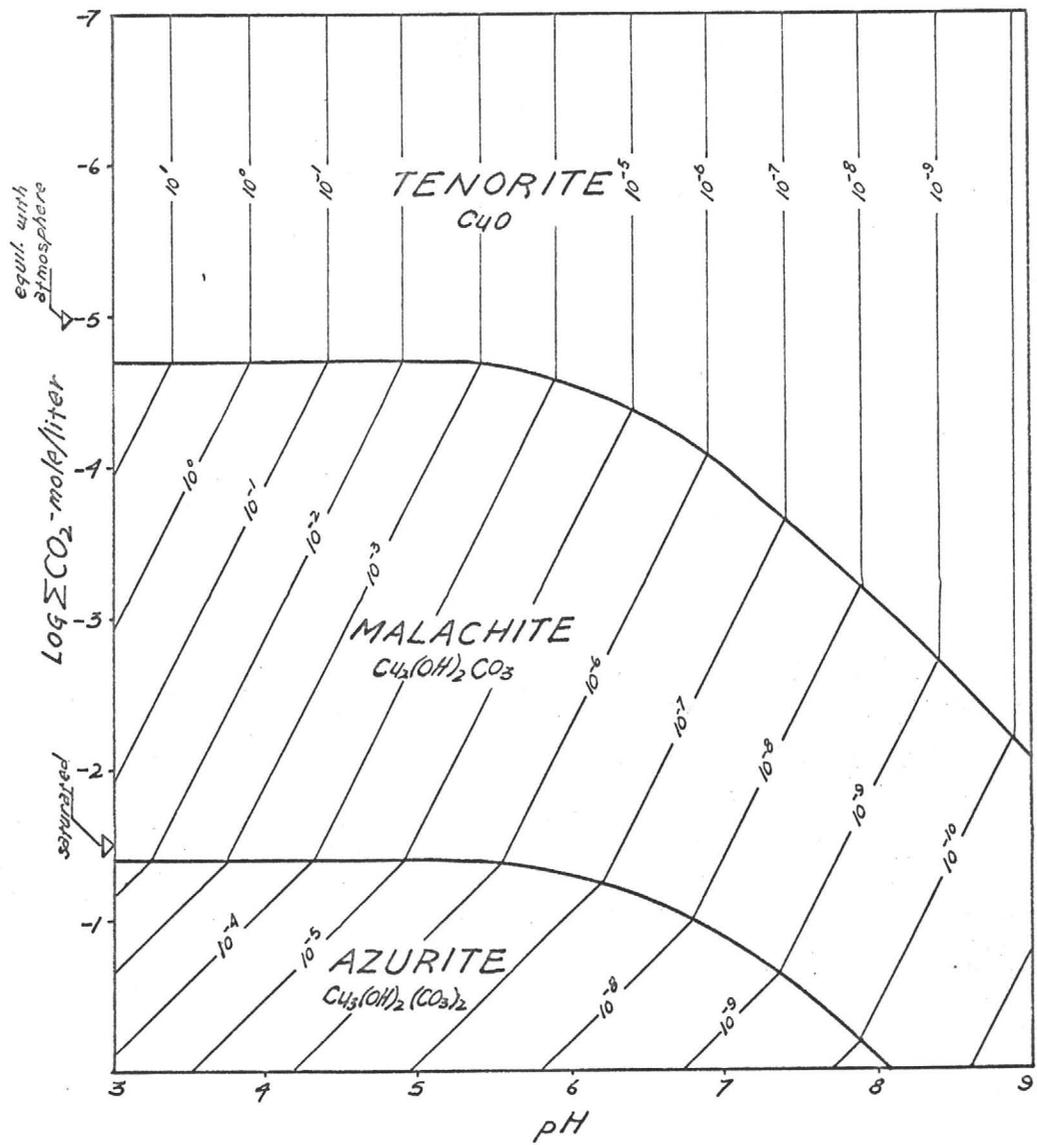


FIG. 33.
 STABILITY FIELD OF ATACAMITE VS
 ANTLERITE AND BROCHANTITE
 at 25°C

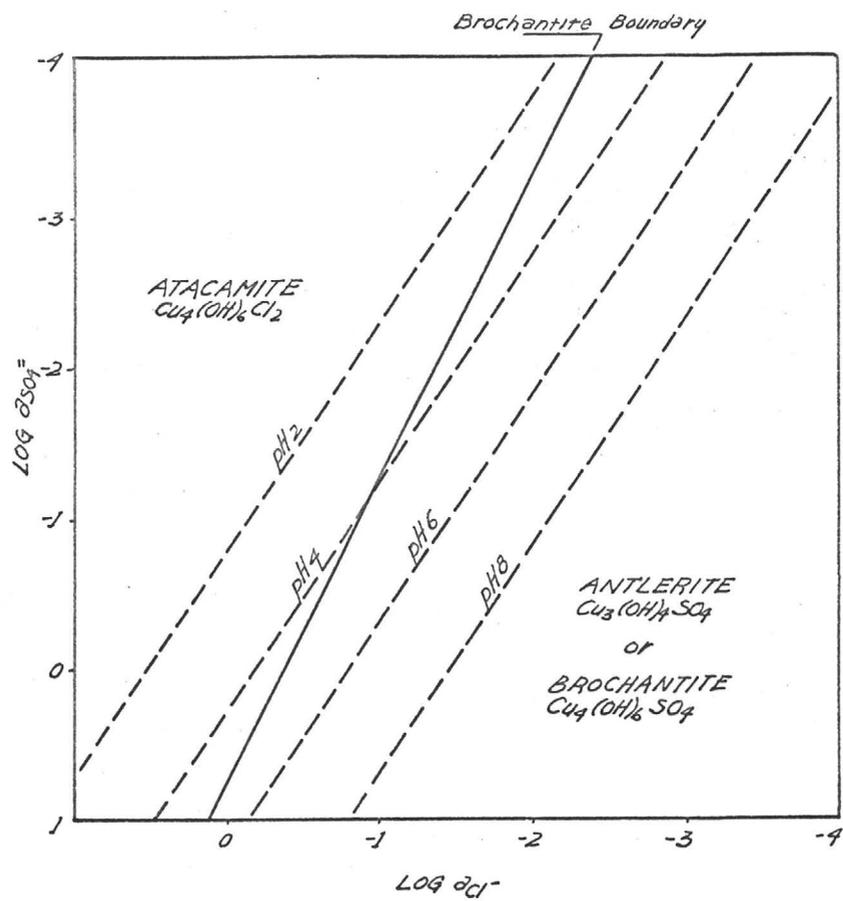
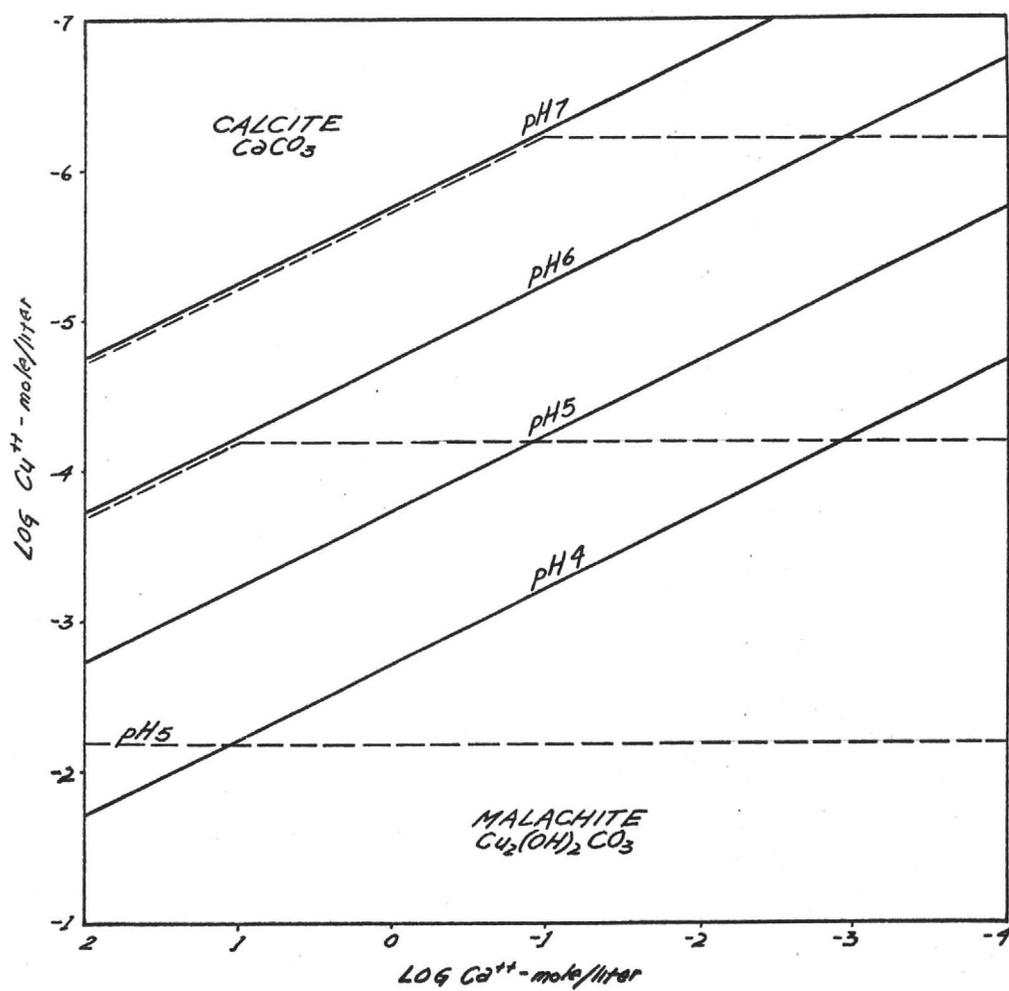


Fig. 31.
STABILITY FIELDS OF CALCITE vs MALACHITE

Dashed lines indicate limiting case where $\Sigma\text{CO}_2 = 10^{-4.7}$
and tenorite is in equilibrium with malachite.



represent only models from which possible mineral occurrences or associations can be predicted or explained. They may differ from the natural system through a failure to evaluate kinetic factors, metastability and unknown complexes, or transitional species.

The calculations are based on the premises that the activity of a metal ion is defined by the equilibrium constant if the activity of the anion is specified, the activity of the hydroxyl ion is defined when the pH is specified, and that the solid phase will consist of the least soluble mineral where equilibrium is achieved.

Chalcanthite. Chalcanthite does not generally persist at outcrop because of its large solubility or because of dehydration. It is often abundant at shallow depth, however, and readily forms as incrustations or efflorescences on mine walls or on the floor and walls of open pits. It clearly forms from a very concentrated solution during evaporation and is readily redissolved.

The pentahydrate forms in the evaporating solutions and is stable below 108°C. It dehydrates in a dry atmosphere to a powdery whitish monohydrate that is probably not always recognized in capping.

Chalcanthite generally occurs free but may be in proximity to other water soluble sulfates, such as yellowish brown coquimbite, translucent greenish melanterite, and white fibrous alums. Underground it forms as stalactitic masses, platy fracture fillings, and clusters on exposed faces. When exposed in open pits, it is generally admixed with clay and presents a dramatic appearance far greater than its quantitative significance. It has no direct role in the interpretation of capping, but by isolating copper in a transient phase it influences the nature of the more stable phases that are subsequently formed.

Antlerite. Antlerite does not occur commonly or is not recognized often. It was a major ore mineral at Chuquicamata, Chile, where for many years it was called brochantite. Both antlerite and brochantite are commonly identified as "malachite", and when qualitative chemical tests are made the more common name "brochantite" is frequently assigned. However, even when adequate optical or chemical tests are made, antlerite is rarely detected and appears to be of minor significance in domestic copper deposits.

Because of the almost unique occurrence of large tonnages of antlerite in the former oxidized ore at Chuquicamata, its formation has been attributed to a very arid environment. Bandy (1938) has stressed the factor of high solution concentration caused by slight wetting of the voluminous soluble sulfates, but at Potrerillos, a similar deposit on the Atacama Desert, the predominant oxidized mineral is brochantite. Jarrell (1939) has speculated that this occurred because the acidity of the leaching solution was lower at Potrerillos where there is less pyrite.

The instability of antlerite at temperatures comparable to those

existing widely at the present time and probably during the oxidation of domestic copper deposits explains its relative absence. The presence of antlerite does not provide clear evidence of a past warmer climate, however, and the rate of oxidation or solution complexity may be important factors.

Brochantite. Brochantite appears to be present in all the porphyry copper deposits, and when proper tests are made is often found to be relatively abundant. Extensive tests made at Morenci, Arizona indicated that it is the principal green oxidized copper mineral associated with porphyry ore, although malachite is abundant in the peripheral sedimentary replacement deposits and may have been more abundant near the pre-mining surface.

Brochantite also forms, with chalcantite, as an incipient oxidation product in chalcocite ore exposed by mining in open pits. It occurs as powdery films or minute spherulites on chalcocite and may constitute more than ten percent of the total copper contained in a normal sulfide ore. It may not be detected by superficial examination but was present in all enriched ore examined in the Southwest. It is generally conspicuous and may be the only oxidized mineral present in enriched sulfide veins. The brochantite is also common as the "verdigris" on bronze statues and plaques or copper coins.

Therefore, brochantite appears to be the first copper mineral formed during the oxidation of enriched chalcocite orebodies in the Southwest. When oxidation progresses to the stage where pyrite decomposes, the brochantite is probably destroyed. It will certainly not persist in an environment in which ferric iron is being transported, but reprecipitates in coarsely fibrous masses or layers in fractures or voids where the evidence of solution migration is clear.

Atacamite. Atacamite, the basic cupric chloride, has been reported to occur in some mines in the southwestern United States, and it is probably more abundant than now recognized.

The stability of atacamite relative to brochantite is dependent only on the anion concentrations. In an environment where antlerite normally forms, atacamite is more stable when pH is high but the chloride concentrations must be very large. It is probable that atacamite forms by replacement of earlier formed minerals in chloride solutions derived from saline ground water, hot springs, or playa deposits.

Tenorite. The black cupric oxide forms in a weakly acid or basic environment, probably from relatively dilute solutions. Its formation is analogous to hematite in that it is considered to form from a gelatinous precipitate of a hydroxide or hydrated oxide.

The solutions, after migrating from the decomposing sulfides, may be neutralized by reaction with silicate minerals and locally becomes as basic as pH 8. Iron is generally absent from the solutions before tenorite precipitates, although manganese is almost always coprecipitated with the copper.

The tenorite generally shows evidence of solution migration even in a limestone environment. It forms in layers or nodules, rarely in crystals, which concurs with the evidence that gelatinous precipitates are formed when tenorite is synthesized by neutralization of copper solutions. It may be derived from cuprite or native copper and occurs as coatings on the surface of these minerals, but this relationship is rarely seen in the capping of the porphyry orebody.

Forming relatively late, it succeeds the basic sulfates and is closely associated with malachite, azurite, and chrysocolla. Of this group, all of which formed late from transported solutions, tenorite is most often the first to precipitate, and the copper carbonates often appear to have been derived from it. Some trace of tenorite is present in most specimens of copper carbonate, and they clearly form in a similar environment.

Black coatings or nodules consisting of copper, iron, or manganese oxides frequently occur in capping. They may be pulverulent to pitch-like, thinly layered, or minutely botryoidal. The metals occur in various ratios characteristic of mixtures and silica is commonly present. Materials of this type have been called "copper pitch", or melaconite, and other names have often been applied to local varieties.

The copper mineral contained in these mixtures is probably either tenorite or an amorphous cupric oxide, but some specimens contained delafossite, a copper-iron oxide. The vitreous varieties are often transitional from normal blue chrysocolla, and zoned or banded black and blue specimens occur. The black specimens differ chemically from chrysocolla only in a high manganese content, but a black color can be produced in normal chrysocolla by heating (Schwartz, 1934).

When cupric oxide is precipitated the initial color is blue. When allowed to age the gelatinous precipitate dehydrates and changes in color to green, brown, and black. These are the colors of natural chrysocolla or chrysocolla-like minerals. When manganese is precipitated with the copper, it does not completely mask the blue copper precipitate but appears to accelerate the transformation to a black color. The color change is retarded when gelatinous silica is precipitated with copper.

The change in color has been reported to be influenced by factors such as temperature, alkalies and certain salts, or the colloidal concentration (Weiser, 1926). These factors are erratic in their effect and, as characteristic of other gels, slight changes in the method of preparation or aging may influence the nature of the product.

Cuprite. Cuprite is often abundant in vein or replacement deposits and near the bottom of leached capping. It is very commonly associated with native copper, and alters to tenorite or malachite. Because it is stable in a less oxidizing environment than normally encountered near the surface, it is significant chiefly as an intermediate phase that may influence the nature of subsequently

formed cupric minerals. However, in reactive environments or where pyrite is not abundant it may persist in the capping.

Malachite and Azurite. The ubiquitous basic carbonates are associated with copper deposits of all types and were formerly a major ore, especially in veins and replacement deposits in limestone. In common with most carbonates, they are very soluble in strong acid and therefore form only in weakly acid or basic environments. They precipitate late, or perhaps most commonly are derived from earlier formed minerals, and probably only chrysocolla is immune to this alteration.

The solubility of these carbonates is dependent only on the total carbon dioxide in the solution and the acidity, and no stability field exists in a system in which the carbon dioxide content is low. When the total carbon dioxide in the solution reaches or exceeds $10^{-4.7}$ moles per liter (at 25°C), tenorite is no longer stable except in basic solutions and malachite preferentially forms. At slightly larger concentration of carbon dioxide the malachite field also replaces part of the normal brochantite field when the sulfate concentration is less than 10^{-5} mole per liter. If the carbon dioxide in solution is increased, the brochantite field is further reduced and, when a concentration of CO_2 of $10^{-1.4}$ moles per liter is reached, azurite becomes the stable phase and completely supplants the former malachite field.

The stability of malachite and azurite therefore depends on the solution and dissociation of carbon dioxide, and rainwater, or any solution in equilibrium with the atmosphere, is therefore not capable of precipitating the copper carbonates except at higher temperatures in which mineral solubility is reduced. It is evident that malachite should be the principal carbonate formed, even in a limestone environment, and the relative absence of azurite, forming only in saturated or near saturated solutions of CO_2 , is also understandable.

The transformation to the most stable carbonate appears often to proceed relatively rapidly, and many mislabeled museum specimens are attributed to this. Both minerals commonly coexist, however, with no fixed sequence of formation, and the long-standing ambiguity about "first formed" carbonate is unavoidable. Present consensus favors azurite as most commonly being the later mineral to form.

Chrysocolla. The most common copper mineral in porphyry capping is chrysocolla. It is associated with, but often later than, the late-forming minerals tenorite, malachite, and azurite, and appears to have formed in solutions removed from the acid environment of the decomposing sulfides. No quantitative evidence relating to the chemical aspects of its formation is available, and considerable doubt exists about its character.

The common "chrysocolla", which varies in composition, and other copper silicates such as diptase, bisbeeite, ajoite, and shattuckite, some of which are found in a single district, are believed to have formed in a similar environment. Because specific evidence is lacking, they are assumed to be of equal significance in capping.

Conclusions

The formation of supergene enriched ores and oxidized capping probably occurred during the Tertiary period, and the sulfide ore is being modified or destroyed at the present time. The changes that occur within the capping are minor and are confined to the further leaching of some copper and iron near the surface and the alteration of some earlier-formed copper oxides and basic sulfates to copper carbonates or chrysocolla.

During the incipient oxidation of copper sulfides, chalcocite and chalcopyrite are leached at comparable rates. Brochantite forms on chalcocite but the copper derived from chalcopyrite migrates because of the lower copper-sulfate ratio and the greater acidity; chalcantite forms as a transition phase if evaporation occurs. Cuprite may form early, especially in limestone or other reactive environments, but it is not generally abundant in porphyry ores. Antlerite is unstable at lower temperatures, probably below 18°C, and is rare in ore deposits, but brochantite is more common than generally believed. The early precipitates are modified after the enriched chalcocite coating the pyrite is denuded or the rapidly decomposing chalcopyrite is consumed, and the environment becomes solely pyritic. All of the stable copper minerals present in the upper part of the capping show evidence of being formed from migrating solutions or of being derived from other oxidized copper minerals.

Tenorite, malachite, azurite, and chrysocolla form late from relatively basic solutions removed from the zone of decomposing sulfides. Malachite will not form at 25°C in solutions in equilibrium with the average partial pressure of CO₂ in the present atmosphere and azurite will form only in buffered solutions in which CO₂ is supersaturated. Malachite forms readily, often with tenorite, especially in or near a limestone environment, but azurite is relatively rare. Both of the carbonates are more stable at higher temperatures, and some azurite may form by dehydration.

Although oxidized copper minerals are not generally conspicuous in capping, some are always evident locally. However, geochemical anomalies most commonly reflect unseen copper that is intimately, although not uniformly, associated with iron minerals.

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The conclusion from field and petrographic observations is that there are perceptible differences in the distribution and nature of the oxidation products in quartz-sericite disseminated cappings above quartz-disseminated ores and protores in which the ratios of pyrite to copper sulfides are different, and these differences are due to physico-chemical behavior of the substances involved. It should be noted, however, that there are still greater differences in the oxidation products in cappings with different gangues above ores with nearly the same ratios of pyrite to copper sulfides, each ore having the same gangue as the capping above it. Therefore a conclusion as to the ratio of pyrite to copper sulfides which a capping formerly contained can only be reached, on the basis of this dissertation, if the capping consists essentially of quartz and sericite. In studying altered outcrops consisting of other minerals the work of Locke, Blanchard, Morse, and Boswell on gangue neutralization should be extended and contacts between sulfide ore and oxidized Metores should be examined in each case as recommended by Locke, Blanchard, Morse, and Boswell.

RESULTS OF OBSERVATIONS

The sulfide minerals along the columnar sections at Morenci were found to be pyrite, chalcocite, and covellite; those along the columnar sections at Bingham Canyon, pyrite, chalcopyrite, and covellite. The minerals formed by the oxidation of the sulfides at Morenci and at Bingham were identified as goethite, hematite, and jarosite,

Morenci---pyrite, chalcocite, covellite
Bingham---pyrite, chalcopyrite, covellite

---goethite, hematite, jarosite

At Morenci by far the largest number of the linings of the cavities left by sulfides consist of fibrous hematite; a small number consist of goethite. Both the hematite linings and the goethite linings have botroidal interior surfaces.

At Bingham Canyon the places of most of the sulfide grains have been marked by cavities lined with fibrous goethite. These linings have botryoidal interior surfaces.

Morenci---cavities filled with fibrous hematite
Bingham---cavities filled with fibrous goethite

red scratch

predominantly

↑ pale brown scratch

The minerals formed by weathering at Morenci are: Nontronite, quartz, and opal. The minerals formed by weathering at Bingham are: Nontronite, and gypsum. It is possible that other minerals have been formed in minor quantities by weathering of the gangue at the two localities. All the minerals produced by oxidation are believed to have been determined.

Morenci---weathering products: nontronite, qtz., opal
Bingham---weathering products: nontronite, gypsum

In many thin sections the entire change from entirely unoxidized sulfide sprinkled ore to completely oxidized capping was observed within a microscopic field one-eighth inch in diameter, one side of the field being

dotted with iron and copper sulfides with no oxidized iron minerals, the other side of the field with no sulfide grains but dotted with cavities of the same sizes and shapes as the sulfide grains in the first side, these cavities being partly filled with goethite, hematite, or jarosite, or mixtures of these minerals. In the oxidized capping sides of the field there are also scattered through the gangue varying amounts of the goethite and hematite in minute spherulites and jarosite in subhedral and euhedral crystals, both being much smaller than the sulfide grains in the ore sides of the field.

Oxidation front may be sharp line.
Oxidation products replace gangue as well as sulfides.

In quartz-sericite capping, where the ratio of pyrite to combined copper sulfides is relatively low, the ratio of indigenous iron oxides to transported iron oxides and of total hematite to total goethite are higher than in the quartz-sericite capping immediately overlying quartz-sericite waste in which the ratio of pyrite to copper sulfides is high.

In qtz-sericite capping

Ratio of py to Cu sulfides low---Ratio indigenous to transported high
Ratio hematite to goethite high

Up Cu sulfides---Up indigenous limonite
Up hematite

Also obtained were values of the ratio of pyrite to copper sulfides in quartz-biotite ore and the ratios of indigenous iron oxides to transported iron oxides and of total hematite to total goethite in the overlying quartz-biotite capping. The values indicate that changing the gangue with only a small change in the ratio of iron to copper sulfides produces a greater change in the ratio of indigenous to transported iron oxides than increasing the ratio of pyrite to copper sulfides many times in the same gangue. changing the gangue with only a small change in the ratio of pyrite to copper sulfides also changes the ratio of total hematite to total goethite in this case.

Small change in gangue---great change in ratio and character of limonite.
Rules of preceding paragraph are rigidly applicable only in qtz-sericite gangue.

Observations are that: capping containing hematite as a replacement of gangue has a brick red color and is correlated with pyritic waste in which the total per cent. of sulfides is low; capping containing hematite and goethite in the cavities left by sulfides has a maroon to seal brown color and is correlated with ore or at least with protore in which the proportion of pyrite to copper sulfides is low; capping containing goethite and jarosite as replacements of gangue has a yellowish-brown color and is correlated with pyritic waste in which the total per cent of sulfides is moderate to high.

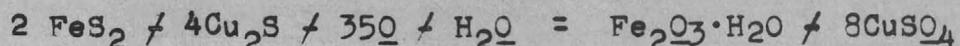
pale orange-red

Brick red hematite replacing gangue---pyritic waste with low total sulfide
Yellowish-brown goethite and
Jarosite replacing gangue-----pyritic waste with high total sulfide
Maroon to seal brown hematite and
goethite in cavities left by sulfides---ore or protore with low Py to
Cu sulfide ratio.

It is implied that this is rigidly applicable in Qtz-sericite capping; much less so in other gaggues.

RESULTS OF EXPERIMENTS

Morse and Locke suggested that two limiting cases in the complete oxidation of pyrite and chalcocite correspond to molecular ratios of pyrite to chalcocite of 1 to 2 and 2 to 1 respectively and are connected with the chemical equations:



and



The first reaction involves the minimum amount of pyrite necessary to supply sulfur for the formation of normal cupric sulfate from all the copper provided none is used in the forming of ferric sulfate from the iron. The second involves the minimum amount of pyrite necessary to supply sulfur for the formation of normal cupric sulfate from all the copper and normal ferric sulfate from all the iron. In the first case Morse and Locke suggested that the copper is leached but the iron is left in place of chalcocite-coated pyrite grains as indigenous iron oxide. In the second case they suggested that the copper is leached and no iron oxide is left in place of chalcocite-coated pyrite grains but the iron may be precipitated in the gangue as transported iron oxide. Morse and Locke stated that the equations are only approximate, for the precipitation is conditioned not only by the ratio between acid and bases but also by the concentration of the solution.

This work has shown that (contrary to the assumption of Morse and Locke) a molecular ratio of pyrite to chalcocite of 2 to 1 is not sufficiently great to bring about the solution of all the iron and all the copper in the relative amount of water likely to be present in the natural systems, in spite of the fact that with this ratio sufficient sulfur is present to form normal ferric sulfate from all the iron and normal cupric sulfate from all the copper.

I have ascertained the molecular ratio of pyrite to chalcocite necessary to bring all the iron as well as all the copper into solution to be 5.3 to 1, at the H₂O per cent of 96.06. Under the same conditions the ratio of pyrite to covellite must be 1.1 to 1, and the ratio of pyrite to chalcopyrite to be 2.9 to 1. A somewhat higher ratio would be required with a higher percentage of water, and a lower ratio with a lower percentage of water.

The supply of sulfur for the formation of cupric and ferric sulfate is a limiting factor as suggested by Morse and Locke; however, the minimum theoretical amount is insufficient to bring about solution of all iron and all copper. According to experiments and calculations the following ratios of Py to Cu sulfides would suffice to bring all Fe and all Cu in solution and leave no indigenous oxides.

- Py:Cu --- 5.3:1
- Py:Cpy -- 2.9:1
- Py:Cov -- 1.1:1

In the capping of the only disseminated porphyry copper deposit in a quartz-sericite gangue in which the molecular ratio of pyrite to chalcocite is known to be as low as 1 to 2, that of the deposit of Miami, Arizona, oxidized copper minerals are found generally throughout the capping. This is what would be expected from the data accumulated by this investigation.

At the other extreme in respect to the ratio of pyrite to copper sulfides, however, in the quartz-sericite capping above the pyritic waste at Bingham Canyon, in which the ratio of pyrite to copper sulfides is about 10.8 to 1, not all of the iron escaped from the sulfide cavities; in fact an appreciable part of the iron remains in most of the sulfide cavities even with this ratio. The reason for this appears to be that the groundwater attacking the grains of pyrite and chalcocite and (or) covellite and (or) chalcopyrite disseminated through quartz-sericite gangue contains a small amount of potash derived from the sericite, potash being an effective precipitant of oxidized copper compounds.

At Miami it works---at Bingham it does not, at least not completely. In a qtz-sericite capping, ratio 10.8 to 1, "an appreciable part of the iron" remains as indigenous limonite due to the presence of a small amount of potash derived from the sericite.

That the amount of potash is small, however, is proved geologically by the general absence of oxidized copper compounds in the capping above sulfide-bearing quartz-sericite rock in which the molecular ratio of pyrite to chalcocite is greater than 1 to 2. If the amount of potash present in the solution were considerable, copper would also be precipitated either as basic sulfate and (or) cupric oxide, and would persist in the capping either in this form or converted into a still less soluble basic carbonate or into copper silicate.

The potash, although present in small amount, plays an important role in the formation of hematite and jarosite, as in its absence only goethite and the compound $3Fe_2O_3 \cdot 4SO_3 \cdot 9H_2O$ would be formed.

The small amount of potash yielded by the decomposing sericite is not sufficient, however, to cause the deposition of hematite where the total percentage of sulfide in the rock is moderate to high and the ratio of pyrite to chalcocite and (or) covellite is high. In such ore or protore goethite and some jarosite precipitate. To a large extent in this case they precipitate in minute spherulites and disks finely distributed in the gangue and thus color the rock brown or yellowish-brown.

The presence of potash can upset the previously stated rules on the stability of oxidation products in the gangue as it tends to precipitate oxides of Fe and Cu. It must be present for the formation of Hematite and jarosite. The amount of potash in a normal sericite capping is not sufficient to upset the interpretation of leached qtz-sericite capping except in cases such as the Bingham Canyon waste where some indigenous limonite remained in cavities.

It is believed that in the absence of CuO a high concentration of K_2O in relation to the concentration of SO_3 must be reached in

5

order to precipitate hematite, in a moderate concentration of CuO a somewhat lower concentration of SO_2 than in the preceding case suffices to precipitate hematite. This hypothesis helps to explain the influence of the reduction in the ratio of pyrite to chalcocite in the precipitation of hematite instead of goethite, the total percentage of sulfides remaining constant.

With a very small total percentage of sulfides, hematite may be formed even though the ratio of pyrite to chalcocite is high. This hematite is, however, deposited in the gangue rather than in the cavities. It tends to crystallize in extremely thin, rounded, fibrous plates in the sericitic cleavage spaces and impart a brick red color to the capping.

Regarding the rule for the ratio Hematite-goethite, a high concentration of potash is necessary to precipitate hematite in the absence of CuO . This is brick red and in the gangue.

In disseminated deposits in which the ratio of pyrite to chalcocite is high, oxidation may not be thorough at any particular time, that is to say, ferrous oxide may be present. Nonthorough oxidation reduces or retards precipitation of iron compounds. The possible nonthorough oxidation in some deposits does not, however, where it occurs, diminish the difference between the oxidation products in cappings over disseminated ore and those over pyritic waste but rather intensifies the difference. Nonthorough oxidation is also almost certainly less favorable for the formation of hematite than thorough oxidation.

Nonthorough oxidation, the presence of ferrous oxide, inhibits the precipitation of iron compounds.

per la gent

April 14, 1966

Mr. Joseph Durek, Chief Geologist
Morenci Division of the Phelps
Dodge Corporation
Morenci, Arizona

Dear Joe:

With reference to your interest in the mineral brochantite I thought the following might be interesting. It is from a recent Masters Thesis by L. Clark Arnold at the University of Arizona. You may not have seen this information.

Sincerely,

JOHN E. KINNISON ✓

JEK/pjc
Enclosures (2)

RECEIVED
MAY 10 1966
STANDARD ELECTRIC

Brochantite, $\text{Cu}_4(\text{SO}_4)(\text{OH})_6$

Brochantite was found in the large arkose-garnetized lime fault on the 150-foot level and sparingly in the 100-foot level stope. Identification of the basic sulfate was confirmed by X-ray diffraction. The mineral occurs as a light- to dark-green powder within fractures in, and as crust upon, milky quartz or garnetized limestone (fig. 2). The darkness of color depends upon the amount of intermixed covellite, the occurrence and relationship of which will be discussed below.

Jarell (1944) in his work at Chuquicamata finds that sulfates in general are formed by precipitation from solution and not as replacement of original sulfides and that brochantite in particular forms from solutions having a low concentration of SO_3 , while chalcantite results from solution of high concentration of SO_3 . Garrels (see Anderson, 1955, p. 332), on the other hand, emphasizes the importance of pH in the formation of supergene sulfates, claiming that brochantite results from neutralization of dilute cupric sulfate solutions, while chalcantite forms by evaporation of solutions having high cupric sulfate concentration.

In the San Xavier West mine, brochantite has clearly formed from solution, and a possible process will be discussed in a later section.

The extreme acidity of the zone appears to be the result of oxidation of pyrite in relatively nonreactive surroundings, i. e., in an environment of low carbonate concentration.

Brochantite has a field of stability in the pH range from 4.8 to 5.8, and Eh may vary from +0.3 upward to the stability of water in this pH range. In view of the close association of chalcantite and melanterite with brochantite, the assumption of similar upper Eh boundaries for the system, which includes brochantite, seems reasonable.

Assuming similar values of Eh for the environment, the problem of antlerite, whose stability field should lie between that of chalcantite and brochantite, still exists. Drawing conclusions from the absence of a mineral species is obviously dangerous, but the absence or at least the paucity of various species is theoretically interesting.

A reaction to form brochantite from antlerite can be written:



$$\Delta F_R^{\circ} = -67.055 \text{ Kcal/mole,}$$

and to form chalcantite from antlerite,



$$\Delta F_R^{\circ} = -16.05 \text{ Kcal/mole.}$$

From the above antlerite appears to be metastable with respect to chalcantite, and if formed, would tend to give way to brochantite or less readily to chalcantite.

March 15, 1965

Dr. G. H. Schwartz
Department of Geology
University of Minnesota
Minneapolis, Minnesota 55455

Dear Dr. Schwartz:

I wish to thank you for the two reprints of papers by you which I received today. Your visit and comments here in the office and on the Silver Bell trip were very informative and enjoyable and I wish to extend my thanks for your interest in porphyry copper alteration in general and in the problems we discussed.

Very truly yours,

ORIGINAL SIGNED BY
JOHN E. KINNISON

JOHN E. KINNISON 

JEK/jak
cc: JHCourtright

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

October 11, 1966

TO: J. H. COURTRIGHT

FROM: J. E. KINNISON

OXIDE PIT, SILVER BELL
TACTITE

The north wall of the oxide pit is characterized by a narrow band of tactite which contains a high pyrite content but very little copper. This high pyrite zone--nearly massive in places--turns dark brown or black when exposed to the atmosphere after mining. This seemed unusual to me, and as a mineralogical check to determine the cause, I had the surface film of black material analyzed on the visual spectrograph at the Arizona Bureau of Mines. The results indicate a high concentration of manganese, and this is probably the cause of the dark color.

The spectrograph also indicated the presence of zinc and silver. I therefore had two hand specimens of this tactite assayed by Hawley and Hawley, the results of which assay were: Ag 0.12 oz and Zn 2.02%. As these were hand specimens taken principally to check the black surface color, no conclusions regarding the distribution of Zn and Ag may be made. It is worth note that they are present.

JOHN E. KINNISON JEK:pjc
cc: JABriscoe

FEB 28 1968

FEB 28 1968

BRECCIA PIPES IN THE WEST TINTIC AND SHEEPROCK MOUNTAINS, UTAH

By HAL T. MORRIS and RUDOLPH W. KOPF, Menlo Park, Calif.

Abstract.—Three large breccia pipes of volcanic origin cut folded and faulted sedimentary rocks of Precambrian and Paleozoic age and volcanic rocks of Tertiary age in the Cherry Creek area, Juab County, Utah. Their most characteristic feature is the presence of giant inclusions of quartzite, argillite, boulder phyllite, shale, and limestone that have been transported upward from strata that are several thousand feet below the surface. The inclusions range in size from microscopic dust to a block that is 1,200 feet long and 500 feet wide; they constitute about one-third of the material filling the pipes. The matrix in which the larger inclusions are embedded resembles arkosic tuff, consisting of shattered fragments of quartz, potassium feldspar, plagioclase, sparse biotite, and pumiceous shards in addition to the particles of exotic rocks. Locally this matrix has been chloritized, pyritized, and silicified, but no ore deposits are known to be associated with the pipes.

Breccia pipes characterized by giant blocks of Precambrian and Paleozoic sedimentary rocks embedded in a matrix of quartz-rich tuffaceous material and rock fragments have recently been recognized in the Cherry Creek area of west-central Utah (fig. 1). These intrusive masses are noteworthy because of their large size, and because of the great distances, as much as several thousand feet or more, that even the largest of the exotic inclusions have been transported upward from depth.

Cherry Creek is a short perennial stream about 15 miles west-southwest of Eureka, Utah, that separates the central and southern parts of the West Tintic Mountains from the southern tip of the en echelon Sheeprack Mountains. Three breccia pipes have been recognized to date in the area; the Hassel pipe is near the southeastern edge of the Sheeprack Mountains, the Cherry Creek pipe extends southeastward across the ridge dividing Cherry and West Cherry Creeks, and the Maple Peak pipe, largest of the three, underlies the greater part of the high, backbone ridge of the

southern West Tintic Mountains including Maple Peak (fig. 2).

Acknowledgments.—The observations and interpretations presented in this report are largely in variance with earlier conclusions about the geology of the West Tintic and Sheeprack Mountains; however, we have made frequent use of the reports of Butler and others (1920), Stringham (1942), Cohenour (1959), and, particularly, Groff (1959).

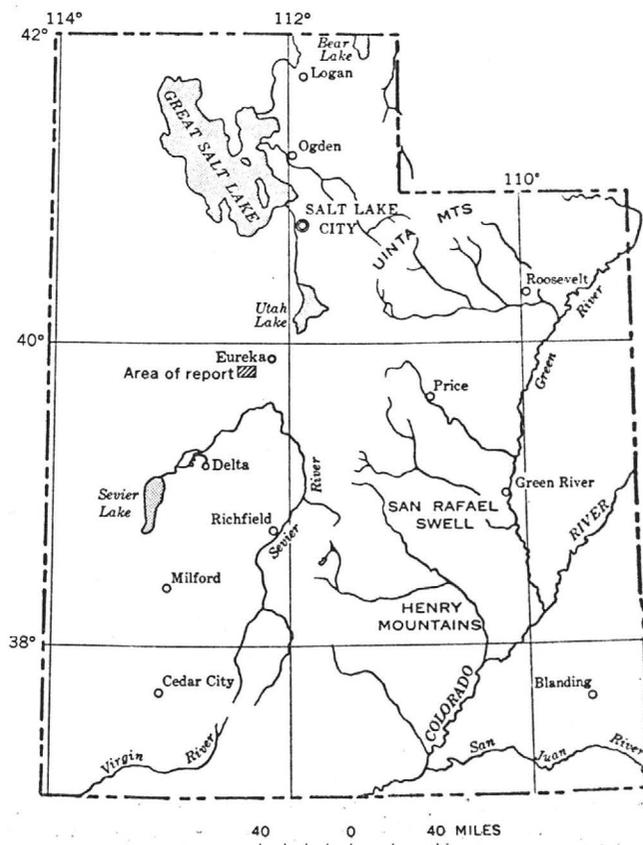
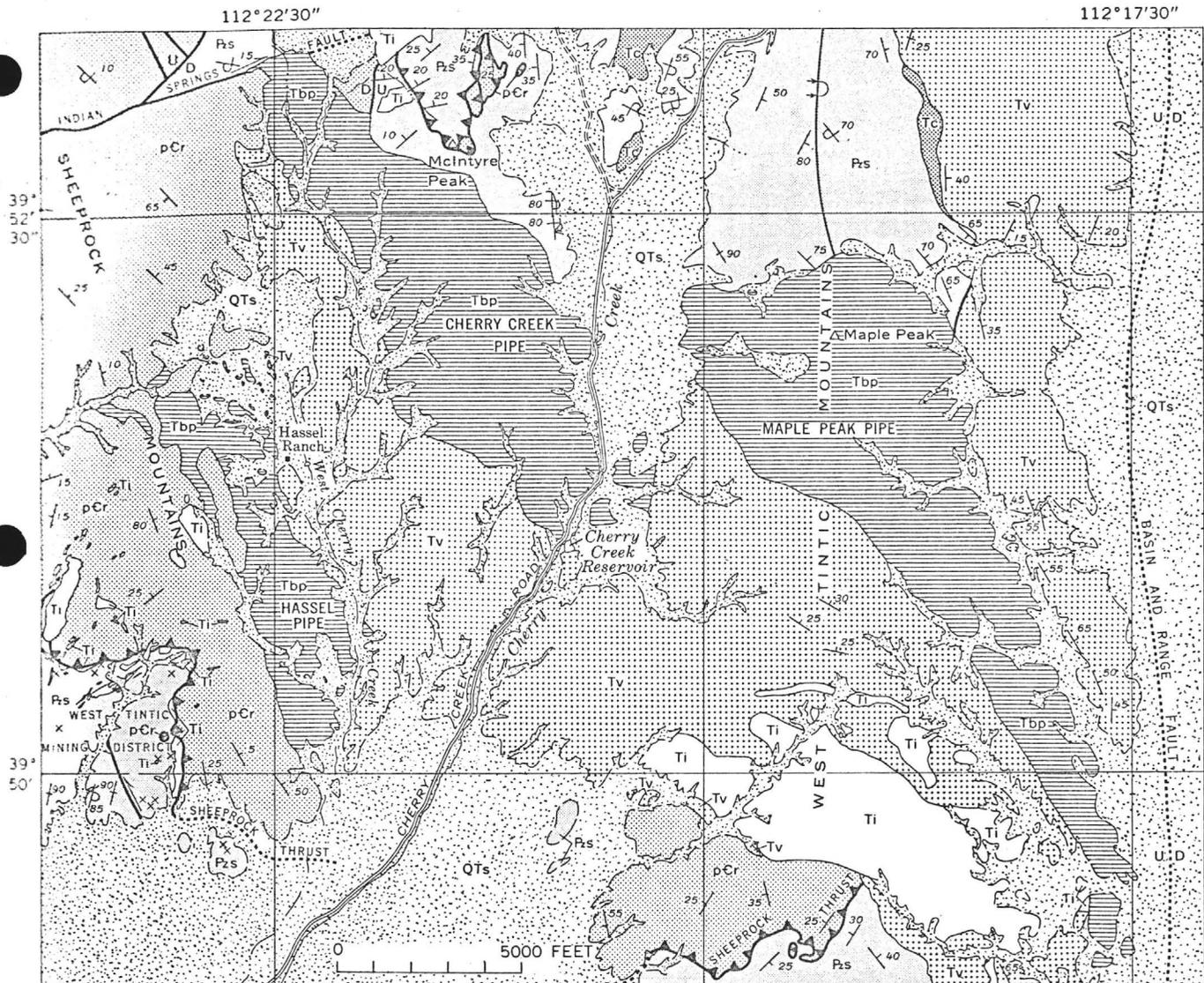


FIGURE 1.—Index map of Utah, showing location of Cherry Creek area (diagonal pattern).



EXPLANATION

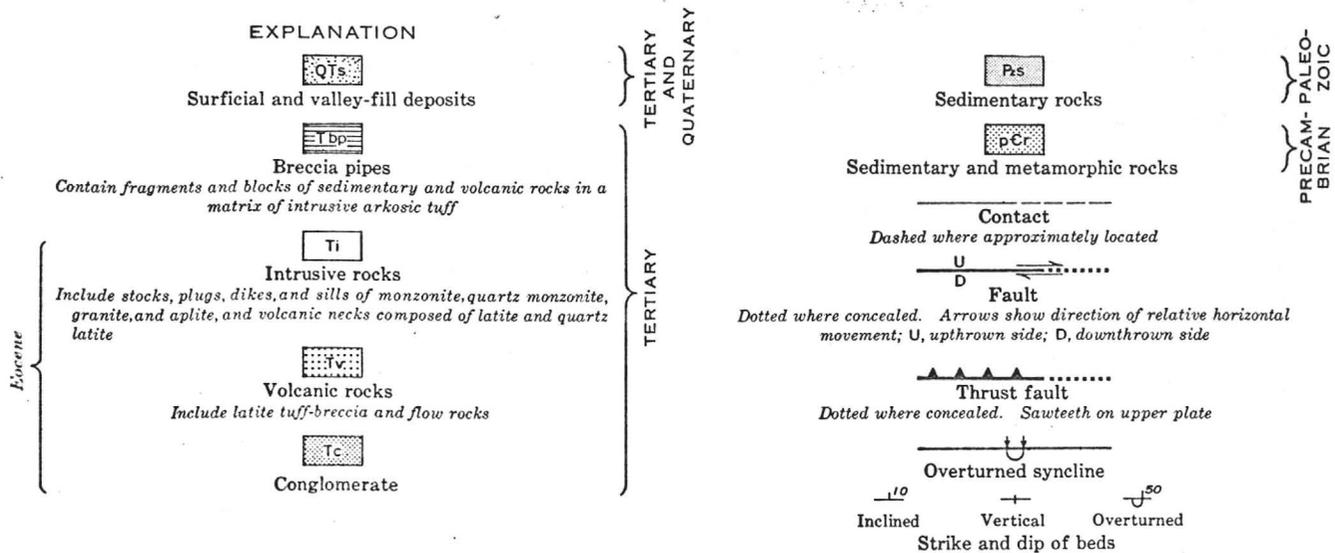


FIGURE 2.—Generalized geologic map of the Cherry Creek area, West Tintic and Sheeprock Mountains, Utah.

Capable assistance during the field investigations leading to the present report was furnished by J. T. Abbott, L. T. Benton, Rodney Wilson, T. T. Sumida, and Rubem Cobré.

GEOLOGIC SETTING

The West Tintic and Sheeprock Mountains are parts of a complex, fault-broken horst located in the east-central part of the Great Basin. The rocks exposed in the area range in age from late Precambrian to Recent. The Precambrian rocks consist of argillites, boulder phyllites of glacial origin, quartzites, and quartzite conglomerates with an aggregate thickness of more than 13,500 feet; they have been assigned to the Sheeprock, Dutch Peak, and Mutual Formations by Cohenour (1959, p. 17-28) and Groff (1959, p. 12-28). The Paleozoic rocks include strata of each geologic period from the Cambrian to the Mississippian and have an aggregate thickness of approximately 20,000 feet. Except for about 3,500 feet of quartzite and shale in the lower part of the Cambrian section and about 1,400 feet of carbonaceous shale and quartzite in the upper part of the Mississippian section, the Paleozoic rocks are chiefly limestones and dolomites.

Unconformably overlying the Precambrian and Paleozoic rocks, and an intervening discontinuous unit of Tertiary conglomerate, is a sequence of latitic and quartz latitic volcanic rocks comparable in composition and stratigraphic and structural relationships with the middle Eocene volcanic rocks of the East Tintic Mountains (Morris and Lovering, 1961, p. 124-126). The lowest volcanic units in both areas consist of pyroclastic deposits that fill eastward- and south-eastward-draining valleys, some of which were hundreds of feet deep prior to the volcanic eruptions (Morris and Anderson, 1962, p. C1-C4).

Cutting the volcanic and older rocks are many igneous intrusive bodies ranging in composition from latite and monzonite to granite, and in size from narrow dikes to plugs and stocks. These intrusive bodies form part of an eastward-trending zone of intrusions that extends from the Deep Creek Range to the Wasatch Mountains (Mabey and others, 1964; and Hilpert and Roberts, 1964, p. 30). Many of the latite intrusions in the Cherry Creek area were obviously the source vents for the petrographically similar volcanic rocks, but most of the other intrusives apparently crystallized at depth during the waning stages of volcanic activity. Some of these rocks and all the older volcanic and sedimentary rocks are cut by the breccia pipes and locally are overlain by valley-fill and upland alluvial deposits of Pliocene to Recent age.

The general geologic structure of the Cherry Creek area consists of imbricate plates of thrust-faulted and folded Precambrian and Paleozoic strata that are cut by tear faults and broken and delimited by normal faults of the Basin and Range fault system. The Precambrian and lower Paleozoic rocks of the area form the upper plate of the Sheeprock thrust fault that originally extended across folded and faulted strata of Ordovician to Mississippian age that are believed to be in the upper plate of the concealed Tintic Valley thrust (Roberts and others, 1965, p. 1946-1948, 1952-1953).

The Basin and Range fault bordering the West Tintic Mountains (fig. 2) is inferred from geophysical data presented by Mabey and Morris (1967) and is probably similar to concealed faults near the southwestern border of the Sheeprock Mountains.

BRECCIA PIPES

Form and character

The breccia pipes in the Cherry Creek area are elongate in plan, the long axes striking about N. 30° W. The smallest breccia pipe, here termed the Hassel pipe from the nearby Hassel Ranch, is 11,000 feet long and 2,500 feet wide at its widest outcrop; the Cherry Creek pipe is about 16,000 feet long and 5,500 feet wide in the central part; the Maple Peak pipe, which is tadpole shaped in general outline, is more than 22,000 feet long and 6,800 feet wide near Maple Peak. Most of the contacts of the breccia pipes with their wallrocks are moderately well defined and readily followed except where they are concealed beneath surficial deposits. However, in areas underlain by volcanic rocks that superficially resemble the tuffaceous matrix of the breccia pipes, the contact may be recognized by close-spaced fractures in the wall rocks, zones of weak alteration parallel to the edge of the breccia pipe, and locally by small globs and stringers of remelted country rock.

The material filling the breccia pipes is characteristically a massive chaotic breccia of highly variable grain size and composition. Locally a steep planar structure that developed in response to lamellar flow in the fluidized breccia filling is strongly developed parallel to the walls of the pipes. In some parts of the Hassel and Cherry Creek breccia pipes, this planar structure was intricately folded during the last stages of injection of the breccia.

Composition

The most distinctive and impressive feature of the breccia pipes of the Cherry Creek area is the presence of giant inclusions of exotic rocks, some of which

have been displaced several thousand feet upward from underlying strata. These inclusions locally constitute virtually all the material filling the pipes, but more commonly they are embedded in a matrix of light-gray to buff tuffaceous breccia and rock fragments. Overall, the exotic inclusions probably constitute approximately 35 percent of the bulk composition of the breccia pipes, although locally a superficial examination would suggest a higher proportion. Not all the inclusions are large, however, and some parts of the pipes contain such an abundance of small angular rock fragments that they resemble concrete.

The exotic inclusions range in size from irregular-shaped blocks and slabs more than 1,000 feet long to particles that are barely discernible with a hand lens. One of the largest masses noted is an unbroken slab of limestone exposed near the western base of Maple Peak that is at least 1,200 feet long and 500 feet wide. Irregular-shaped blocks and slabs 50 feet or more in length are common, although they are less abundant than rounded, boulder-shaped masses 2-20 feet in diameter (fig. 3).

The inclusions were obviously derived from all the older rocks recognized in the West Tintic and Sheep-creek Mountains. These rocks include quartzite, phyllite, argillite, and conglomerate of Precambrian age; quartzite, limestone, shale, and chert of Paleozoic age; and latite, quartz latite, monzonite, quartz monzonite, and aplitic granite of Tertiary age. Massive igneous rocks, such as quartzite and chert, appear to have resisted crushing and abrasion; commonly the

inclusions composed of these rocks are well rounded and have smooth surfaces that are polished and striated. Some of the smaller masses of phyllite and limestone are also rounded but generally are not polished because of their softness and susceptibility to solution and reaction.

No sorting of the inclusions is discernible except for a slightly greater abundance of fragments near the edge of the breccia pipes that were obviously derived from the nearby wallrocks. The larger inclusions are more resistant to erosion than the tuffaceous and fragmental matrix and locally cap hills and ridges. A particularly large cluster of giant quartzite fragments underlies Maple Peak and has led to the erroneous impression that these rocks are a klippen of the Sheep-rock thrust fault.

Under the microscope the fine-grained matrix of the breccia pipes is seen to consist of unsorted angular and broken crystals of quartz, orthoclase, andesine, biotite, and fragments of rock, all embedded in a rock powder that locally is silicified, calcitized, and chloritized. A few of the igneous minerals preserve entire crystal outlines, but most of them have been fractured into sharp-edged particles ranging in size from 0.5 mm to the finest dust. The largest and least broken of the igneous minerals are the quartz grains, which constitute as much as 25 percent of selected samples of the tuff. Apparently many of the quartz grains were rounded by resorption prior to eruption and may have resisted crushing and breaking as much as by their sphericity as by their hardness.

Zonation

A rude compositional zonation is recognized particularly across the Maple Peak breccia pipe. The central area of this pipe is dominantly composed of tuffaceous material and rare boulder-sized clasts of sedimentary rocks. Peripheral to this core is an irregular zone containing abundant exotic inclusions of Precambrian and Paleozoic rocks, including the largest blocks of these rocks. Outward from this zone these inclusions progressively diminish in number and become subordinate to less rounded blocks and fragments of the wallrocks, which locally become so numerous that they make the selection of the contact between the breccia pipe and the country rocks somewhat arbitrary. A similar zonal arrangement of a tuffaceous core, an intermediate zone of exotic inclusions, and a border zone of brecciated contact rocks is also primitively developed in the Cherry Creek and Hassel breccia pipes.

The central zone of the breccia pipes closely resembles ashfall arkosic tuffs and commonly has been mistaken for a pyroclastic deposit. It is less resistant



FIG. 3.—Outcrop of the Cherry Creek breccia pipe near the Cherry Creek Reservoir. The exposed part of the large rounded inclusion, which is limestone of Mississippian age, is 100 feet high and 25 feet wide. The other partly exhumed inclusions consist of Cambrian quartzite and Cambrian to Silurian limestone in a matrix of tuffaceous breccia and rock fragments. Cherry Creek has been entrenched into flood plain a few hundred feet.

than the adjacent zone of abundant inclusions and locally is cut by canyons and gulches. The intermediate zone of inclusion-rich breccia typically weathers in relief and is characterized by a chaotic assemblage of exotic blocks of all sizes and composition. In this zone, blocks of fossiliferous Mississippian limestone may lie adjacent to Precambrian boulder phyllites, or any other rock that may be hundreds or even thousands of feet higher or lower in the stratigraphic column, and indicate a thorough mixing or churning of the breccias. Toward the edge of the pipe, the zone of inclusions gradually merges with the narrow border zone that consists chiefly of brecciated wall rocks. In areas where the pipes cut volcanic rocks that superficially resemble the tuffaceous and fragmental matrix of the pipes, the contact is commonly placed at the limit of rotated blocks and the few scattered exotic inclusions.

ORIGIN

The thorough brecciation of the matrix and inclusions of the breccia pipes of the Cherry Creek area, as well as the chaotic nature of the pipes, their shattered wallrocks, abundance of rounded inclusions, and association with rhyolitic or quartz latitic igneous material, all suggest an explosive emplacement. Such an emplacement is also supported by the occurrence of arkosic ashfall and welded tuffs in the Cherry Creek area (Groff, 1959, p. 118) that were apparently derived from material erupted through these vents. It is conceivable that the breccia pipes were formed when a partly crystallized, gas-rich magma reached fissures that extended to the surface. The initial phase was probably the development of the vents in the manner originally proposed by Daubreé (1891), who postulated that diatreme channelways were drilled by escaping gas and steam and the vents were produced by volcanic explosions. After the channelways had been developed to the surface, the magma probably continued to evolve gas, which became charged with crystal fragments, pieces of country rock, and pumiceous shards. During this and succeeding phases, surficial eruptions deposited welded and ashfall tuffs, and the channelways doubtlessly were enlarged through abrasion by the churning mass of debris.

The inclusions of sedimentary rocks probably were derived from giant slabs that had been stoped-out at depth by the invading magma; however, some slabs and blocks may have originated through rock bursts that doubtless took place when the velocity of the gas and debris column increased sufficiently to create a sharp drop in pressure across the walls of the pipe. Heat derived from the rising gasses and through fric-

tion of the churning mass of debris pyrometamorphically case-hardened the surface of some boulders and locally remelted the volcanic wallrocks and formed irregular patches and stringers of partly fused tuff.

Unlike the down-dropped inclusions in the diatremes of the Navajo and Hopi Indian Reservations (Shoemaker, 1956, p. 182), which resulted from repeated eruption and collapse of the diatremes, the inclusions of sedimentary rocks in the breccia pipes of the Cherry Creek area are all from underlying rock units. This fact is confirmed by the sparseness of inclusions composed of volcanic rocks, which overlay the sedimentary rocks at the time of the eruptions. The occurrence of slabs of readily identified Precambrian quartzite, boulder phyllite, argillite, and conglomerate adjacent to the Mississippian strata forming the northern and northeastern wallrocks of the Cherry Creek and Maple Peak pipes indicate an upward dislocation of many thousand feet. The absence of fragments derived from older Precambrian crystalline rocks may probably be explained by the great thickness of the late Precambrian and younger sedimentary rocks, which have been repeated by thrust faulting in the Cherry Creek area, and by the possibly high level that was reached by the parent magma prior to the formation of the breccia pipe.

The upper parts of the Cherry Creek breccia pipes have long since been removed by erosion, but it may be conjectured that craters were formed at the original surface, first by explosion, and possibly later by subsidence. Any crater deposits that may have been laid down during this interval, such as stratified tuffs, siltstones, or marly limestones, have been eroded.

ECONOMIC ASPECTS

The breccia pipes in the Cherry Creek area are similar in many respects to mineralized breccia pipes in other areas, particularly the Braden pipe in Chile, which is the localizing feature of one of the largest copper ore deposits in South America, if not the world (Lindgren and Bastian, 1922; Howell and Molloy, 1960). However, no evidence of ore deposits closely associated with the pipes, or of fragments of older ore bodies, was recognized in the Cherry Creek area. The weak hydrothermal alteration of the tuffaceous matrix and of some of the wallrocks adjacent to the pipes is suggestive, however, of some hydrothermal activity. The most obvious alteration is a bleaching of the mafic minerals and groundmass of both the volcanic rocks and the matrix material, apparently resulting principally from the weathering of introduced pyrite and the action of weak primary argillizing solutions. Incipient patches of hydrothermal chlorite minerals and

some secondary calcite, which probably originated from the limestone inclusions and rock flour, were also observed in thin sections of the tuffaceous and fragmental matrix. The abundance of unaltered limestone fragments in the pipes indicates the relative weakness and general paucity of hydrothermal solutions associated with the pipes of the Cherry Creek area, as well as the absence of ore bodies at depth in the subsurface limestones that were incorporated into the breccia pipes.

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John E. Knicker

With my compliments

Oleott Gate,

Box Pipes

Shoshone Range

Nevada

rhyolite or quartz latite porphyry that cut all other rock types in the pipes and extend into the wall rocks.

The pipes were formed by an up-and-down pump action impelled by intermittent rise of the magma in the plugs. Brecciation occurred during upward movement of the magma and associated explosive volcanism. Breccia also was formed by subsidence, collapse stoping, and possibly rock-bursting during subsidence of the magma. The fine breccia thus formed ahead of the magma and, in turn, became intrusive, eventually working its way to or near the surface.

INTRODUCTION

THREE breccia pipes in the Shoshone Range, Nevada, were conduits during the Tertiary for a center of explosive volcanism. Excellent exposure by erosion, including sections 1,600 feet in depth, led to the hope that detailed mapping would give clues to the mechanism that formed the conduits and their breccia.

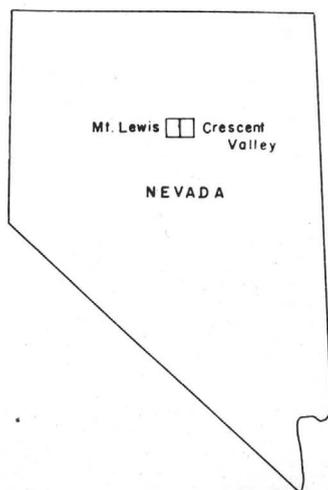


FIG. 1. Index map of Nevada showing location of the Mt. Lewis and Crescent Valley quadrangles.

The Shoshone Range is in the Mt. Lewis and Crescent Valley quadrangles near the town of Battle Mountain in north central Nevada (Fig. 1). Study of the breccia pipes grew out of the mapping of the two quadrangles by a U. S. Geological Survey field party. I am greatly indebted to James Gilluly, George Snyder, Harald Drewes, and Reuben Ross for many valuable field observations. Aaron C. Waters, Johns Hopkins University, gave much assistance in the study of the petrography of the rocks and in compilation of this report.

REGIONAL GEOLOGY

The breccia pipes are along the crest of the northern part of the Shoshone Range. The range begins southwest of Austin, Nevada, and trends slightly east of north to the Humboldt River. Crescent Valley lies to the east and

the Reese River Valley to the west of this northern part. Maximum altitude is 9,680 feet at Mt. Lewis, about 5,000 feet above the floors of the neighboring valleys. The range is carved from a fault rock that was tilted eastward during late Tertiary time along normal faults on the west side. The northern part of the range consists primarily of Paleozoic sedimentary rocks intruded by the breccia pipes, by numerous dikes, and by several small stocks of Tertiary igneous rocks ranging in composition from quartz diorite to rhyolite. Late Tertiary tuff, welded tuff, agglomerate, and breccia and a few basalt flows have been spared from erosion on the flanks of the range and in a few fault blocks within it. It is probable that Tertiary volcanic rocks and conglomerate covered the site of the entire range prior to its uplift.

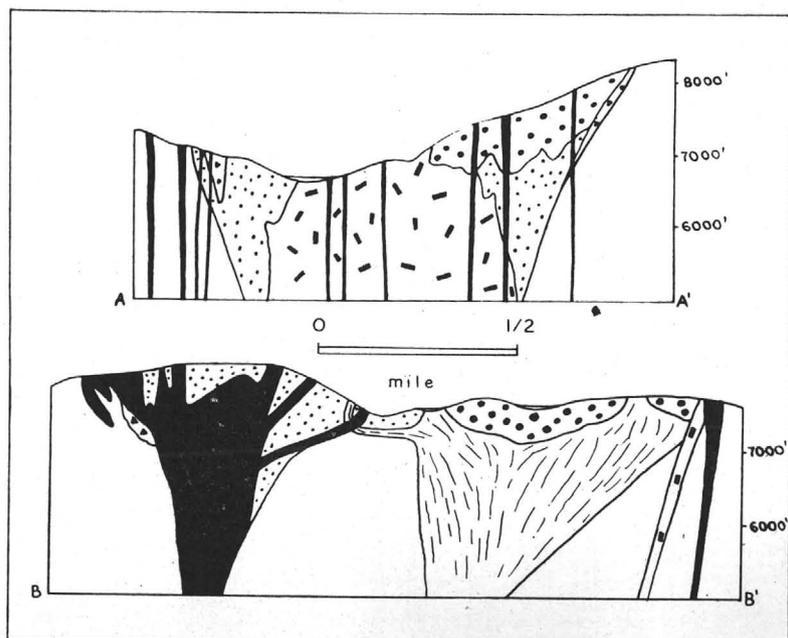


FIG. 3. Cross sections of the breccia pipes. Vertical and horizontal scales equal.

The Paleozoic rocks of the northern Shoshone Range are divided into two main units by the Roberts Mountains thrust, first mapped and described by Merriam and Anderson (13) in the Roberts Mountains about 40 miles to the southeast. The upper plate of the thrust consists primarily of Ordovician, Silurian, and Devonian chert, greenstone, quartzite, graywacke, arkose, argillite, and shale along with a subordinate amount of Carboniferous, Permian and Triassic limestone, shale and conglomerate. The lower plate consists of Cambrian, Ordovician, Silurian, Devonian and Mississippian quartzite, shale, limestone, and dolomite in stratigraphic units found within much of eastern Nevada and western Utah and well illustrated by the section at Eureka,

breccia is best exposed on the topographic nose extending from the north wall (hereafter called the north nose) and on the south side of the south fork of Horse Creek.

Near the top of the topographic nose extending into the pipe from the east (hereafter called the east nose), the contact between the wall rock and coarse breccia is sharp but irregular. Along the north side of the pipe, the contact is also irregular but the wall rocks have been fractured to a distance ranging from 1 to 20 feet, without having been moved from their original positions.

The coarse breccia is a mixture of large and small fragments ranging from microscopic size to large blocks as much as 100 feet in length. Most of the large blocks are fractured; and all fragments, of whatever size, are angular, indicating that movement has been insufficient to round them.

The composition of the fragments of the coarse breccia reflects the lithology of the adjacent wall rocks. Where the wall rock is chert, the breccia consists primarily of chert fragments. Where the wall rock is limestone, the breccia fragments are of limestone. Admixture of rock types other than those in the adjacent wall rock is slight, and fragments of Tertiary porphyries are very scarce.

Some blocks of the coarse breccia have subsided into the pipe. On the north nose, large blocks of greenstone of a distinctive coarse ophitic texture lie 100 to 300 feet below the outcrop of the same kind of greenstone in the adjacent walls of the pipe. On the south side, the coarse breccia consists primarily of large blocks of siliceous shale, now opposite chert in the wall. The shale has subsided about 100 feet from its normal position above the chert.

The absence of size sorting, the angularity of the fragments and blocks, their obvious relation to the adjacent wall rocks, and the evidence of subsidence all suggest that landsliding and slumping of the margins of the pipe produced the coarse breccia. Furthermore, on the north and south sides of the pipe, fine breccia intrudes the coarse along curving dikes that roughly parallel the margin, and dip steeply into the pipe. These resemble the sole faults or slip planes commonly present beneath landslides.

Fine Breccia.—Fine breccia occupies much of the inner part of the pipe and, where coarse breccia is absent, extends to the edge. Its intrusive relationships, small grain size, rounding of some fragments, heterogeneity of rock type, and siliceous dense matrix distinguish it from the coarse breccia.

Fine breccia intrudes the coarse breccia on a scale ranging from through-going dikes isolating large blocks of coarse breccia to branching and irregular veinlets filling fractures in coarse breccia blocks. Many dikes approximately parallel the edge of the pipe and intervene between the wall rock and masses of coarse breccia, suggesting that the fine breccia has wedged the coarse away from the adjacent wall. Where dikes cut coarse breccia composed of relatively small fragments, the edges of the dike are irregular and the dike incorporates some of the coarse breccia fragments. Dikes that cut large blocks have sharp contacts with local short apophyses. No dikes of fine breccia extend into the wall rock (Fig. 4).

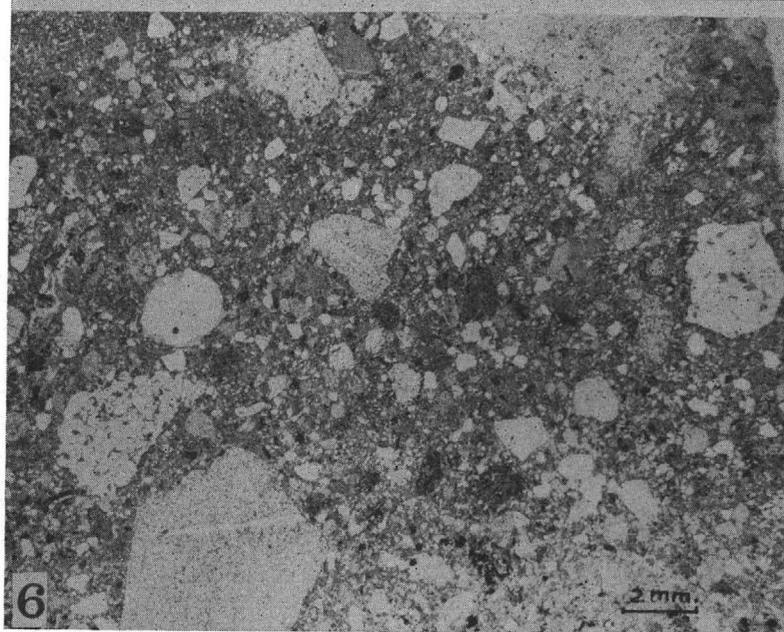
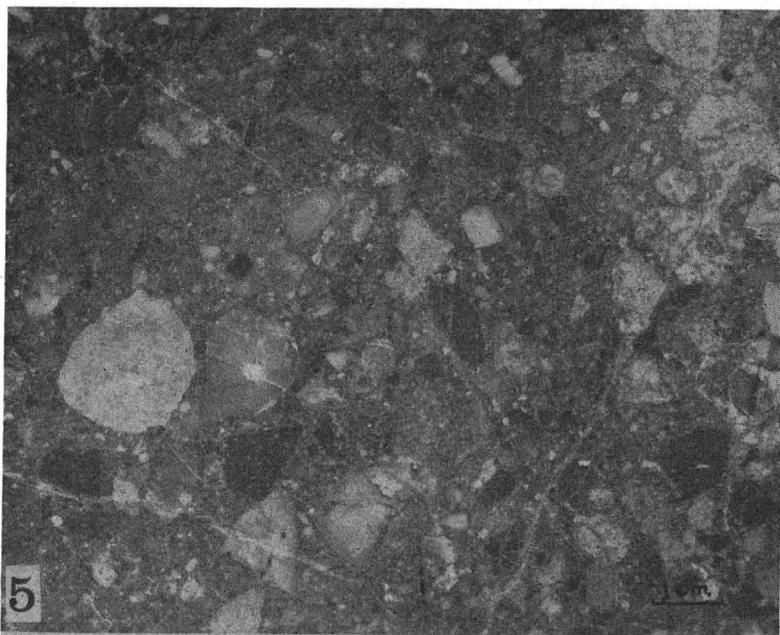


FIG. 5. Photograph of a slab of fine breccia, Horse Canyon pipe.
FIG. 6. Photomicrograph of the matrix of fine breccia, Horse Canyon
breccia pipe. Plain light.

Conglomerate.—Two blocks of Tertiary conglomerate are exposed on the north nose, one close to the marginal coarse breccia at an altitude of about 7,700 feet, and the other at an altitude of about 7,500 feet. Conglomerate also covers the east nose from an altitude of 7,000 feet, low in the pipe, to about 8,100 feet.

The conglomerate contains sand grains, pebbles, and a few cobbles of Paleozoic sediments and Tertiary porphyries and resembles the fine breccia in grain size and mixture of rock types. A greater proportion of rounded rock fragments and the presence of bedding distinguish the conglomerate from the fine breccia.

The bedding in the blocks on the north nose consists of lenses and streaks of subangular to round pebbles 2–3 cm in diameter interlayered with beds of sand size and of typical fine breccia. Cross-bedding and scour between beds is evident in some of the round pebble beds. In many places within the blocks, more or less vertical zones of fine breccia truncate the bedding. In other places, the bedding fades into typical unsorted fine breccia. Dips and strikes vary considerably within the block.

The conglomerate on the east nose is made up of small areas of lenses of bedded pebble conglomerate and sandstone mixed with much larger areas of unbedded, unsorted conglomerate that resembles the fine breccia except for the presence of many subround to round pebbles and a few cobbles. Individual beds or a sequence of several beds ranging in thickness from a few inches to 3 or 4 feet can be traced for as much as 50 feet and then grade into unsorted conglomerate or more angular typical fine breccia. A prevalent type of sorting consists of irregular, somewhat elliptical, pods of sand grains enclosed by coarse conglomerate. The reverse relationship is also present.

The presence of conglomerate as much as 1,000 feet below the upper limits of the pipe and from 200 to 1,200 feet below the neighboring spurs indicates subsidence. The subsidence need not have been as much as 1,000 feet as other evidence indicates that the volcanics in this part of the range buried considerable topographic relief.

The two blocks on the north nose are intruded and surrounded by fine breccia. Contact between fine breccia and conglomerate is well exposed on the west side of the north nose at an altitude of about 7,700 feet. The contact zone contains round pebbles and cobbles from the conglomerate enveloped in a matrix of fine breccia. Irregular tongues of fine breccia infiltrate the conglomerate, isolating individual pebbles or groups of pebbles. Here the fine breccia apparently intruded and mixed with poorly consolidated conglomerate. Another contact of the lower block of conglomerate with fine breccia, however, is sharp, the fine breccia truncating bedding in the conglomerate along a jagged irregular contact. Here the conglomerate was apparently well cemented.

The conglomerate apparently resulted from reworking of the fine breccia by running water. Much of it was a loose gravel, although locally some was fairly well cemented. The underlying fine breccia then apparently was mobilized; it intruded and mixed with the conglomerate, destroying much of

monzonite porphyry. This high viscosity may have been due to a low content of volatiles, owing to their loss earlier during the eruptive activity.

Hornblende Andesite Dikes.—The final igneous event in the history of the Horse Canyon breccia pipe was the intrusion of a few, thin, discontinuous dikes of hornblende andesite. These cut the quartz latite dikes and occur both within and outside the pipe; they are sparsely but widely scattered over much of the range and presumably are not genetically associated with the pipes, at least in any direct way.

PIPE CANYON BRECCIA PIPE

General Description.—This breccia pipe is at the head of Pipe Canyon close to the Horse Canyon pipe from which it is separated by a narrow band of quartzite, chert, and greenstone. To the northeast it joins the Rocky Canyon pipe.

It has an irregular somewhat elliptical shape and a long diameter, oriented approximately northeast, of about $\frac{3}{4}$ mile. The west side is steep, but the east side appears to dip west, giving it an east-west cross-sectional shape like a tilted funnel. It cuts across Ordovician sediments and the thrust faults.

Units mapped within it include most of those of the Horse Canyon pipe, although some differ slightly in lithology: (1) coarse breccia; (2) fine breccia; (3) a plug and dikes of rhyolite; (4) dikes of pumiceous vitrophyre.

Coarse Breccia.—Patches of coarse breccia occur around the margins of the pipe but are less prevalent than in the Horse Canyon pipe. The largest exposure is along the south edge where Ordovician chert and greenstone have been broken into large blocks, tilted and rotated but not moved far from their original stratigraphic positions. The other outcrops are in the low saddle east of Peak "8101" and on the south slope of the south fork of Rocky Creek between the 7,400 and 7,600 foot contours.

In these two localities, the coarse breccia consists of fragments of chert, greenstone, siliceous shale, argillite, limestone, fine breccia, rhyolite, quartz latite porphyry, and pumice. Many fragments are subround and range in diameter from 3 inches to 2 feet. The matrix is composed of angular fragments of the same rocks and of quartz and feldspar, surrounded by finely comminuted rock flour filled with shreds and patches of chlorite and feldspar. This breccia has been thoroughly mixed, and the subround fragments indicate considerable abrasion.

Fine Breccia.—Fine breccia fills the southern and eastern half of the pipe. It intrudes the coarse breccia and, in turn, is cut by pumiceous vitrophyre, rhyolite, and quartz latite.

In grain size, shape and angularity of fragments, mixture of rock types, and absence of structure, this fine breccia resembles that of Horse Canyon. There is, however, a major difference: it contains many fragments of collapsed pumice, tuff, pisolitic tuff, and perlitic glass as well as the fragments of wall rocks and Tertiary porphyries. These volcanic rock fragments resemble the pyroclastics in foundered blocks in the Rocky Canyon pipe to the north. Alteration and silicification parallels that of the Horse Canyon pipe.

laid ash falls; massive layers of tuff-breccia; and lenses of probable pond or lake deposits of very fine ash having thin laminations and cross-bedding.

Tuffaceous layers of shards and rock fragments of sand size carry spherical pellets about 5 mm in diameter. Around a center of coarse fragments is a concentric shell in which the grain size decreases outward and shards and rock fragments are so oriented as to give a concentric foliation. Some of the pellets or pisolites are slightly flattened parallel to bedding and others are broken.

Perret (15) has described similar pellets formed by accretion of ash in a moisture-laden eruption cloud. Tanakadate (20, p. 165) found pellets formed by the snow-balling of ash, wet from rains and melting snow, down volcanic slopes in Japan. Rust (19, p. 65-69) attributed concentric pisolites in breccia pipes in Missouri to accretion in an atmosphere of magmatic spray during explosive eruptions.

Grain size in the bedded tuffaceous sediments ranges from the limit of the resolving power of the microscope to fragments of pebble size. Most of the beds are composed of sand, grit, and pebbles, ash and lapilli. Transport by streams was relatively short, as angular to subangular fragments predominate over rounded ones. About 30 percent of the sand grains, pebbles, and cobbles are of Paleozoic sedimentary rocks, and greenstone and the remainder are Tertiary porphyries, glass shards, pumice lapilli, perlitic glass, quartz and feldspar crystals.

Within the blocks of tuffaceous rocks are lenses of hornblende dacite agglomerate. Roughly spherical blocks of dacite porphyry ranging from 1 to 6 feet in diameter lie in a matrix of fractured crystals of quartz, hornblende, and plagioclase and angular fragments of dacite. The dacite is much altered and oxidized.

Explosive volcanism preceded eruption of the pumiceous vitrophyre. The coarse grain size, angularity of fragments and presence of pisolites and block agglomerate suggests a nearby source of the eruptions. The lake beds might have formed in small lakes occupying a caldera in the pipe.

The fragments of Paleozoic sedimentary rocks in the bedded rocks of the foundered blocks have the same general size range, the same general proportions of different lithologies, and the same degree of rounding as the fragments of the Paleozoic rocks in the fine breccia of the Pipe Canyon pipe. Fragments of tuff, perlitic glass, and pumice like those in the tuffaceous sediments are abundant in the fine breccia. This suggests several cycles of brecciation, explosive volcanism, and reworking and deposition by running water. Unfortunately, the absence of contacts between the fine breccia of the Pipe Canyon pipe and the tuffaceous sediments of the Rocky Canyon pipe precludes any firm conclusions regarding their mutual relations.

Pumiceous Vitrophyre.—The main body of vitrophyre occurs between the north and south forks of Rocky Creek. Several dikes extend into the fine breccia of Pipe Canyon, and a small off-shoot intrudes chert on the west wall of Lewis Canyon. Except for this off-shoot, dikes of vitrophyre do not intrude the wall rocks of the vent.

In addition to the small vesicles, large elliptical vugs as much as 3 mm in length and 1 mm thick are common. Many of these vugs contain an inclusion at one end, and, in any particular slide, all such inclusions are at the same end of the vugs. The small vesicles flow around the large vugs as well as the inclusions. Apparently many of the vugs formed because turbulence around the inclusion localized evolution of gas from the magma.

In many slides, inclusions of chert or porphyries have been fractured; the individual fragments have been slightly rotated and pulled apart; and vitrophyre has flowed into the gap but only partially filled it, leaving a dumb-bell shaped vug with an inclusion of the same rock type at each end. This suggests that a viscous magma evolved gas into areas of slightly lower pressure formed by the fracturing and pulling apart of the fragments.

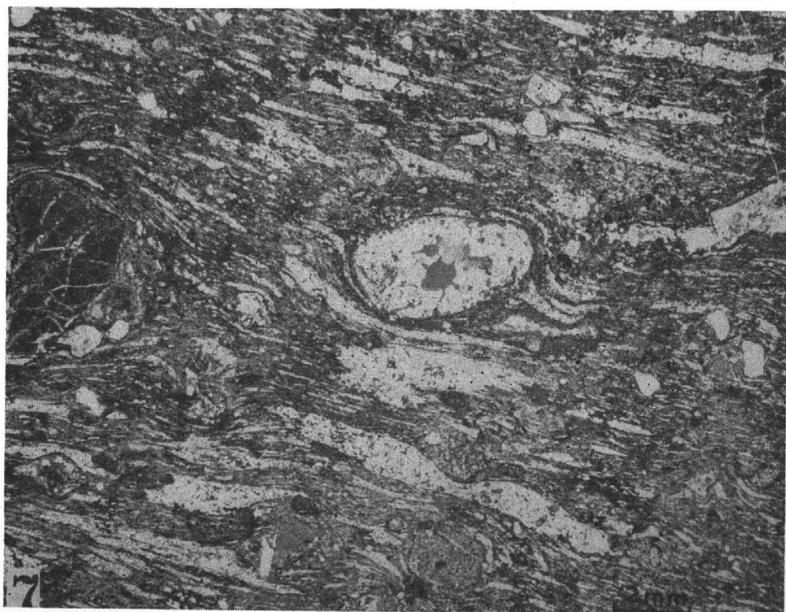


FIG. 7. Photomicrograph of pumiceous vitrophyre, Rocky Canyon pipe. Crossed nicols.

Alteration and devitrification of the pumiceous vitrophyre are widespread. Feldspars are saussuritized; hornblende and biotite in inclusions are converted to chlorite, magnetite, calcite, and quartz. The glassy vesicular groundmass is devitrified and filled with wisps and irregular patches of a yellowish brown birefringent mineral, probably an iron-bearing montmorillonite. Vesicles and vugs are filled with opal, chalcedony, quartz, and the brown clay mineral.

The devitrification was patchy. In some devitrified rocks, the original pumiceous texture is clear. In others, under plain light, devitrification appears to have almost destroyed the pumiceous texture, and reflected or polar-

Locke (10) has proposed essentially the same idea for the origin of the Pilares breccia pipe of Sonora, Mexico, a pipe composed of mineralized, altered, and subsided andesite fragments.

In the Shoshone Range, the dominantly siliceous sedimentary rock fragments show no evidence of widespread solution; solution stoping does not appear to be applicable.

Burbank (6, p. 170-171) described breccia pipes in the Red Mountain mining district of Colorado which have several features resembling those of the Shoshone Range pipes:

The pipes are nearly vertical cylindrical bodies of slightly elliptical cross-section, occupied by breccias and by intrusive bodies of quartz latite porphyry and rhyolite . . . In the more complex pipes the age relations show that breccia was formed first and was followed by intrusions of quartz latite and finally rhyolite.

Many of the pipes are surrounded by a well defined outside wall of vertical sheeting and a zone of curving or spiral fractures in the surrounding wall rock. In many pipes, the breccia grades into the country rock. Burbank (6, p. 177-178) pictured their formation thus.

The passage of magmatic emanations up through favorably jointed and fissured rock may have caused certain chemical or volume changes along some vertical zone of greatest concentration, which impaired the strength of the rock and induced local crackling and crumbling. The zone of disintegration spread outward from the axis along generally curving surfaces—first as the spiral form, controlled by yielding of the rock along planes of maximum shearing stress, and later as the concentric form, controlled by the increasing stresses surrounding the plastic core. As the breccia mass spread into the surrounding rock it tended to assume the form either of a ring zone, or of a cylindrical core.

This hypothesis is difficult to apply to the Shoshone Range because the vertical sheeting and curving fractures are lacking, the contacts of the breccia with wall rocks are relatively sharp, and the pipes and vents are flaring.

The classic areas of Tertiary volcanism in the British Isles provide many examples of breccia believed formed primarily by violent explosive eruptions, many of which are clearly associated with rising acidic magmas and are located along ring dikes (23; 2, p. 199-210; 18, p. 806-810; 17). Tyrrell (23, p. 182) described this example from Arran:

The explosion-breccia of the Central Ring complex consists of a heterogeneous accumulation of fragments of all sizes, ranging from masses hundreds of yards across, down to microscopic chips. The large masses are much fissured, broken, and tumbled; and many of the smaller fragments have suffered micro-brecciation which can be seen even in a microscopic section. The fragments are composed of Old Red Sandstone and Mesozoic rocks which originally spread over the explosive foci, and had already been domed and fissured as the result of the earliest igneous activity of the episode; fragments of the basaltic lavas which were erupted at the earliest stage; and fragments of the acid igneous rocks whose intrusion and explosive condition were the prime causes of the general fragmentation.

A large crater-forming explosion or a sequence of them accompanied by infilling of the crater by debris hurled into the air and by slumping from the walls is not adequate to explain the complexity of the Shoshone Range breccia

Richey (17, p. 168) noted that the walls of many of the vents in Mull and Ardnamurchan are shattered with little displacement of the wall rock fragments and that, in some of the volcanic districts, brecciated rock at depth remained in place. Rust (19, p. 60) found that breccia pipes in Missouri show definite concentrations of fragments of one particular wall rock type. Anderson, Sholtz, and Strobell (1, p. 40) have described breccia pipes from the Bagdad area, Arizona, in which stratigraphy of the wall rocks can be traced through the breccia in the pipes without appreciable displacement.

Rust (19, p. 71-72) called breccia formed in place "authigenic explosion breccias" and proposed the following explanation which was also accepted by Richey (17, p. 168):

Surrounding the confined gas column would be an aureole of rock under the same gas pressure as that in the tube. The amount of gas in this rock would depend on its porosity. At the culmination of the explosion, the compression on the walls and that of the gas contained in the pores of the walls would be at a maximum. . . . Following the explosion, the pressure in the tube would quickly drop to the atmospheric pressure or even less. Slightly after the explosion in the tube there would then be a counterexplosion of the confined gas in the pores of the wall rock, directed toward the center of the tube. This would cause shattering of the gas-bearing rock and projection of great quantities of it into the tube. . . .

"Fluidization"—an industrial process in which gas flowing through a bed of fragments causes violent agitation of the fragments and expansion of the bed until the mass has all the characteristics of a mobile fluid—has been applied by Reynolds (16) to comminution of bed rock to fragments, intrusion of breccia, and authigenic explosion breccias. She cites many examples of this process including the Swabian pipes and many of the Tertiary vents and breccias of the British Isles.

Tweto (22, p. 527) noted that many of the Pando sills in Colorado were preceded by lenses of breccia containing fragments of the sill and of the surrounding sediments. He concluded that gas, expelled by chilling of the magma, brecciated the rocks in advance of the intruding sills and aided in their emplacement. Such a process might also assist in the rise of dikes of magma through overlying rocks.

In addition to these possible mechanisms for brecciation of country rock in volcanic areas, there is another one which was briefly mentioned by Locke (10, p. 446) but which perhaps deserves more consideration than has been granted it heretofore. Rock-bursting occurs both in quarries and in mines and can cause brecciation on a large scale.

White (24, p. 3-6) described rock-bursting in granite quarries at Barre, Vermont as follows:

. . . cracks that formed during or following quarrying operations . . . slope in all directions and may be gentle or steep. It is clear, therefore, that they have no consistent relationship to natural parting surfaces, sheeting, planar structures, and boundaries of the granite, all of which have a more or less constant orientation throughout the district. . . . The cracks have a very consistent relationship to the shape of the quarry in which they lie; without exception they slope toward the deepest adjacent opening or free face. They are certainly the result of the tendency

which flew from the face. Immediately afterwards a stone about 12 inches by 8 inches was seen gradually peeling off the face about 30 feet away . . . a lenticular stone about 7 inches in diameter and $\frac{3}{4}$ inches maximum thickness flew from the face to a distance of 12 feet with a report similar to that previously heard. (26, p. 8).

Between these two extremes are many variations in the type of rock-bursting and its products. Crane (8, p. 160) distinguished three types of less violent rock-bursting: (1) flaking or spitting, (2) spalling in which large fragments thin in comparison with their width break from the face, and (3) wedging, the breaking of large masses, often weighing tons, from pillars. The result of various forms of rock-bursting is to surround some tunnels and stopes with a zone of brecciated wall rocks and in some instances to arch or dome a stope upwards leaving a much larger area of broken rock than was originally mined.

Rock bursts can produce a variety of breccias. Some are incoherent masses of angular fragments of all sizes ranging from dust to blocks weighing tons. Others consist of small fragments described as "small as a man's fist," or "small stone like road-metal." One observer reported complete disintegration of a hanging wall "so that it had little more cohesion than sand" (26, p. 12, 14).

The depth at which rock-bursts begin to occur differs from place to place and from mine to mine. In the Rand gold mines, it becomes a serious problem at 2,000 to 3,000 feet (26, p. 38). In the Lake Superior copper mines, rock failure begins at about 1,000 feet and increases in intensity with depth. In almost any mine, it is a constant hazard at depths of 6,000 feet or greater (8, p. 38).

Rock-bursting is most violent in the flintiest, most silicified rocks. In the Rand, the massive quartzite of the hanging wall readily bursts (26, p. 21), and in the Lake Superior region the hard, strong, and brittle trap bursts most frequently. Crane (8, p. 6) concludes as a rule of thumb that rock which is hard to drill is the most explosive.

The immediate cause of rock-bursts is excavation of the rock, leaving free faces. Other conditions being favorable, the rock will burst if an opening is made in it. The rock is under stress, primarily from the weight of superincumbent rocks, although other factors have been cited (5, p. 30). When part of the stress is relieved asymmetrically by formation of a free face, the stress becomes directed towards the opening, the rock becomes strained and, if strained beyond its elastic limit, will brecciate and burst into the opening.

Bridgeman (4) subjected cylinders of crystals and of porphyry, andesite, and granite in which a cylindrical interior hole had been drilled to high hydrostatic pressure up to 7,000 kg/cm² and found that the cylinders failed by a mechanism resembling rock-bursting. The cavities were enlarged and filled with fragments of irregular shape and size that had flaked or spalled off the sides of the interior cylindrical hole. In the porphyry and andesite, there was no cracking or flowage of the remaining outside shell of rock, and, in the granite, slight flowage occurred without fracturing. Bridgeman (4, p. 266-267) summed up his results thus:

causes further brecciation by the rapid escape of gas, perhaps by rock-bursting into the pipe, and perhaps by "authigenic" brecciation. Once the pressures have been diminished by eruption, a period of subsidence follows, accompanied by slumping, collapsing, and perhaps rock-bursting, which further enlarges the volume of breccia ahead of the main body of magma. The latter invades the breccia in dikes and apophyses and solidifies; fragments of the breccia are incorporated into the upper parts of the magma. As the magma continues to cool and crystallize, gas pressure builds up again. Another cycle of eruption, brecciation, and intrusion of magma and gas follows.

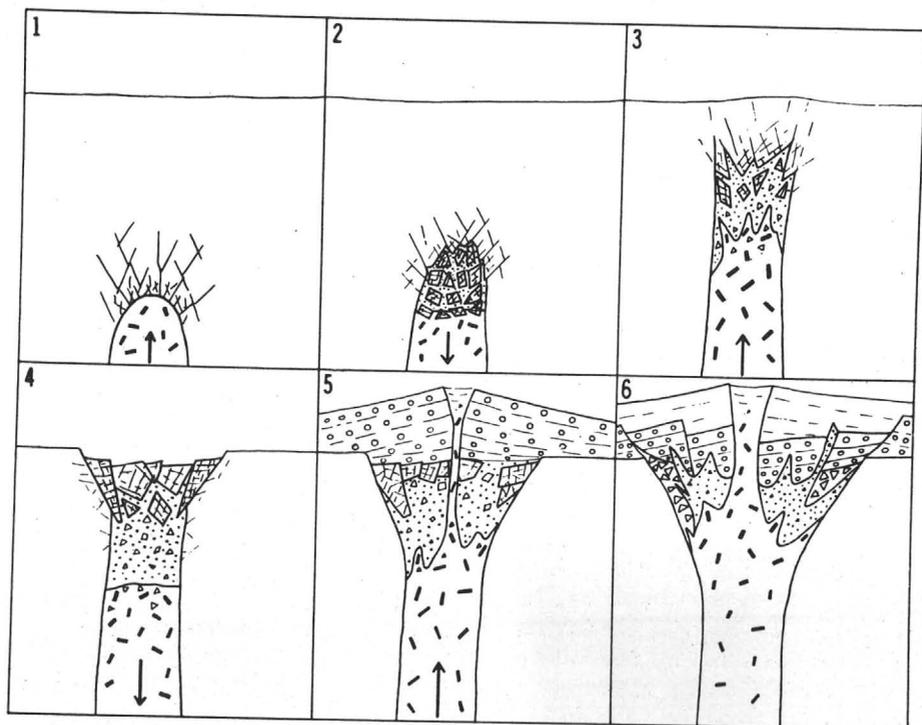


FIG. 8. Schematic diagram showing steps in the formation of the breccia pipes.

Dikes of magma previously injected into the breccia are fractured and their fragments added to the breccia. Each successive cycle of eruption, brecciation, and subsidence increases the volume of the breccia, grinds it to a finer grain size, rounds some of the fragments, and thoroughly mixes them. The magma becomes more and more filled with inclusions. Eventually the breccia works its way to the surface where it intrudes and mixes with breccias and tuffs formed by previous eruptions. There it is also reworked by streams and perhaps covered by tuffs and extrusive breccias. Subsidence occurs again; the walls of the now open crater tend to landslide or rock-burst; another intrusives impulse mobilizes the fine breccia which surrounds and injects the

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25. Williams, Howell, 1929, Geology of the Marysville Buttes, California: Univ. of California Publications, Bull. of the Dept. of Geological Sciences, v. 18, p. 103-220.
26. The Report of the Witwatersrand rock burst committee: Union of South Africa, 1925.

Linnicon

January 25, 1966

Mr. Richard L. Mauger
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The University of Arizona
Tucson, Arizona 85721

Dear Mr. Mauger:

This will acknowledge with thanks a copy of the Annual Progress Report to AEC transmitted by your letter of August 5. Also acknowledged is your letter of August 18 asking for comment on Appendix 12 of the AEC Report. This is a somewhat belated reply, but other matters prevented my taking care of it earlier.

First, I should say that this study of Laramide intrusives in associated copper mineralization is certainly a worthwhile project and should be of prime interest to those engaged in the search for metals as well as those in science.

I can readily accept the thesis in general as to the close association of Laramide igneous activity and copper metallogenesis (convincingly demonstrated by the histogram, page A-XII-19) but object strenuously to the classification of any part of porphyry copper mineralization as magmatic. Although not prepared to argue the validity of the statement (page A-XII-1, paragraph 2) "Experimental evidence is given to show that under magmaticno workable mechanism for simultaneously removing lime and fixing potash in an igneous rock undergoing alteration", I wish to call your attention to compelling field evidence against a magmatic origin for the copper (and iron) sulfide deposits.

This evidence is simply the fact that in the field, pervasive alteration and sulfide mineralization form distinct zones which in places are sharply discordant with the intrusive pattern. Essentially all pre-mineral rock formations, Laramide and older intrusives, sediments, volcanics, and Precambrian schist, are altered and mineralized. But outside the zone, all rock, including the Laramide intrusives, is unaltered and unmineralized. Thus, a close spatial relationship does not appear to exist. That is, alteration-mineralization, controlled by some deep-seated zone of structural weakness, occurred as a separate and later event.

There are few illustrations to be found in the literature simply because relatively few alteration zones have been mapped. An excellent

Mr. Mauger

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January 25, 1966

Illustration of the lack of this close spaced relationship occurs at Ely, Nevada. Here, as at Silver Bell, a long, relatively narrow zone of mineralization-alteration cuts sharply across irregular stock-like bodies of monzonite. Papers on both districts are scheduled to appear in the Wilson volume. To further emphasize the point I am trying to make, I have plotted the outline of the zone of alteration-mineralization on the enclosed geologic map of Silver Bell.

The largest mass of monzonite lies west of the Oxide pit, just outside the southwest edge of the zone of alteration-mineralization. However, note the tongues of monzonite extending into the zone, and farther north note the irregular dike-like monzonite bodies that cross the margin of the zone. Clearly, the alteration-mineralization has been superimposed on a pre-existing intrusive pattern.

In the vicinity of the Oxide pit and northwestward for several thousand feet, the zone appears to be in part confined to the limits of the alaskite intrusive, but south and west of the El Tiro pit mineralization-alteration dies out several thousand feet short of the edge of the alaskite mass.

Yours very truly,

J. H. COURTRIGHT

JHC/kw
Enclosure

cc: Paul Damon
J. E. Kinnison ✓

P. S. Also, thank you for the copy of Bikerman's Geological and Geochemical Studies of the Roskrige Range, Pima County, Arizona.

Rough Draft

Notes on Table 1



GEOLOGIC CHARACTERISTICS OF 26 MAJOR
PORPHYRY COPPER AND MOLYBDENUM DEPOSITS

by

J. David Lowell and John M. Guilbert

Deposit

Deposit (Column 1)

The foldout Table 1 permits comparison of relevant geologic detail of 26 porphyry copper and porphyry molybdenum ore deposits in the New World. Data were collected for as many deposits as possible, omitting only those deposits for which modern descriptions have not been published or those which have been discovered so recently that descriptions are not yet in print. For obvious reasons, greater attention has generally been paid to North American deposits. The table has been kept as factual and as true to the published descriptions as possible, although careful interpretation was sometimes required simply in the selection of the appropriate column in which to enter information. Factual information, generally known but not necessarily in print, is also judiciously included. Entries for most of the deposits have been checked and verified by the geologists and authors most familiar with them. Abbreviations used in the table are given on the page opposite the foldout.

Preore Host Rock

Preore Host Rock (Column 2)

This column cites rock types and ages into which the igneous host rocks of the respective deposits have been intruded. Mineralization may occur in these preore rocks, as at Bingham and Safford, or the preore host

rocks may be too remote, at least laterally as at Butte. An appraisal of the the local economic importance of preore rocks is given in Columns 14 and 15 under "Orebody." It is apparent from Column 2 that the porphyry deposit host rocks are emplaced generally high in the geologic column. Of the 25 deposits for which preore host rock ages are available, 9 have penetrated into late Cretaceous preore materials, another 5 are in older Mesozoic sections, 4 are in Paleozoic rocks, and 7 occur in Precambrian rocks only. In several of these latter deposits, younger sections of the geologic column can be projected over the present exposures of mineralized intrusive rock without adding more than a few thousand feet of cover. It is implicit that most of the porphyry deposits formed within a few thousand feet of the surface, many perhaps less than a mile from the surface.

Igneous Host Rock

Name and Age (Columns 3 and 4)

The third major portion of Table 1 describes the igneous rocks in which and with which the porphyry deposits occur. The names of Column 3 apply to the intrusive units of most intimate association with the orebodies in both space and time. Ages cited in Column 4 generally apply to the intrusive host rocks themselves rather than to the ore deposits associated with them, but several considerations indicate that ore deposition was essentially contemporaneous with intrusion within the precision of measurement of the K-Ar technique. Age dating of the Laramide-Cenozoic interval in the Southwest reported by Damon and Mauger (1966) has indicated two distinct pulses, one of Laramide plutonic activity between 50 and 75 million years ago and one of dominantly extrusive activity during the mid Tertiary time approximately 30 million years ago.

Ages in Table 1 are for deposits in British Columbia and South America as well as southwestern American deposits. Five out of 26 deposits

are reported in the mid Tertiary range of 30-37 million years, 17 out of 26 are probably in the Laramide range of 59 to 72 million years, 3 are in the Nevadan range of 122 to 143 million years, and 1 deposit has a 200 million year Triassic date. Of the Southwest deposits included in Table 1, all are of Laramide age except three mid Tertiary deposits (Climax, Questa, and Bingham) and two Nevadan-age deposits (Bisbee and Ely). Two of the three mid Tertiary deposits are porphyry molybdenum deposits.

A tabulation of British Columbian deposits recently published by White, Harakal, and Carter (1968) indicates that 5 out of 15 copper and/or molybdenum deposits have potassium-argon ages in the range of 165 to 205 m.y., 8 are in the range of 45 to 55 m.y., and the remaining 2 are 100 m.y. and 140 m.y. old respectively. Although the authors do not consider the geographic distribution of these British Columbia dates in terms of belts, posting them indicates that the 165-205 m.y. dates are concentrated in a N 70 W-trending belt just east of the Coast Range batholith. This belt also contains the Endako and Boss Mountain molybdenum deposits which have ages of 142 and 100 m.y. respectively. These molybdenum deposits average about 60 m.y. younger than the copper deposits in the belt. Just west of the 165-205 m.y. belt is a cluster of Laramide-age (50-79 m.y.) deposits along the east border of the Coast Range batholith. Farther to the southwest near the west border of the Coast Range batholith recent age dating suggests the presence of several stocks and some mineralization of mid Tertiary age.

The pattern emerging in British Columbia seems to be one of parallel, overlapping, northwest trending belts of mineralization which increase in age from west to east. It is interesting to note that two of the porphyry molybdenum deposit dates are substantially younger than the surrounding cluster of porphyry copper deposits. An analogy might be drawn between

this situation and the presence of the relatively young Climax and Questa porphyry molybdenum deposits associated with the southwestern American porphyry copper province.

The single South American age in Table 1 is for Toquepala, Peru, and falls in the Laramide range (59 m.y.). However, geologic relationships together with recent absolute age dating by Chilean government geologists indicate that many of the South American porphyry copper deposits are of mid Tertiary age.

This fragmentary evidence suggests that repeated pulses of intrusive activity and porphyry copper mineralization have occurred in each of the principal porphyry copper districts, but that in a very general way the locus of mineralization may have progressively shifted from British Columbia to the Southwest to Peru and Chile in successive periods of activity. That the Southwestern porphyry copper deposits are dominantly of Laramide age is now well established.

Controlling Structures (Column 5)

Column 5 lists attitudes of regional-scale structures thought to have controlled the emplacement of the stocks and batholiths and hence ultimately the porphyry deposits themselves. Consideration was given to local structure as evidenced by published mine and district maps in preparing Column 5, but many bounding faults shown on these maps are of postore age or of multiple age such that their preore importance cannot reliably be established. Greater reliance was therefore placed upon direct statements in text than upon maps. Several authors comment that the specifics of controlling structures were obliterated by the intrusions which they guided. Posting of data from Column 5 on a coarse Rose diagram base indicates the importance of the northwest and northeast structures in localizing the deposits in southwestern North America. Of the 28 bearings

cited in Column 5 for this deposit group, 11 are northeast, 10 are northwest, 3 are north northwest, and 2 each fall in N-S and E-W orientation. The northeast group reflects both regional Precambrian schistosity and apparent important Laramide stresses. The importance of the northwesterly group to porphyry copper deposit distribution is considered by Mayo (1954), Schmitt (1966), and Guilbert and Sumner (1968).

Shape and Size (Columns 6 and 7)

The shapes of intrusions, like determinations of their size (Columns 6 and 7), are difficult to establish meaningfully, both having been affected by a number of external variables. Degree of exposure of a pluton is certainly affected by original depth of intrusion and by the nature of post-intrusion tectonic and erosional history. The Boulder batholith has been exposed for tens of miles in each direction, while a postulated southern Arizona batholith (Ettinger, 1955) may be implied by the numerous stocks and shallowly exposed cupolas of this area. Essentially cogenetic and contemporaneous extrusive activity is a shape-size factor, as are regional and local contemporaneous and later faulting and uplift. It is apparent from Table 1 that most of the host igneous bodies exhibit minor elongation, and that districts with strong structural control also tend to involve pronouncedly elongate stocks. A plot of short dimension against long produces a broad cluster with a slope of about 2 suggesting a low incidence of equidimensional intrusion and thus perhaps a low incidence of nonstructurally guided stock-batholith emplacement. Column 7 lists the size of igneous host rock outcrops for each district, the numbers having been taken from text or measured geologic maps. These dimensions are in part subject to the same uncertainties as Column 6. They indicate that the porphyry copper deposit environment was commonly developed in stocks with cross sections of well under a square mile at the elevation of ore deposition. There appear

to be two host rock size populations, one group less than a mile square and another smaller group of very large dimensions, with relatively few intrusive hosts falling in the middle-size range.

Mode of Emplacement (Column 8)

These entries adopt the terminology and confirm the conclusions of Stringham (1966) extended to include the additional porphyry copper deposits described here. Emplacement of the porphyry copper deposit host rocks is shown to be almost totally passive. Implicit in this dominance is the importance of replacement, resorption, and assimilation with respect to shouldering aside and other manifestations of forceful intrusion, and the likelihood that both lateral and vertical petrologic zoning might be more common than has been recognized. Consideration of Column 8 with Columns 41 and 42, the latter brecciation and shattering specifically within the orebodies, reveals that brecciation and/or shattering are associated with ore deposition in every porphyry deposit, even where emplacement of the host stocks is passive. This disparity suggests that the brecciation and shattering are themselves "passive," and that they can commonly be expected to have been "blind" and probably of solution origin. Forceful intrusion and active, even explosive brecciation as at Toquepala, are apparently of rare occurrence. The extent of magmatic stoping, assimilation, and metasomatism appears mechanically and kinetically inconsistent with extremely shallow emplacement, but moderately near-surface environments are again indicated.

Stock-Dike (Column 9)

The "stock-dike" column (Column 9) indicates that stocks and stocks with subordinate associated diking are far more typically associated with porphyry copper deposit genesis than are dikes, dike swarms, or breccias alone. Implicit is the association revealed in Column 6 of porphyry deposits with equidimension to oval bodies rather than with tabular

or linear ones. Twenty-three of the 26 deposits involve important stock development and a high ratio of stock characteristics to dike forms.

Sequence of Intrusion and Rock Types Mineralized (Columns 10 and 11)

The sequence of intrusion column reinforces early observations (Buddington, 1933) of the association of copper deposits with intermediate to felsic igneous rocks. Except for generally late diabase dikes, no rocks more mafic than diorite occur in the direct sequence of "intrusive" events associated with copper deposit formation. Granodiorite and quartz monzonite and their aphanitic and hypabyssal equivalents are overwhelmingly most important to the porphyry copper deposits, with more felsic variants common to the porphyry molybdenums. Most of the papers consulted in the preparation of Table 1 were carefully explicit on the sequence of intrusive events and compositions, but uncertain field relationships coupled with paucity of absolute age determinations seldom permit unequivocal identification of the beginning and ending of the magmatic episode that involved ore mineralization. No attempt is made in Column 10, therefore, to determine whether the events listed are parts of a single complex intrusive event or successive consanguineous intrusions. Much older and much younger rocks, as described in the appropriate references, are excluded. Column 11 shows that all of the igneous rocks of Column 10 are mineralized in 22 of the 26 deposits tabulated and the latest rocks are mineralized in 2 of the remaining 4.

Several relationships are apparent from Columns 10 and 11. The sequence is generally from dioritic to monzonitic rocks, commonly with the development of late latitic to rhyolitic or "quartz feldspar" intrusions. Typically, all of these rock types at a given locale are mineralized, so it is evident that mineralization either spanned or succeeded, however briefly, the emplacement of plutonic rocks where both plutonic and

hypabyssal rocks occur. The association of porphyry copper deposits with intermediate plutonic rocks is impressive but not as universal as the association with porphyritic rocks, the latter occurring in all 26 districts in Table 1. The lamprophyre or "late diabase" event is less common in the porphyry coppers than it has been thought to be (Spurr, 1925), late diabase having been reported in only 5 of the 26 districts. The general trend, clearly, is from dioritic plutonic toward more felsic hypabyssal rocks with all rock types typically mineralized. The degree to which the shift from dioritic through granodioritic to monzonitic rocks may reflect K-feldspar enrichment via ore-deposition-related potassic alteration (Peters, et al, 1966) will be considered below. Dioritic rocks commonly occur at intrusion margins, as at Ajo and Mineral Park, with progressively more K-feldspathic rocks inward, a relationship not apparent in the table. The distribution is consistent with apparent felsic-component enrichment accompanying potassic alteration near the central portions of some porphyry copper deposits.

Orebody

Outward Shape (Column 12)

The porphyry copper deposits almost all have circular or oval cross sections. At least four of the deposits have clearly defined low-grade centers which produce a ringlike orebody shape in plan. It is difficult to interpret the vertical dimension of hypogene mineralization in most deposits because relatively little data are available substantially below the surface exposure or on precise distribution of primary and secondary sulfides with depth, but the tabulated hypogene mineral bodies seem to fall into three general configurations:

1. Sixteen deposits have the general shape of a steep-walled cylinder. Included in this group are two deposits (Cananea and Toquepala) which approximately coincide in space with breccia pipes.

2. Seven deposits have the general shape of a stubby cylinder or flat, inverted cone, or shield form. All three of the porphyry molybdenum deposits fall in this group.

3. Three deposits (Inspiration, Ely, and Safford) have a gently dipping, tabular shape. This form may represent a Type 2 deposit elongated by a controlling preore structure or by postore displacement.

Boundaries (Column 13)

In all of the deposits studied, the orebody boundaries are at least in part the original gradational or "assay wall" boundaries. All of the orebodies have been intersected by a postore erosion surface. Eleven of the 26 deposits are bounded by at least one postore fault. Two of the deposits coincide closely with breccia pipes which are preore or contemporaneous with ore.

Percent in Igneous Host and Preore Rocks (Columns 14 and 15)

In several deposits, 100 percent of the mineralization is in igneous host rocks (Butte, Castle Dome, Copper Cities, Endako, and Mineral Park). All of the deposits contain some ore in igneous host rocks, but the bulk of mineralization at Bisbee, Mission, and Ray is in preore rocks. Something like 30 percent of all mineralization associated with porphyries occurs in preore rocks, a figure again suggesting cupola-type or at least high-level magmatic development of the porphyry environment.

Dimensions (Column 16)

Horizontal dimensions of the tabulated deposits range from 250 x 1200 feet for the La Colorada pipe at Cananea to 6000 x 13,000 feet for Morenci and the difficult-to-limit Butte district, the fringes of which may reach to dimensions like 20,000 x 50,000 feet (only the highly "porphyry equivalent" for Butte is cited in Column 16). The average deposit size

deduced from published descriptions and maps is perhaps surprisingly 3500 x 5000 feet.

Total Ore Tonnage and Grade (Columns 17, 18, and 19)

Of the 26 deposits tabulated 12 are estimated to contain over 500,000,000 tons of ore, 6 fall between 100,000,000 and 500,000,000 tons, and 8 contain less than 100,000,000 tons. These tonnage estimates must be considered only approximate. Tonnage figures are rarely published, and these numbers are calculated from published deposit dimensions, mill capacities, and so on, and could be considered essentially public information.

Included in these figures are a number of deposits in which ore grade depends on secondary chalcocite enrichment. Average grade of copper ore is 0.80% Cu, and average grade of hypogene mineralization, where this information is available, is 0.46% Cu. Eleven copper deposits contain at least 0.5% Cu in hypogene mineralization, and ten contain less than 0.5% Cu. Molybdenum deposits average 0.16% Mo in grade. It has been noted that there is apparent regional zoning of primary copper from higher contents to lower ones eastward in southwestern United States, with molybdenum content concomitantly increasing eastward.

Hypogene Alteration

This section of Table 1 (Columns 20 through 27) is part of and in parallel with the two sections which follow: the first on Hypogene Mineralization (Columns 28 through 35), the second on Occurrence of Sulfides (Columns 36 through 42). These three blocks are set up so that alteration, mineralization, and sulfide occurrence for a single zone in a given deposit are reported in the three columns with identical headings; for example, the innermost alteration zone at San Manuel-Kalamazoo consists of quartz, K-feldspar, biotite, and minor anhydrite (Column 25), the sulfides

occurring with it are pyrite, chalcopyrite, and molybdenite (Column 32, with amounts), and they occur as disseminations more significantly than veinlets (Column 40). It must be restated here that the table is based as completely as possible upon published descriptions, descriptions which are hardly uniform in approach, detail, and even terminology. Several deposit descriptions were based on temporal rather than spatial relationships; these deposits we entered as earliest equals innermost, and so on outward. Several deposit descriptions involved separate and poorly related descriptions of alteration, mineralization, and occurrence, and we have made every effort to match appropriate spatial and mineralogical data. Question marks in the table generally denote uncertainty of placement of the information rather than uncertainty in the data itself.

In discussing the alteration of porphyry copper deposits, we have adopted four alteration assemblages, the potassic, phyllic, argillic, and propylitic. The potassic assemblage is generally one of quartz with at least two of the three minerals K-feldspar, biotite, and sericite. Sericite, where present, is subordinate to minor. Anhydrite appears increasingly important and diagnostic as a trace mineral, along with other calcium salts. Potassic assemblages commonly yield abruptly to an assemblage consisting essentially of quartz, sericite, and pyrite, which we have called the phyllic assemblage. The usage is adopted to distinguish this characteristic sericite-dominated assemblage from the generally next outward argillic zone. The argillic zone, well established in the literature, consists of important but not quantitatively dominant phyllic minerals which are as properly designated argillic--kaolin and montmorillonite, with lesser sericite and chlorite. The fourth category is the propylitic assemblage alteration minerals, which are dominated by chlorite, epidote, and carbonates. (See Hemley and Jones, 1964; Creasey, 1966; and Meyer and Hemley, 1968

for greater mineralogical detail on these assemblages.) These are the assemblages abbreviated Pot, Phyl, Arg, and Prop in Table 1.

Review of the data in Table 1 reveals some repetitive, unifying, alteration features of the porphyry copper deposit group. The table was set up so that if a phyllic (Quartz-sericite-pyrite) zone was described it was placed in Column 24 headed "Inner Zone." Other assemblages were then entered wherever they fell according to the descriptions. As the table developed, it became apparent that what could best be described as the innermost zone was typically potassic, the inner zone phyllic, the intermediate zone argillic, and the outer zone propylitic. The assemblages were thus entered where no contrary evidence was at hand. There are, therefore, some open spaces in the table where an assemblage, for example, one consistent with "argillic," was not observed or described.

Known Extent Beyond Ore and Peripheral Zone (Columns 20 and 21)

Column 20 records the stated or mapped extent of alteration beyond the outer reaches of the orebody itself. These distances are somewhat uncertain since different observers drew the outer line on different criteria. External alteration is narrowest around the Bethlehem, B.C., deposit, a characteristic of a majority of the Canadian porphyry deposits. Other deposits show alteration in thousands of feet, averaging approximately 2,500 feet. The higher numbers probably represent some merging of hydrothermal with low-rank metamorphic effects, the two being discernible only with difficulty. Significant is the fact that detectable alteration effects do indeed extend laterally to an average distance of half a mile beyond porphyry orebodies. This may well be a low figure, since some authors drew the outer limit on the basis of "bleaching" and the presence of sericite, phenomena that may not mark the outer limit of alteration.

Peripheral Zone (Column 21)

The peripheral zone column was included principally to permit notation of skarn zones of which 5, at Bingham, Mission-Pima, Morenci, Santa Rita, and SilverBell, are reported, and of alteration associated with the commonly described peripheral mineralization. The mineralization is noted for all 26 deposits, but alteration associated with it is in effect not described; Column 21 should be filled with ND symbols, since data for the mineralization is reported in Column 28. Where alteration mineralogy is given, it is of mixed affinity, dominantly propylitic, with sericite mentioned at Questa.

Outer Zone (Column 22)

Mineralogic notation is given for 20 of the 26 deposits in Table 1, with "propylitic" for Ely, Nevada. Of these 20 descriptions, 18 include chlorite, 16 include epidote, and 12 include a carbonate, 10 of which specify calcite. Quartz is cited 7 times, sericite 6 times, zoisite-clinozoisite 5, kaolin 3, montmorillonite 2, and albite, hematite, specularite and rutile(?) once each. More important than numerical frequency, clearly, is the occurrence of assemblages, and by far the most common is chlorite-epidote-calcite. Replaced minerals are seldom discussed; these replacement minerals are presumably dominantly after amphibole, biotite, and plagioclase. As indicated, it may be difficult to distinguish between a hydrothermally propylitized assemblage and a low-rank metamorphic facies. It is significant that this assemblage has affected by far the largest volume of rock. The chlorite, epidote, calcite propylitic assemblage always occurs outside the ore zone and beyond the phyllic and argillic volumes as will be developed later.

Intermediate Zone (Column 23)

This column proved to receive predominantly argillic assemblage descriptions. Silicification is clearly more important here than in the Outer Zone, and the dominant minerals are quartz, kaolin, montmorillonite, and sericite. Argillic assemblages, whether or not they actually fall in Column 23, are discernible in the descriptions of 21 of the 26 deposits, if quartz-sericite-kaolinite (4 occurrences) be included as argillic. Most of the assemblages cite quartz first. Kaolin is cited singly or before montmorillonite in 17 out of the 21 assemblages for which mineralogic data are given. Three deposits indicate montmorillonite zonally beyond kaolin, and 7 involve sericite, including the four quartz-sericite-kaolinite occurrences mentioned above. An argillic assemblage is unreported from 5 deposits.

Inner Zone (Column 24)

Into the Inner Zone column fall most of the quartz, sericite (pyrite) assemblages, the chief ore bearers of the porphyry copper deposits. The zone is reported unequivocally as a pervasive quartz, sericite assemblage at 19 porphyry districts, as quartz, major sericite, minor K-feldspar at 3 more, and as quartz, major sericite, minor kaolin at 3 more. Only at Esperanza is a quartz, K-feldspar pair reported zonally outside of an unusual quartz, sericite, K feldspar, biotite assemblage. Creasey (1966) indicates that K-feldspar can be part of his quartz, muscovite assemblage; that assemblage occurs at Bagdad, Bingham, and Chuquicamata. Creasey states (1966, p. 62) that "Quartz, sericite, pyrite without either a clay mineral or K-feldspar associated is a common assemblage that does not fit into any of the three previously described alteration types. If clay were present [as at Bagdad, Bingham, and Chuquicamata--JDL, JMG], it would belong to the potassic." Since the assemblage appears by far

most commonly as quartz, sericite, pyrite in the porphyry copper environment, the term "phyllic" is urged as a distinct type for that deposit group. Advanced argillic alteration, involving chiefly pyrophyllite, dickite, and topaz (Meyer and Hemley, 1968), is associated with phyllic assemblages at Butte and Bisbee. It is not reported elsewhere but may only have escaped detection.

The phyllic assemblage of Column 24 is the highest intensity exposed alteration assemblage in at least six districts.

Innermost Zone (Column 25)

This column is perhaps the most surprising of the hypogene alteration data block. It indicates that potassic alteration, in spite of relatively scant attention given it per se in the literature, is encountered at most of the porphyry copper-molybdenum deposits as either an early or an innermost assemblage or both. It is reported as simple quartz, K-feldspar, biotite(?) only at Endako, as quartz, K-feldspar, biotite, sericite at 7 deposits, and as quartz, K-feldspar, biotite with chlorite, albite, fluorite, anhydrite, or tourmaline at 7 more. Quartz, K-feldspar, sericite is reported at Silver Bell, and quartz only with K-feldspar occurs at Mineral Park and Questa. Quartz, phlogopite, tourmaline occurs at Cananea, but it may not be innermost there. Anhydrite at several locales is given in parenthesis in Table 1 because it has not been described in print, but pieces of anhydrite from Ajo, Bingham, Esperanza, Questa, San Manuel-Kalamazoo, and Santa Rita are on hand to swell the published occurrences at Butte, El Salvador, and Toquepala. Anhydrite is also reported from Braden, a deposit not included in Table 1. Other characteristics of the potassic zone are briefly described by Meyer and Hemley (1968) and Guilbert and Lowell (1968). Ore values commonly occur at the interface between potassic and phyllic alteration zones, as developed below. The

potassic zone is almost always most central or deepest or earliest if a time sequence is discernible.

Zoning Sequence from Center and Bottom (Columns 26 and 27)

The upward and outward zoning sequence of alteration assemblages is seldom reported as such in the articles upon which Table 1 is based, but their systematic entry by description or from map or diagram reveals a remarkable and doubtlessly significant sequence. Most significant is the fact that 6 and possibly 7 (the position of phyllic alteration at El Salvador is uncertain) of the deposits show alteration assemblages in the same outward sequence: potassic, phyllic, argillic, and propylitic. Significant also is the fact that even where certain assemblages are not reported, the remaining assemblages fall into the same order. Two deposits, possibly 3, show only potassic and phyllic, 4 show the sequence lacking only argillic, and 6 show the sequence starting with phyllic and including argillic and propylitic. Either the geology or the descriptions prevent assignment of sequence for a few deposits. Vertical sequence or zonation is generally much less well known and described, so assignments can be made in Column 27 only for Butte, Climax, El Salvador, and San Manuel-Kalamazoo. Except for uncertainty with the El Salvador sequence, the order is consistent with lateral zoning and supports the conclusion that outward and upward zoning of the 26 major porphyry copper and molybdenum deposits is reliably shown to be of potassic, phyllic, argillic, and propylitic assemblages. Mineralizational conclusions will be developed in the next sections.

Hypogene Mineralization

As has been shown by many authors and articles, hypogene ore mineral assemblages are closely interrelated in time and space with porphyry copper deposit alteration mineral assemblages. The designation of

pyrite and magnetite as ore minerals rather than as alteration minerals, for example, is largely an arbitrary decision.

In Table 1, sulfide-oxide mineral assemblages have been described in Columns 28-35 with reference to the same zones defined by alteration minerals in Columns 20-27. The excellent consistency apparent through each of the mineralization zones and the consistent variation from one particular assemblage to another outward from the center suggests that this is a valid framework.

Peripheral Alteration Zone (Column 28)

This column contains base and precious metal occurrences which form a discontinuous ring typically near the outer edge of the propylitic zone. The occurrences tend to be only small to medium sized deposits, although large lead-zinc deposits with or without precious metals occur in this zone at Santa Rita, Bingham, and Butte. At least minor occurrences of peripheral mineralization are found in all 26 of the deposits studied. Peripheral mineralization was a geometrically diagnostic feature consisting of arcuate clusters of mines or mineral prospects in 22 of the deposits. Minerals found in this zone are commonly sphalerite, galena, silver, chalcocopyrite, gold, and pyrite. Less commonly, specularite, enargite, famatinite, tetrahedrite, barite, and manganese and vanadium minerals are found.

Outer Alteration Zone (Column 29)

This zone generally corresponds to the propylitic alteration zone, and mineralization is generally restricted to pyrite, though sparse chalcocopyrite is usually present together with variable amounts of bornite, molybdenite, magnetite, specularite, rhodochrosite, sphalerite, galena, and rhodonite.

Intermediate Alteration Zone (Column 30)

This corresponds roughly to the argillic alteration zone, and the bulk of mineralization is usually pyrite with a high pyrite to chalcopyrite ratio which averages 23:1 in the deposits for which quantitative figures are available. Variable amounts of bornite, molybdenite, tennantite, sphalerite, galena, enargite, chalcocite, and huebnerite have been found in this zone. Hypogene ore-grade mineralization may overlap into this zone, but this zone is generally outside of the orebody.

Inner Alteration Zone (Column 31)

This zone commonly corresponds to the phyllic alteration zone and typically contains abundant pyrite and high total sulfides together with pervasive sericitization. Pyrite content averages about 5 percent for the 26 deposits, or about 8 percent, excluding the porphyry molybdenum group. Pyrite to chalcopyrite ratio averages 12.5:1. This zone commonly constitutes the ore zone in porphyry copper deposits, especially those in which chalcocite enrichment has occurred. In addition to pyrite, chalcopyrite, molybdenite, and variable but generally small amounts of bornite, chalcocite, sphalerite, enargite, and magnetite occur.

Innermost Alteration Zone (Column 32)

This zone is generally equivalent to the potassic alteration zone and is usually the central zone in the concentric alteration-mineralization pattern. Total sulfide content is low to moderate with an average pyrite content of about 1 percent and a pyrite to chalcopyrite ratio of 3:1 in the deposits tabulated. This zone may reach hypogene ore grade, and it probably accounts for the majority of ore grade materials in solely hypogene ore deposits. It also forms the "low-grade center" in a number of deposits. Five of the 26 deposits show some development of a low-grade center. The mineral assemblage is chalcopyrite, pyrite, and molybdenite,

uncommonly accompanied by bornite. Furthermore, where copper and molybdenum occur in the same deposit, molybdenite is decidedly more abundant in the more central or deeper portions of the deposit.

Overall Abundance Major Ore Minerals (Column 33)

In the porphyry copper systems which were tabulated, pyrite is by far the most common mineral present. Following in order of abundance are chalcopyrite, bornite, enargite, and molybdenite. Molybdenite was present in all 26 of the deposits, a fact not previously recognized.

Zoning Sequence from Center (Column 34) and from Bottom (Column 35)

The typical lateral sequence appears to be pyrite, molybdenite, then pyrite, chalcopyrite, molybdenite, bornite grading outward to pyrite, chalcopyrite and to sphalerite, galena, silver, gold. Apparent reversals were noted in only three camps.

Vertical zoning sequence information is extremely limited because most deposits for which information is available have been explored by mine openings or drill holes only to shallow depths as compared with their original vertical dimension. Scant information available from 12 deposits suggests that typically a pyrite, chalcopyrite, molybdenite assemblage grades upward into pyrite. An apparent reversal of this gradation has been reported in two deposits. It must be concluded that present evidence on vertical zoning is still inconclusive.

Occurrence of Sulfides

Occurrence of hypogene sulfides in porphyry coppers is typically in the form of veinlets or disseminated grains. This habit is probably related to the fact that crackle brecciation is present throughout most of the volume of mineralization and alteration. As a broad generalization, the porphyries give the impression of being large masses of homogeneous

material penetrated by a reticulate network of fractures and mineralized by a massive infusion of fluids which soaked the mass rather than concentrating mineralization in tabular masses or replacements.

Occurrence of Sulfides in Peripheral, Outer, Intermediate, Inner and Innermost Zones (Columns 36, 37, 38, 39, and 40)

A progressive general gradation in sulfide occurrence has been noted in almost every deposit tabulated in Table 1. This sequence progresses from veins in the peripheral zone to veinlets in the outer zone, to veinlets and minor disseminated values in the intermediate zone, to veinlets approximately equal to disseminated in the inner zone, to disseminated greater than veinlets in the innermost zone. The tendency for disseminated mineralization towards the core may result from metasomatism or recrystallization of the rock and healing of earlier veinlets. The absence of prominent veins in most of the alteration zones may indicate that a crackle brecciation zone behaved as an incompetent mass which would not support through-going fissures and in which, therefore, veins could not form.

Breccia Pipes and Crackle Zones (Columns 41 and 42)

Of 26 deposits tabulated, breccia pipes are present in 19 and are mineralized in 18. Two of the deposits, Toquepala and Cananea, are mineralized breccia pipes in which ore limits are nearly coextensive with the limits of the pipes. The mineralized breccia pipes (Toquepala in particular) show evidence that the alteration zones around the deposits have been telescoped into a relatively thin alteration halo, and alteration assemblages within the orebody overlap.

A well-developed crackle zone is present in 25 of the deposits but is largely absent in the scanty mineralization of the Mission-Pima orebody. Crackle zones are usually circular in outline and are always

larger than the orebodies. They typically fade out laterally within the zone of propylitic alteration. Crackle texture is often less distinct near the center of the porphyry copper system, particularly if a potassic alteration zone is present.

Supergene Sulfides

Supergene Sulfides (Column 44)

Of the 26 deposits studied, 22 contain supergene sulfides, and secondary enrichment was required to reach marginal ore grade in 10 districts. Chalcocite is present in each of the deposits where secondary sulfides occur, and it constitutes the chief copper enrichment mineral. Covellite is reported in 12 deposits, and digenite is reported at Butte, Montana.

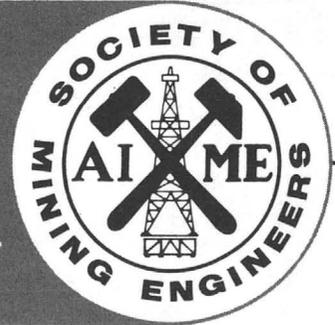
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DIFFERENCES BETWEEN BARREN AND
PRODUCTIVE INTRUSIVE PORPHYRY

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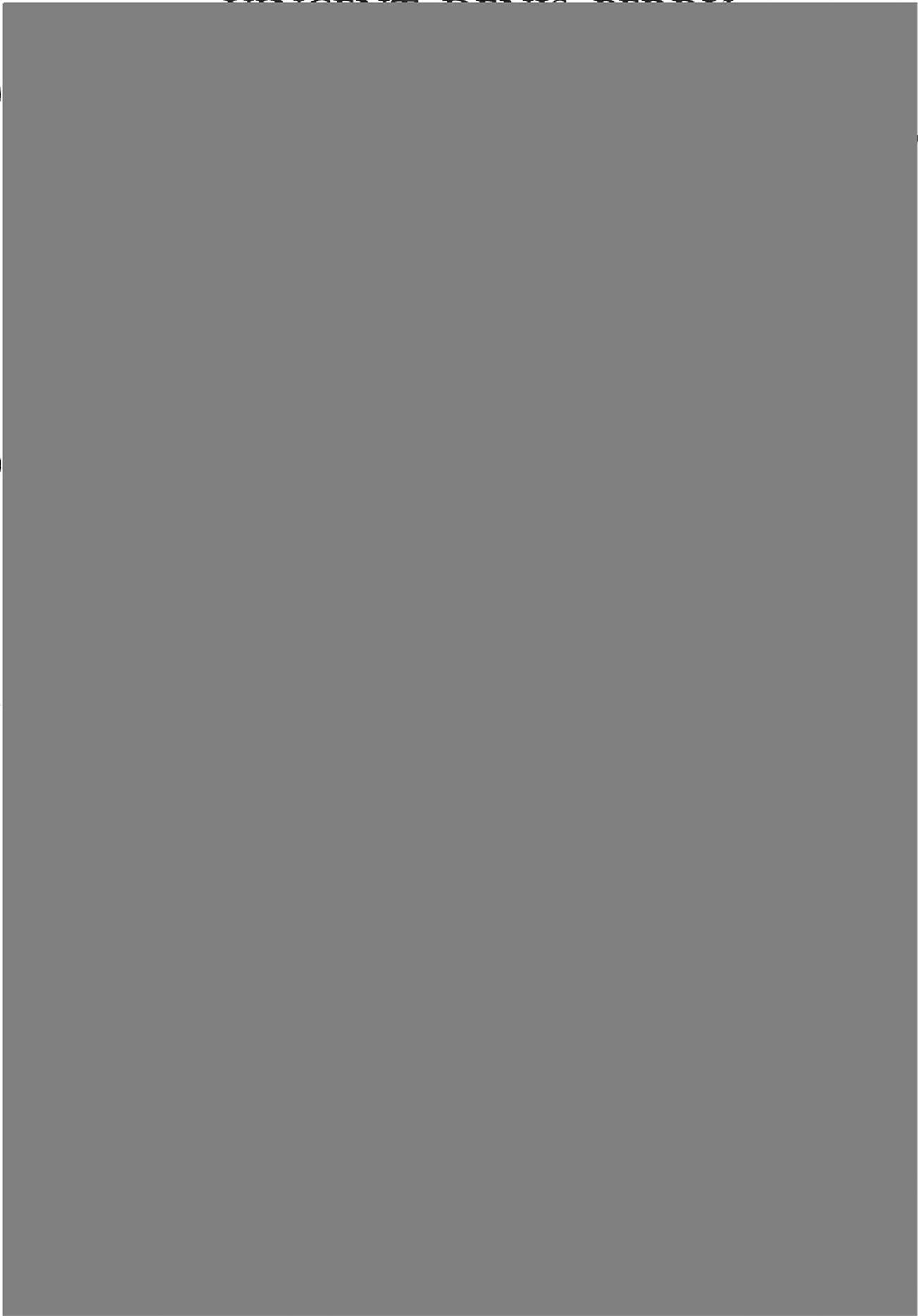
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