The Arizona Geological Society and the University of Arizona

1981 Symposium on

"RELATIONS OF TECTONICS TO ORE DEPOSITS IN THE SOUTHERN CORDILLERA"

AGS/UA Mine Tour and Field Trip data for

TRIP #4

"Copper Creek - Tiger - Kalamazoo Deposits"

March 18

Leaders: A. Cockle (Newmont),
J. Guthrie (Newmont),
and Magma staff.

Field Trip Coordinator: Greg Wessel, (GMRC).

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ARIZONA GEOLOGICAL SOCIETY
P.O. BOX 40952, UNIVERSITY STATION
TUCSON, ARIZONA 85719

TO: Registrants for AGS Field Trip #4, Copper Creek-Tiger-Kalamazoo Deposits

As field trip chairman for the Arizona Geological Society, I would like to take this opportunity to welcome you to the Southwest and thank you for registering for this field trip. Your overwhelming interest in this symposium and for the field trips in particular has provided the Society and our profession a unique opportunity to observe, examine, and discuss on a first hand basis the geology of a number of diverse structure-tectonic settings scattered throughout Arizona and adjoining southwestern New Mexico.

The central theme of the symposium is tectonics and its relationship to ore localization; however, as for specific trip content, this must necessarily remain in the able hands of each respective field trip leader. This particular excursion will take you to Copper Creek, Tiger, and the discovery outcrops above the Kalamazoo extension of the San Manuel orebody. It is intended to provide registrants with a blend of Laramide and mid-Tertiary structure-tectonics, epizonal plutonism, and contrasting base-precious metal alteration-mineralization. The consequence of post-mineral listric normal fragmentation at San Manuel-Kalamazoo will be underscored if time permits.

Our appreciation is extended to Newmont Exploration Limited for providing Mssrs. Allen Cockle and James Guthrie ample time to prepare and lead this trip and to the Magma Copper Company staff for granting us permission to visit their operations at Tiger and Kalamazoo. The continual efforts of the trip's logistics coordinator, Greg Wessel from Gulf Mineral Resources Co., is similarly appreciated.

Again, welcome to the American Southwest, happy rock knockin', and here's hoping that each of you will take the time to contribute to the trip's success by participating in many stimulating discussions of the rocks at hand on their terms.

Sincerely,

Tom L. Heidrick

Tom L. Heidrick
AGS Field Trip Chairman

TLH/gr

The 1968 J. David Lowell article Geology of the Kalamazoo Orebody from Economic Geology is reprinted with permission from the Society of Economic Geologists.

ITINERARY

4. COPPER CREEK-TIGER-KALAMAZOO DEPOSITS

General Leader: J. O. Guthrie (297-7281)
Coordinator: Greg Wessel (882-4030)

March 17, 1981	
7:30PM	Overview and discussion session, University of Arizona campus, Room - Economics 110. (see map below)
March 18, 1981	
6:30AM	Leave U of A student Union
6:30-8:00AM	Travel to Copper Creek
8:00-11:30AM	Traverse to Railroad Pipe and review alteration-mineralization
11:30-12:00PM	Return to bus
12:00-12:30PM	Lunch at Copper Creek
12:30-1:15PM	Travel to San Manual
1:15-4:00PM	Tiger geology, alteration-mineralization, structure-tectonics
4:00-5:00PM	Kalamazoo visit
5:00-6:00PM	Return to Tucson with stops at #1-Sheraton Pueblo Inn and #2-U of A student Union

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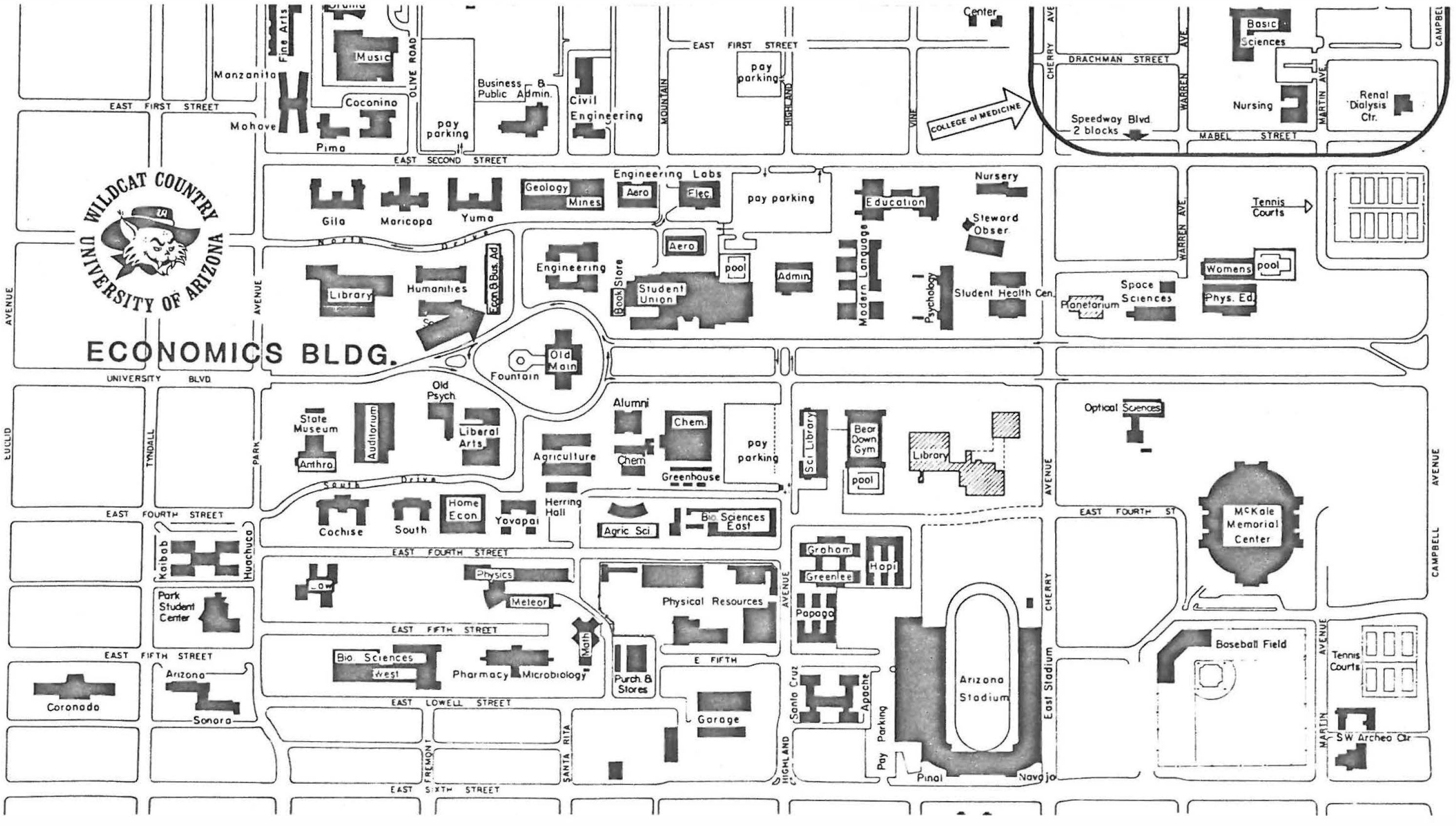
Support vehicle:	Greg Wessel, Norm Lehman, Joe Shearer

2 Buses



TECTONICS FIELD TRIP #4

George Even/Freeport Exploration
Gregory Wessel/Gulf Mineral Resources
Robert J. Stuart/Freeport Exploration
David F. Briggs/Quintana Minerals Corporation
Norman E. Lehman/Amax Exploration
James R. Norris/University of Arizona
Steven Peters/
Jan C. Wilt/Consultant
Henry G. Kreis/ASARCO
Peter G. Vikre/ASARCO
David M. Brown/Texasgulf, Inc.
Barry French/U. S. Borax
Bob Helming/Duval Corporation
Chris Puchner/Anaconda Copper
Charles Haynes/Aluminum Company of America
L. K. Lepley/
Ralph Higgins/Conoco, Inc.
David Wahl/
William Peters/University of Arizona
Perry Durning/Fischer-Watt Mining
Stephen Reynolds/Molycorp
Ann Cochran/University of Arizona
Henry Truebe/University of Arizona
John White/Texasgulf Western, Inc.
Libby Anthony/University of Arizona Student
Maurice Magee/Pincock, Allen & Holt
Wayne Bartlett/Continental Materials
Michael Greeley/Arizona Dept. of Mineral Resources
Francis Sousa/St. Joe American Corporation
Pete Sainsbury/AirSamplex Corporation
J. David Miller/Union 76 Molycorp
Ronald Lyon/Stanford University
Richard P. Standish/Rocky Mountain Energy
Michael McFarlane/Chromalloy Mining & Milli
Lee C. Alstead/Chromalloy Mining & Milling
Paul Eimon/Chevron Resources
Steve Kay/Gold Fields Mining
Jerry Willis/Gold Fields Mining
John Proffett/Consultant
John A. Brady/Armco Material Resources
Jeffrey Rassuchine/Nevada Resources
Jim Bright/Nevada Resources
Peter Hahn/Nevada Resources
John Roylance/Rexcon, Inc.
Mike Fiannaca/Lacana Mining
Dr. M.J. Walawender/Dept. of Geol. Sciences
Earl Cook/Texas A&M
Wim Groeneweg/DRACO
Warren Rehn/U.S. Geological Survey
Arthur Leger/
Jerry Harrold/Denison Mines Inc.
Russell Powers/Denison Mines Inc.
Wayne Kemp/Freeport Exploration
Mark Hudson/Colorado School of Mines
Theodore Ball/
Dale Anderson/Urangesellschaft USA
Ben Dowegan/
Peter Mesard/Exxon Minerals

TECTONICS FIELD TRIP #4, continued

John Wood/Amax Exploration

Christopher Candee/Amax Exploration

Robert McCusker/Amax Exploration

John Thomas/Amax Exploration

Keith Rhea/Amax Exploration

Don LeHeup/Amax Exploration

Robert McNeil/Houston International Materials

John Collins/

Grant Newport/Bear Creek Mining

Richard Wardle/NFLD Department of Mines

Bert Jeffries/Canyon Resources Corporation

Albert Hofstra/Aztec Geological Services

Ken Brook/

Philip Pyle/Amax Exploration

Gary Anderson/Resource Association of Alaska

Scott Jenkins/Amax Exploration

Peter Holekamp/HIMCO

Roger Callaway/HIMCO

Melvin Stinson/California Div. of Mines&Geology

Ann Kramer/Colorado School of Mines

J. Bruce Harlan/

Kathryn Pillmore/Colorado School of Mines

Robert Seklemian/

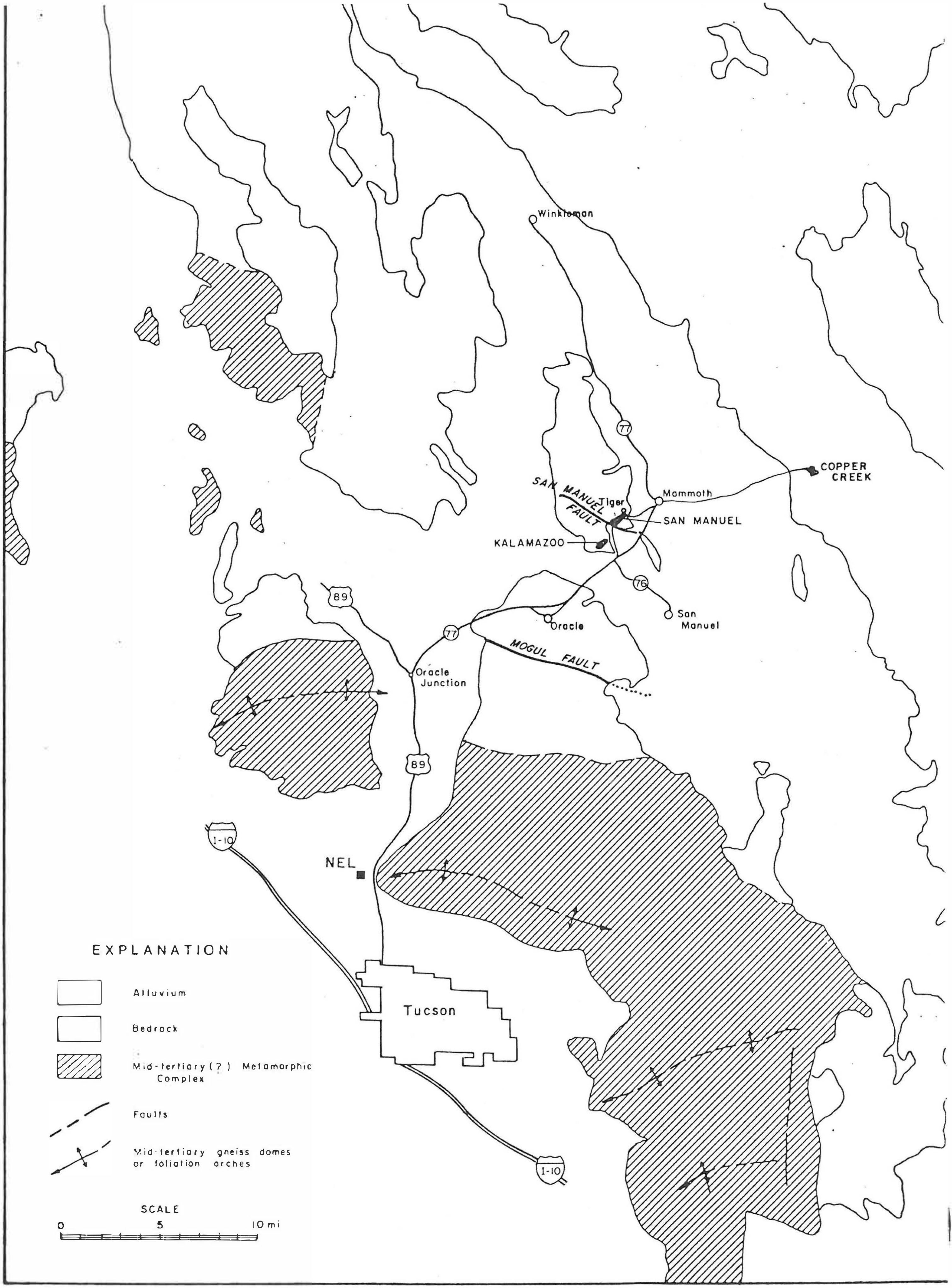
Jim Schearer/

Stephen Reynolds/

F. T. Graybeal/Speaker

J. Rytuba/Speaker

Joe Worthington/Speaker


Winkleman
77
SAN MANUEL FAULT
Tiger
Mammoth
COPPER CREEK
SAN MANUEL
KALAMAZOO
76
San Manuel
89
Oracle
77
MOGUL FAULT
Oracle Junction
89
I-10
NEL
Tucson
I-10
EXPLANATION
Alluvium
Bedrock
Mid-tertiary (?) Metamorphic Complex
Faults
Mid-tertiary gneiss domes or foliation arches
SCALE
0
5
10 mi

COPPER CREEK FIELD TRIP

(AGS-U of A March 19-20, 1981 Symposium)

The Copper Creek District consists of a Laramide igneous complex that includes granodiorite, diorite and several varieties of porphyry. The Laramide rocks intrude Precambrian, Paleozoic and Mesozoic rocks including Cretaceous(?) age volcanics. The area was subsequently covered by mid-Tertiary volcanics, and has been exhumed by relatively recent uplift and erosion.

The field trip has been designed to give a brief introduction to the tectonic features of an individual breccia pipe associated with the Copper Creek porphyry copper mineralization system.

The buses will travel north from Tucson, then swing to the east, along the north side of the Catalina Mountains. From the town of Oracle the route drops into the San Pedro Valley, passing the San Manuel deposit and smelter. The San Pedro River is crossed at Mammoth. From Mammoth the route climbs to the east toward the Galiuro Mountains and crosses over the Plio-Pliestocene Gila Conglomerate. The clay and silt units exposed in the wash just east of the river are part of the Lake bed facie of the Gila. Some of these units contain gypsum. The Lake beds rapidly grade into and are interfingered with the coarse sand and conglomerate beds typical of the Gila.

The Gila Conglomerate is in fault contact with the Glory Hole Volcanics. These volcanics are andesitic and latitic agglomerates, lavas, flow breccias and tuffs that have been thermally metamorphosed by the intrusion of the Copper Creek granodiorite stocks to dark, fine-grained, hornfelsic-textured rocks.

The Glory Hole Volcanics exhibits a very strong east-west set of fracturing. This is the predominant "open" vein direction in the district. The areas of very strong alteration and breccia pipe development occur as rough, resistant, reddish-stained outcrops. The main alteration product is fine-grained quartz and sericite, with up to 10% pyrite and minor tourmaline. On crossing the creek, a breccia pipe can be seen just north of the stream.

STOP-1 - Precipitation plant site, Ranchers Exploration and Development Corp.

The bus will park here and the remaining trip will be by foot. The total round-trip distance will be just over 1 mile. (Figure 1.)

The Ranchers in-situ leaching operation is completed. They are in the process of shutting down. The area of the leaching is the site of the Old Reliable Breccia Pipe. The Old Reliable contained four million tons of 0.08% copper. The principal copper minerals are chalcocite, chalcopyrite, malachite, chalcanthite and chrysocolla. An area of 400 feet in diameter and 350 feet in depth was fractured in place.

The road bed seen along the north side of the canyon is an old railroad grade. It was built during the 1940's to carry ore from the Old Reliable and the Childs-Aldwinkle mines to a mill site almost a mile up the Canyon. The Old Reliable furnished copper, and the Childs-Aldwinkle furnished copper and molybdenite.

The tailings in the side canyon came from an old mill up the canyon near the Childs-Aldwinkle mine. The foundations of the mill are still present to the east along the road.

On leaving the bus we will proceed up the road. It will be a long walk to the next stop, so please stay close.

The first outcrop on the road is the Glory Hole Volcanics. The black color of the rock is in part due to fine-grained biotite. The contact between the granodiorite and volcanics is just to the east. For the next 2,500 feet, you will get a very close view of the Copper Creek Granodiorite. The granodiorite is cut by widely-spaced veins with quartz-sericite-chlorite alteration selvages. Almost all veins in the Copper Creek District are east-west, or within 15° north or south. Many are steep, but an occasional flat vein is present.

STOP 2 - Dark Porphyry

This is a typical plug of dark porphyry. Some good exposures of its contact with the granodiorite can be seen just below the road on the southern side of the creek. Some veining with pyrite is seen across the creek. At the eastern end of the plug, the dark porphyry and granodiorite exhibit intense quartz-sericite alteration. For those of you who want to risk the climb, it can be viewed. Continue up to the railroad bed and walk eastward to the next stop. For those who wish easier paths, follow the road across the creek and to the path to STOP 3.

STOP 3 - Breccia Pipe

This breccia is exposed as three separate bodies aligned in a northerly direction. (Figure 2). Items to be noted are the sharpness of the contact, its control, the variations in fragment size and shape, the alteration within the breccia and the surrounding host, and the close association between breccia and dark porphyry.

(a) Dark Porphyry. On the path below the railroad bed the contact of the dark porphyry and granodiorite is exposed. The porphyry shows moderate quartz-sericite alteration.

(b) At the southwest corner of small southern-most breccia can be seen the control of east-west and north-south fractures. Some other features to note are:

1) the sheeting at the contact;

2) the rapid diminishing of alteration beyond the pipe;

3) the steepness of the contact;

4) presence of some tourmaline.

(c) By traversing across the middle breccia body from the railroad bed uphill, an idea of its variable breccia texture, and alteration, plus the contact relations can be gained. At this elevation, to the north, is a level area with a deep open shaft. BEWARE, as it is most difficult to extricate a person from it.

(d) In this area, on the railroad bed, the breccia fragments are easily seen. Both alteration and fragment shapes can be observed. Note the overall tightness of the breccia. The zone of sheeting at the contact, just east of the railroad bed, is relatively wide.

(e) Septum of unbrecciated, weakly-altered granodiorite. This coincides with one of the subordinate fracture directions.

(f) The northern breccia contains a large dark porphyry block at the railroad bed level. Note the vuggy character and the presence of copper oxide in the porphyry. This northern breccia is more intensely altered and contains less copper mineralization than the southern breccia.

(g) Figures 3 to 8 show the fracturing pattern, Cu, Mo, Pb, Zn rock-chip geochemical values and sericite alteration intensity for this breccia.

On leaving this stop, return by the path to the canyon bottom and go directly west along the main road to the buses.

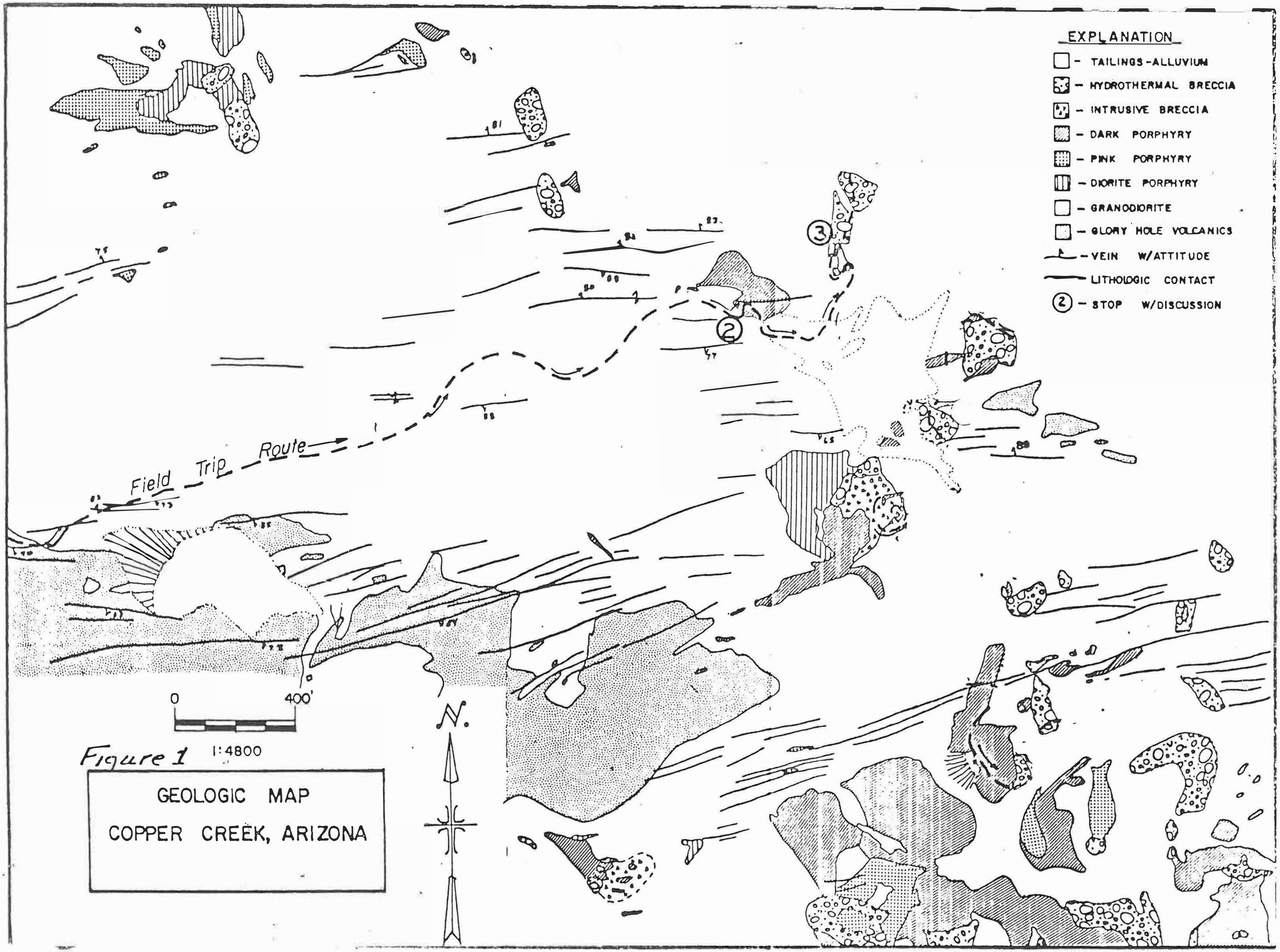


Figure 1

GEOLOGIC MAP
COPPER CREEK, ARIZONA

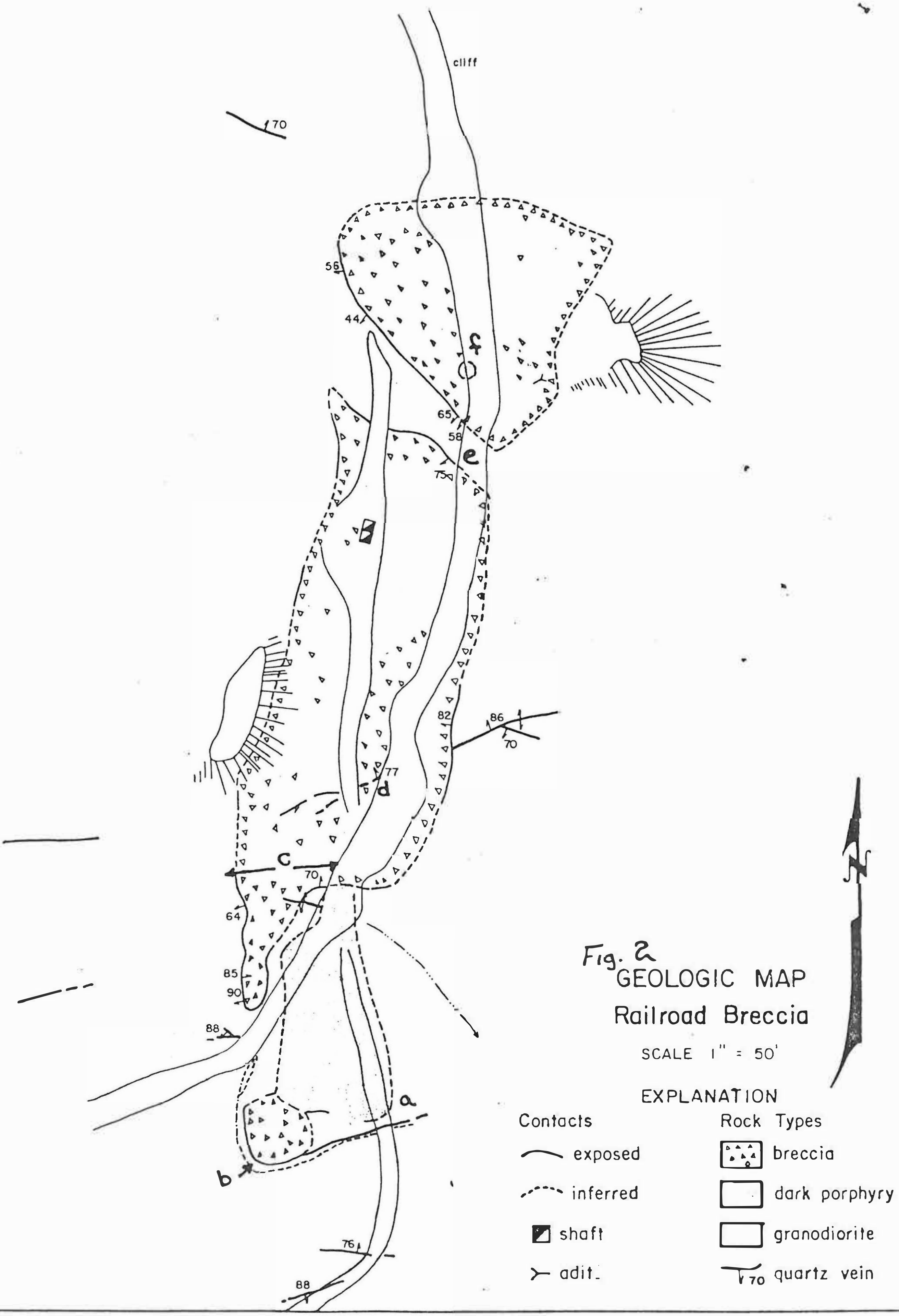


Fig. 2
GEOLOGIC MAP
Railroad Breccia

SCALE 1" = 50'

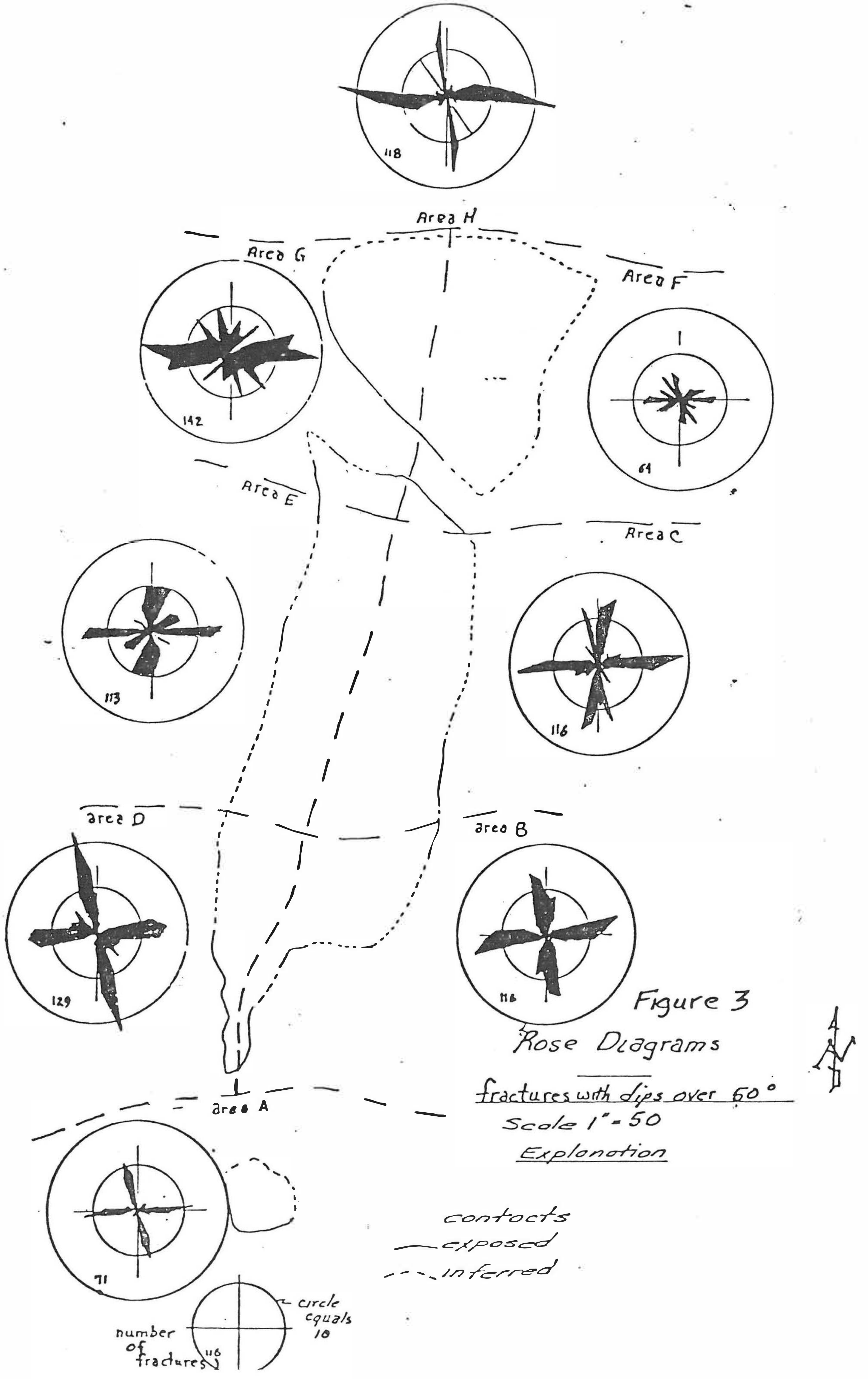


Figure 3
Rose Diagrams

fractures with dips over 60°
Scale 1" = 50

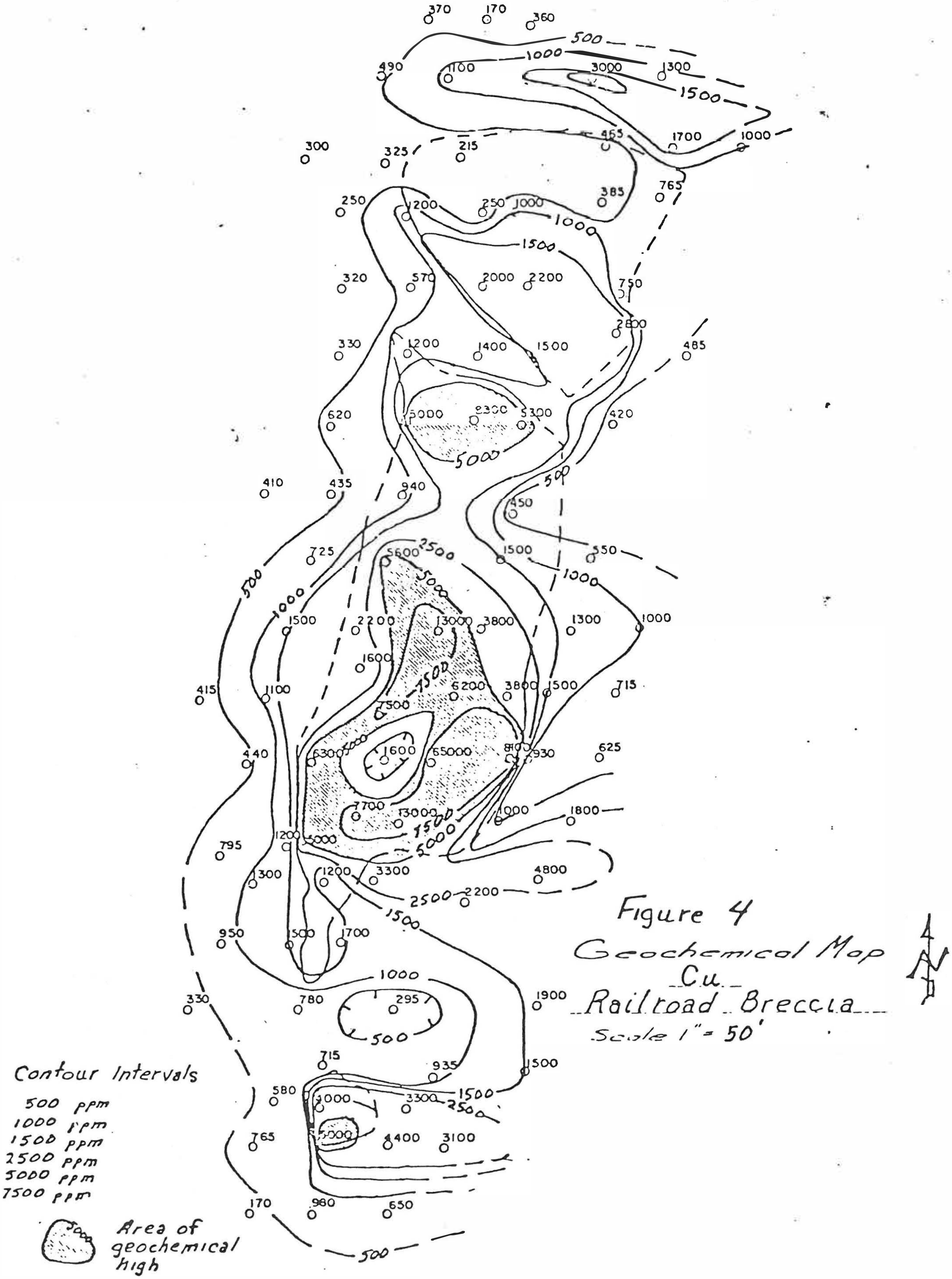


Figure 4

Geochemical Map

Cu

Railroad Breccia

Scale 1" = 50'

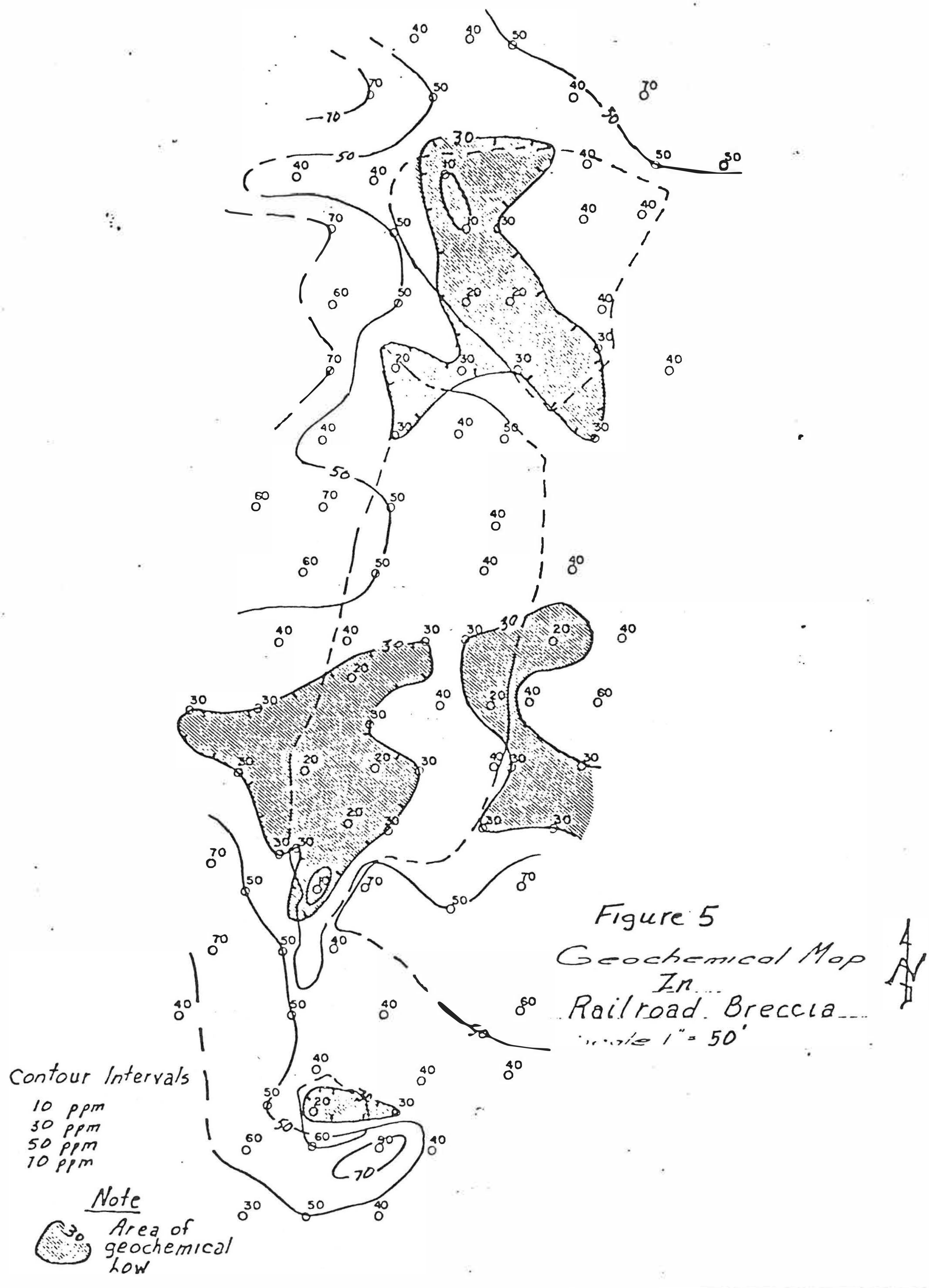


Figure 5
Geochemical Map
Zn
Railroad Breccia
Scale 1" = 50'

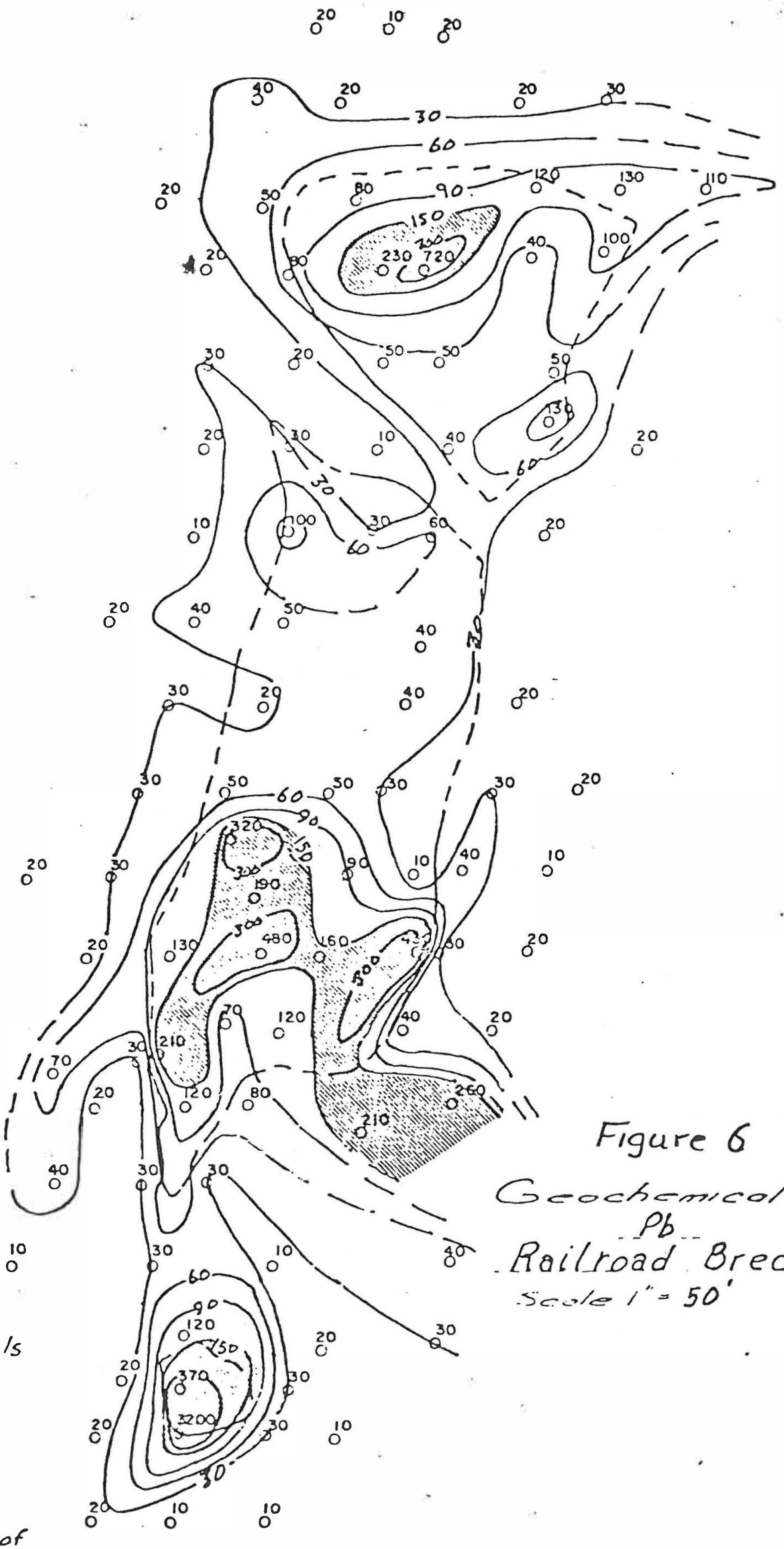


Figure 6

Geochemical Map

Pb

Railroad Breccia

Scale 1" = 50'

Contour Intervals

30 ppm
60 ppm
90 ppm
150 ppm
300 ppm

▨ Area of geochemical high

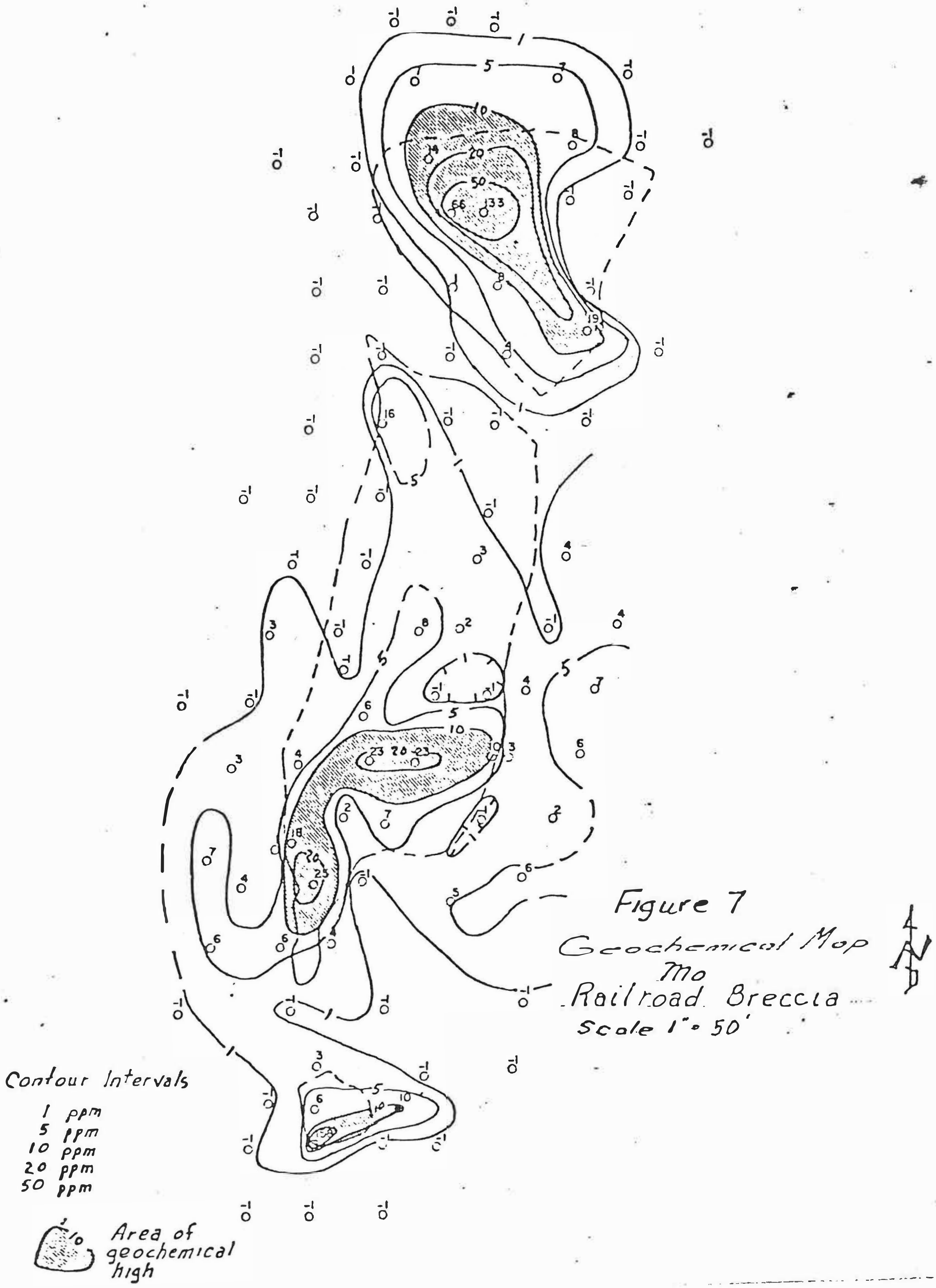


Figure 7
Geochemical Map
Mo
Railroad Breccia
Scale 1" = 50'

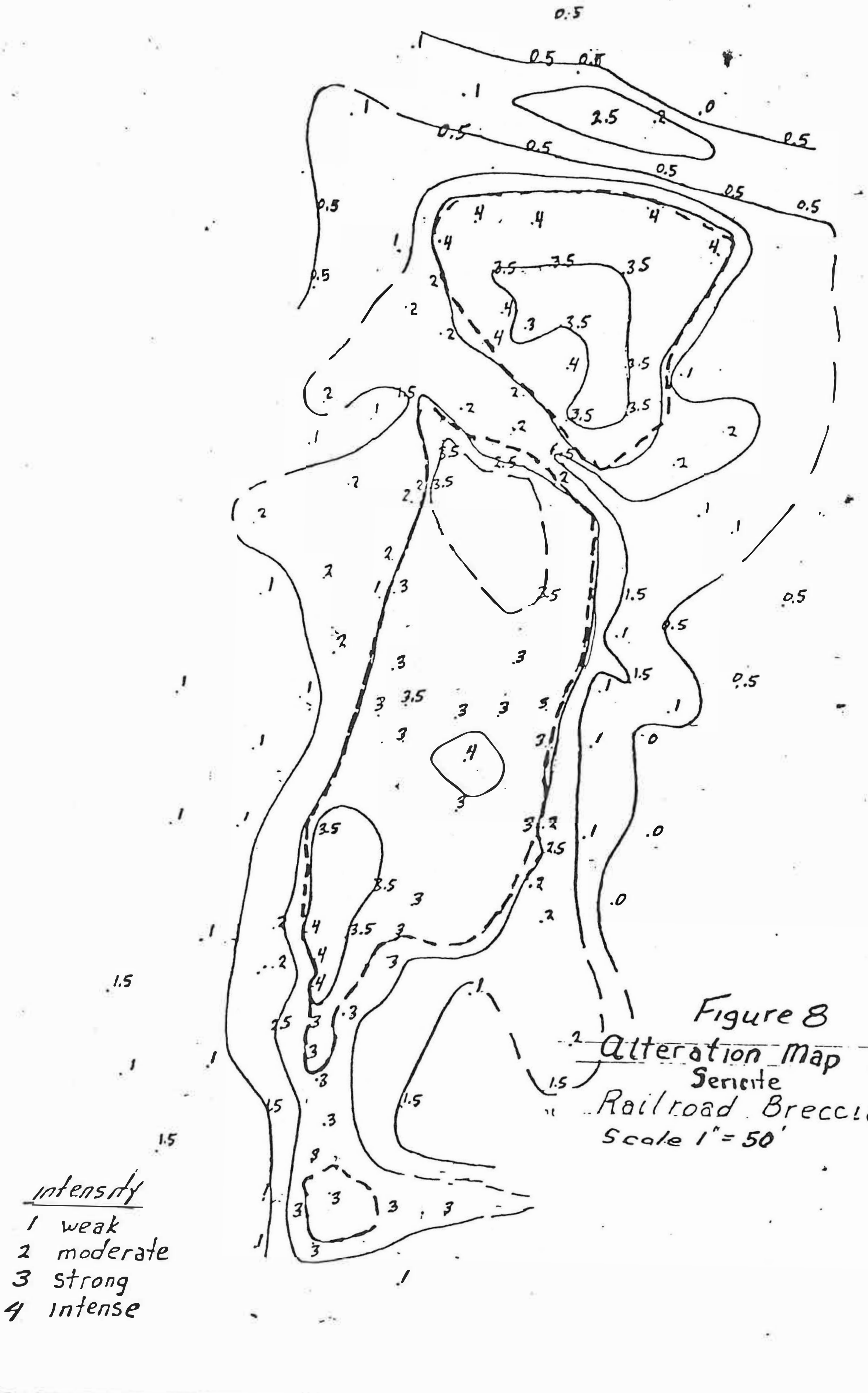


Figure 8
Alteration Map
Sericite
Railroad Breccia
Scale 1" = 50'

THE GEOLOGY OF THE COPPER CREEK AREA, BUNKER HILL MINING DISTRICT, GALIURO MOUNTAINS, ARIZONA

by

J. O. Guthrie [1] and D. G. Moore [2]

Abstract

Copper Creek is located 14 miles northeast of San Manuel on the western slope of the north-central Galiuro Mountains in the Bunker Hill mining district, Arizona. Copper Creek is important in understanding the porphyry copper system because it furnishes the chance to study the upper-level occurrence of a deep mineralized porphyry copper deposit.

Minor outcrops of Precambrian and Paleozoic sedimentary rocks are found in the eastern and northeastern portions of the district. In the north, west, and south portions is a thick heterogeneous sequence of andesitic and dacitic volcanic rocks designated as Cretaceous(?) Glory Hole Volcanics. Intrusive into these older rocks are three stocks of Copper Creek granodiorite and associated porphyries. Overlying the intrusive rocks are the Galiuro Volcanics, a thick sequence of Tertiary flows, tuffs, and agglomerate. Plio-Pleistocene Gila Conglomerate is in fault contact with the older rocks along the western edge of the district. The Copper Creek stocks consist of an equigranular phase (Copper Creek granodiorite) and a porphyritic phase (dacite porphyry). The porphyritic phase is divided into pink porphyry, feldspar porphyry, and dark porphyry varieties.

The principal structural trends are east-northeast, northwest, and north, expressed by fracturing, veins, faults, and the shapes and alignment of the intrusions and breccias.

Spacially and chronologically associated with the dacite porphyry are breccia pipes. Gensis of the breccias is closely linked with emplacement of the dacite porphyry stocks. Intersecting structures localize and control the emplacement of the porphyries and the shapes of the breccias.

Significant porphyry copper mineralization is present in the American Eagle basin located in the south-central portion of Copper Creek. The copper mineralization occurs 2,000 feet or more below the surface in an area of relatively intense veining and clusters of breccia pipes and dacite porphyry plugs. The deposit is a low-sulfide system averaging approximately 3 percent by weight total sulfides. In the upper portions, the sulfide is predominantly pyrite, which grades downward into the predominantly chalcopyrite zone. Bornite and some molybdenite occur at the base and below this zone. The mineralization shows strong fracture and breccia control throughout the system.

Zones of pervasive alteration are not well defined at Copper Creek. In the American Eagle basin sericite is the dominant alteration product. It is associated with the breccia pipes, veins, and many of the dacite porphyry plugs. Potassic and argillic alteration occur as scattered zones, along with lesser amounts of tourmalinization, silicification, and propylitization.

Introduction

Copper Creek, located on the western flank of the north-central Galiuro Mountains, 50 miles north-northeast of Tucson, Arizona, is part of the Bunker Hill mining district. History of exploration and mining activity at Copper Creek began in 1863 with the first recording of mining claims. First mining was for lead and silver at the Blue Bird mine. In 1883, the Bunker Hill mining district was organized and recorded. The first copper exploration began with the Table Mountain Copper Company in

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[1] Newmont Exploration Limited, Tucson, Arizona 85704

[2] Exxon Company, U.S.A., Tucson, Arizona 85705

1897-98. From 1903-1917 prospecting and some production was done at the Old Reliable and other breccia pipes by the Copper Creek Mining Company. The Calumet and Arizona Mining Company did exploration work in northwest Copper Creek from 1907 to 1909. In 1933 the Arizona Molybdenum Corporation obtained the Childs-Aldwinkle mine, which produced until 1938, when mining activity in the district ceased. During this time, total known metal production was over 8 million pounds copper, nearly 7 million pounds molybdenite, over 4 million pounds lead, and in excess of 200,000 ounces silver and 726 ounces gold.

Early copper exploration efforts in the Bunker Hill mining district were concentrated on the mineralized breccia pipes. The first exploration for a porphyry copper-type deposit by deep drilling was done during the middle 1960s by Bear Creek Exploration. Newmont began its exploration effort at Copper Creek in 1966 and was joined in 1971 by Exxon.

Geologic work in and adjacent to the Copper Creek area was done by Kuhn (1941), Creasy, Jackson, and Gulbrandsen (1961), Simons (1964), and Krieger (1968). Information on individual mines or breccia pipes was published by Weed (1913), Kuhn (1938), Denton (1947), Joralemon (1952), and Simons (1964).

Geology

Figure 1 shows the general geology of the Copper Creek area. The Galiuro Mountains are a north-northwest-trending, elongate range along the eastern edge of the San Pedro Valley and are formed mostly of gently east-dipping Tertiary volcanic rocks. Pre-Tertiary rocks underlying the volcanics are exposed along the northwestern flank of the Galiuro Mountains. Copper Creek Canyon cuts into and across the southern portion of these older rocks exposing Precambrian and Paleozoic sedimentary rocks and Mesozoic to lower Tertiary volcanic and intrusive rocks. Plio-Pleistocene semi-consolidated fanglomerate is in fault contact with the western edge of the district.

Pre-intrusive Rocks

Exposures of pre-intrusive rocks occur in the eastern portions of the district. Precambrian Apache Group sedimentary rocks (Dripping Spring Quartzite and Mescal Limestone) with basal Paleozoic sedimentary rocks (Bolsa Quartzite) are found in the southeastern portion. This block of north-south-striking, moderately west dipping units is covered by volcanics to the east and south and is intruded on the north and west. In the east and northeast are broadly folded Paleozoic rocks (Bolsa Quartzite, Martin Formation, Escabrosa Limestone) and Mesozoic rocks (Pinkard Formation). Volcanic rocks overlie them to the north and east and intrusive rocks cut the exposures to the west and south.

Much of the western half and part of the southern edge of the mapped istrict is Cretaceous(?) Glory Hole Volcanics. This rock group comprises a heterogeneous pile of andesitic to latitic tuffs, welded tuffs, breccias, lavas, and flow breccias. They lie unconformably on Paleozoic and Precambrian sedimentary rocks and are overlain by Tertiary volcanics. Thickness of the volcanics is unknown. Thermal metamorphism from adjacent intrusive stocks has strongly modified the volcanic rocks into a dark-gray to black, dense, very fine grained, crystalloblastic-hornfelsic rock. Only on weathered surfaces are the primary volcanic textures sometimes visible. Relict flow features, occasional interbedded lenses of quartzite, and minor fresh-water limestones suggest that the volcanics strike northwest and dip gently to the northeast.

Intrusive Rocks

The Copper Creek granodiorite and associated porphyries intrude the older sedimentary and volcanic rocks. The Copper Creek granodiorite occurs in three northwesterly aligned stocks: the northwest Dry Camp stock, the central Copper Creek stock, and the southern Sombrero Butte stock. Much of the eastern half of the mapped area is the Copper Creek stock.

Copper Creek granodiorite is gray to light gray, medium to fine grained, hypidiomorphic-granular to slightly porphyritic. It consists of 5 to 20 percent orthoclase, 40 to 50 percent plagioclase, 15 to 20 percent quartz, and 5 to 6 percent biotite. Hornblende is occasionally present but is generally replaced by biotite.

Porphyritic intrusive rocks occur as plugs and dikes and are generally clustered within three northwest-trending zones (eastern, central, and western portions of the area). They intrude all previously described rocks. Petrographically, the porphyries have been grouped into diorite porphyry and dacite porphyry. The diorite porphyry is dark gray and consists of fine-grained plagioclase, hornblende, and minor quartz. This rock type is not common and may represent an earlier phase of the granodiorite.

The dacite porphyry group has been divided into three subtypes based on field classification: pink porphyry (eastern porphyry zone and partially in southern portion of central zone);

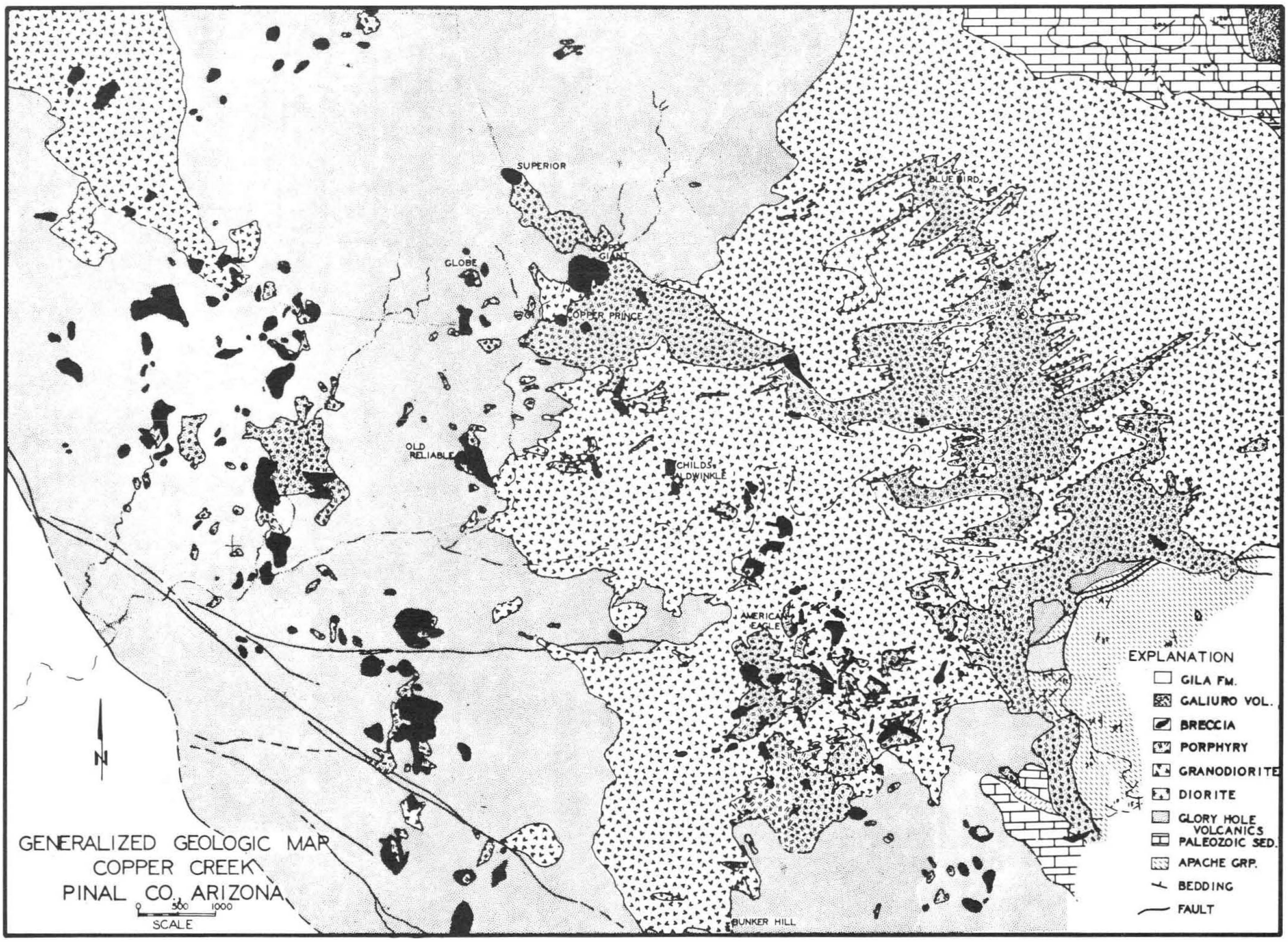

Fig. 1. Generalized geologic map, Copper Creek, Pinal County, Arizona

feldspar porphyry (central zone); and dark porphyry (western zone, 60 percent southern portion of central zone, and less than 5 percent of eastern zone).

Pink porphyry is light pink and has a quartz monzonite composition. It is composed of medium-grained plagioclase (10-15%) and minor biotite (less than 5%) phenocrysts set in a fine-grained, aplitic matrix of quartz and orthoclase.

Feldspar porphyry is gray and has a granodiorite composition. Mineralogically, the porphyry comprises 50 to 65 percent medium-grained plagioclase, up to 5 percent biotite, and occasional rounded quartz phenocrysts set in a fine-grained, xenomorphic groundmass of orthoclase, plagioclase, and quartz. The plagioclase phenocrysts are blocky and somewhat crowded.

The dark porphyry is gray to dark gray and varies from near quartz diorite to granodiorite. Medium-grained phenocrysts of plagioclase (10 to 30%), biotite (5%), and rare rounded quartz are set in a fine- to very fine grained, xenomorphic to felty matrix of plagioclase, quartz, biotite, and orthoclase.

These rocks have been dated by the K-Ar method using biotite. The dates are: granodiorite, 64-68 m.y.; pink porphyry, 59-62 m.y.; and dark porphyry, 52-53 m.y.

Breccia Pipes

Numerous vuggy, highly altered breccias are adjacent to or involved with the dacite porphyries of Copper Creek. These masses have been given the general term "breccia pipes" as several are known to have a near-vertical long dimension. The most common dacite porphyry variety associated with a breccia pipe is dark porphyry. Feldspar porphyry has some breccias associated, but there is none known with the pink porphyry.

Breccia pipes range in size from a few tens of feet to over 600 feet and vary in plan from equant to elongate to irregular. Underground mapping and limited drill data indicate the third dimension of some of them. Shapes indicated are (1) carrot-shaped—breccia flaring upward and tapering downward; (2) two or more aligned breccias coalescing into a single pipe with depth; (3) breccia pinching out into a vein in less than 1,000 feet; and (4) location of lensoid, sheetlike breccia bodies along steep or flat fractures or contacts. Cross sections constructed from drill data, along with surface mapping suggest that some breccias are persistent to over 3,000 feet in depth and that others do not reach the present surface but are blind pipes.

Breccia pipes consist of pebble- to cobble-size, angular to subangular to locally rounded fragments derived from the surrounding wall rock. There appears to be no or very little mixing of rock types. Fragments can vary greatly in size, shape, and texture within a single breccia mass. A zone of well-rounded fragments can occur within a matrix of angular to subangular fragments. Often very large, unbroken blocks up to 100 feet are found surrounded by pebble- to cobble-size fragments. Sometimes the fragments are platy or oblong and are aligned such that a crude layering is apparent. This layering may be interior to the breccia or subparallel to its walls.

Fragments vary from completely altered to quartz-sericite to having a thin rim of quartz-sericite. These fragments can be tightly packed such that intrafragmental areas are absent or minor. Packing in other breccias may be such that large, vuggy areas exist. Intrafragmental areas may be completely filled or may have only minor material present. Quartz-sericite and crystalline quartz are common intrafragmental material. Other materials are tourmaline, pyrite, chalcopyrite, specularite, quartz-orthoclase, and coarse biotite. They may occur separately or in various combinations. The nature of the original intrafragmental filling is unknown.

Contacts between breccia pipes and wall rock are often sharp and generally steep. Wall rock at the contact may exhibit 2-10 feet of closely spaced fractures parallel to the contact or a 1- to 3-foot zone of strongly crushed and moderately altered rock. Alteration of the surrounding wall rock may be limited to a few feet or may extend tens of feet beyond the breccia contact.

Formation of a breccia pipe is associated with the dacite porphyry intrusive rock, based on their close spacial and temporal relationships. Jointing has influenced the location and shapes of the intrusive and breccia bodies. Where several joint sets intersect, a zone of weakness is produced. These zones act as conduits for the emplacement of porphyry plugs and dikes, and forces generated during emplacement cause intense fracturing and brecciation adjacent to and above the porphyry body. These areas of intense fracturing serve as channelways for hydrothermal solutions, which can enhance the breccia texture through alteration and leaching of the fragments. Collapse and additional development of the column of brecciated rock could be promoted through other possible mechanisms, e.g., magma pressure fluctuations, repeated porphyry intrusions, or volume reduction of porphyry by water loss and crystallization. The formation of breccia pipes may result from a number of interrelated processes, and the internal variations between individual breccias only reflect the degree to which a single mechanism functioned during development.

Overlying all previously discussed rocks are the Miocene Galiuro Volcanics. They occur north, east, and south of the area and consist of several thousand feet of andesitic and rhyolitic welded tuffs, flow, ash tuffs, and agglomerates (Simons, 1964; Krieger, 1968). The Plio-Pleistocene Gila Conglomerate is mapped along the western edge of the area. This unit has been faulted down to the west against the older crystalline rocks.

Structure

Joints and veins are the principal structural features mapped. Foliation within the intrusions is almost absent. Rose diagram plots of steeply dipping joints and veins exhibit two major directions, S. 85° E. to N. 70° E. and N. 0° E. to N. 15° W., and two lesser directions, N. 20° W. to N. 55° W. and N. 15° E. to N. 40° E. Flat joints are common at various places in the district. Veining occurs almost wholly in the east-west structural direction. Intrusion and breccia shapes and alignments often exhibit the influence of one or more of these structural directions.

Alteration

A deep porphyry copper system occurs beneath the American Eagle basin. This basin is a topographic feature just south of Copper Creek and is located in the south-central portion of the area. Study of mineralization and alteration of this porphyry copper system is still in its preliminary stages. However, it is apparent that this deposit is a relatively high level, possibly vented porphyry system. Main evidence for shallow emplacement is the abundant breccia pipes and lack of well-defined pervasive alteration zones.

Well-developed, pervasive alteration patterns are not easily recognized on the surface at Copper Creek. Much of the alteration is confined to vein selvages, breccia pipes, and dacite porphyry plugs and their margins. However, some alteration aspects for the different rock types can be generalized. In the Precambrian and Paleozoic sedimentary rocks, the carbonate rocks exhibit the greatest effect. They are mostly recrystallized, with some local argillization and limited calc-silicate development. The Glory Hole Volcanics exhibit pervasive propylitic alteration and silicification with abundant pyrite, especially adjacent to vein sets and where intruded by a cluster of dacite porphyry plugs. Weak, pervasive propylitic alteration with local areas of superimposed potassic and phyllic alteration is common for the granodiorite. Dacite porphyry shows weak to strong phyllic alteration. Very strong phyllic alteration with silicification and local tourmalinization is exhibited by most breccia pipes.

In the American Eagle basin, the rocks contain higher sericite and quartz and lower total feldspar than rocks outside the area. Potassic alteration occurs primarily as the addition of orthoclase by veinlets, vein selvages, or metasomatic replacement. At the surface, potassic alteration is spotty. However, the amount of potassic alteration increases with depth below the basin and a "floor" of fairly intense pervasive potassic alteration underlies the zone of copper-rich mineralization.

Phyllic alteration predominates at the surface in the American Eagle basin. It is confined to vein selvages, breccia pipes and some of the dacite porphyry plugs and their margins; vein selvages are the most common and exhibit well-developed zoning. Quartz-sericite typically borders the quartz-sulfide veinlet. This assemblage grades outward to a quartz-sericite-chlorite zone and to an outer zone of sericite-argillite. This outer zone is characterized by the presence of cloudy to waxy, light-green plagioclase. The alteration product is a mixed mica comprised of sericite, montmorillonite, kaolinite, and illite. With depth the phyllic alteration decreases due to the diminishing size of sericite selvages. This decreasing phyllic alteration and increasing pervasive potassic alteration with depth form an overlapping zone of mixed alteration. Combination of complex vein selvages, i.e., sericite and orthoclase, and the mixed zone of alteration suggest the overprinting of phyllic alteration onto potassic alteration. In the lower portion of the mixed alteration zone and just into the area of intense potassic alteration occurs the zone of significant copper mineralization. There is some suggestion that propylitic alteration may occur below the potassic alteration. Rock from a deep drill hole in the central portion of the American Eagle basin exhibits weak sericite and secondary orthoclase with stronger chlorite-epidote alteration.

Two special alteration minerals, tourmaline and anhydrite, occur at Copper Creek. Tourmaline, schorl variety, is present districtwide and appears to be limited to the upper levels of the deposit. It occurs as acicular crystals in breccias, along veinlets, in quartz-sericite selvages, and as blebs or rosettes in dacite porphyry. Tourmaline may occur alone or may be associated with quartz and pyrite. Purple and white anhydrite is common in the deeper chalcopyrite mineralized zones, occurring as disseminated masses and veinlets.

Mineralization

Significant copper mineralization occurs 2,000 feet or more beneath the surface of the American Eagle basin. It covers an elliptic area approximately 2,500 feet east-west and 1,500 feet north-south. The copper zone underlies a relatively intense east-northeast-trending fracture zone and is associated with a cluster of breccia pipes and dacite porphyry intrusions. Mineralization is hypogene as there is only surficial oxidation and no supergene enrichment. An exception to this is the breccia pipes where oxidization and leaching may occur 100 to 200 feet in depth.

The copper porphyry system at Copper Creek is a relatively low sulfide system in comparison with most Southwest porphyry systems. Dominant sulfides are pyrite and chalcopyrite. Minor amounts of bornite and molybdenite are present in the deeper portion of the system, and galena and sphalerite have been noted in the periphery. Sporadic occurrences of specularite have been noted, especially in some breccias and strongly altered zones. Within the system there is a pronounced vertical zoning of sulfides. Pyrite with very minor chalcopyrite is the principal sulfide in the upper portions of the deposit. With depth, pyrite diminishes and chalcopyrite becomes dominant. Within the copper-rich zone, chalcopyrite is the principal sulfide. At the base of the system, bornite appears and may form up to half of the sulfides. Some high-level chalcopyrite and occasional bornite does occur at Copper Creek and is associated directly with certain breccia pipes.

Surface expression of mineralization at Copper Creek is not overly impressive. Granodiorite and dacite porphyry host limonite-stained breccias and are cut by oxidized quartz-pyrite veins. Visible copper oxides are rare, although geochemically anomalous amounts of copper are found in the veins and breccias.

Sulfide mineralization in the Copper Creek porphyry copper system is controlled primarily by fractures. Other noted mineralization occurrences are disseminated sulfides in quartz-sericite and some porphyries and sulfides as intrafragmental fillings in breccias. In the upper portion of the system, veins are steeply dipping, but with depth nearly horizontal veins become abundant. Rapid decrease in both fracture density and total sulfide content marks the base of the copper-rich zone.

Summary

Copper Creek is the location of past exploration, moderate mine production, and recent discovery of a deep porphyry copper system. Geologic work to date has furnished a preliminary understanding of the igneous activity, hydrothermal alteration patterns, and mineralization within this district. Interpretation of this knowledge forms the basis for the continuing exploration. Copper Creek is important to the understanding of porphyry copper systems because it furnishes a chance to study the upper level occurrence of a deep mineralized porphyry copper deposit.

During Laramide time Precambrian and Paleozoic sedimentary and Mesozoic volcanic rocks of the Copper Creek area were intruded and thermally altered by three granodiorite stocks. The central Copper Creek stock is the site of later dacite porphyry intrusions and related hydrothermal alteration and mineralization. These porphyries occur in and west of the granodiorite stock as plugs and dikes crudely grouped in three northwest-trending zones.

The early pink porphyry appears to be a hydrous potassic and siliceous end member of the granodiorite. There are no known breccias associated and very minor copper mineralization present with this dacite porphyry variety.

Dark porphyry and feldspar porphyry are younger dacite porphyry varieties with which the alteration, mineralization, and breccia pipe development are closely associated. These porphyries occur as plugs, often forming a cluster, and were intruded over a period of time. The location, shape, and clustering patterns of these plugs were influenced by northwest, east-west, and less prominent north-south and northeast structural zones.

The forceful injection of these porphyries into brittle rock caused intense fracturing and brecciation above and adjacent to the plug. This is indicated by the occurrence of intrusion breccias and breccia pipes adjacent to many of the dacite porphyry intrusions. Contemporaneous development of intrusions and brecciation, probably by multiple injections, is shown by the occurrence of porphyry in breccia both as fragments and dikes. Some additional brecciation may be caused by collapse due to volume reduction through magma pressure fluctuations or its crystallization. These zones of fracturing and brecciation became channelways for later hydrothermal solutions. In this manner additional breccia development and textural enhancement occurred by alteration and leaching.

The American Eagle Basin, an area of strong surface alteration and containing a cluster of breccia pipes and dacite porphyry plugs, is where the deep zone of porphyry copper mineralization occurs. In this system the principal alteration and mineralization are fracture controlled. Superimposed on this is the less prominent, but spectacular mineralization controlled by breccia pipes and porphyry plugs. Initial hydrothermal alteration appears to have been potassic. With time and changing hydrothermal fluid composition, the alteration shifted into the phyllic field. This is indicated by the complex vein selvages where potassic alteration often borders the interior sericitic alteration, and the overlapping of serictic alteration onto increasing potassic alteration with depth in the American Eagle basin.

Mineralization in the American Eagle basin exhibits a strong vertical zonal pattern. Pyrite is the dominant sulfide in the upper portions of the porphyry system. With depth chalcopyrite increases to where it is the principal sulfide. Deep within the system bornite occurs. Significant copper mineralization is found in the lower mixed alteration zone and upper potassic alteration zone. Breccia pipes distort this picture somewhat by bringing chalcopyrite and some bornite mineralization high into the system.

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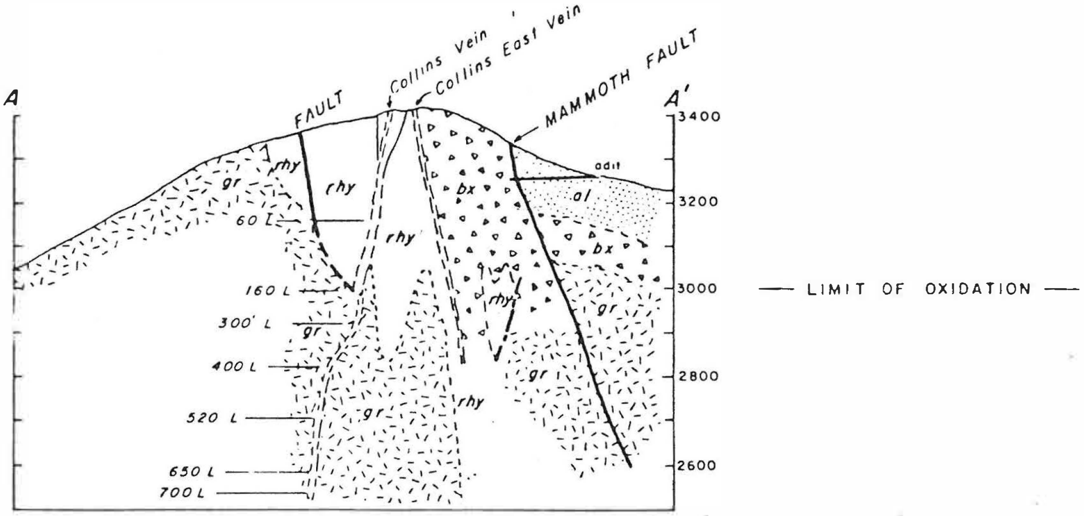
TOUR HIGHLIGHTS - TIGER, ARIZONA

1:00 p.m. Location 1 -- "Site" of Tiger, Arizona; historical review, geologic overview, economic review.

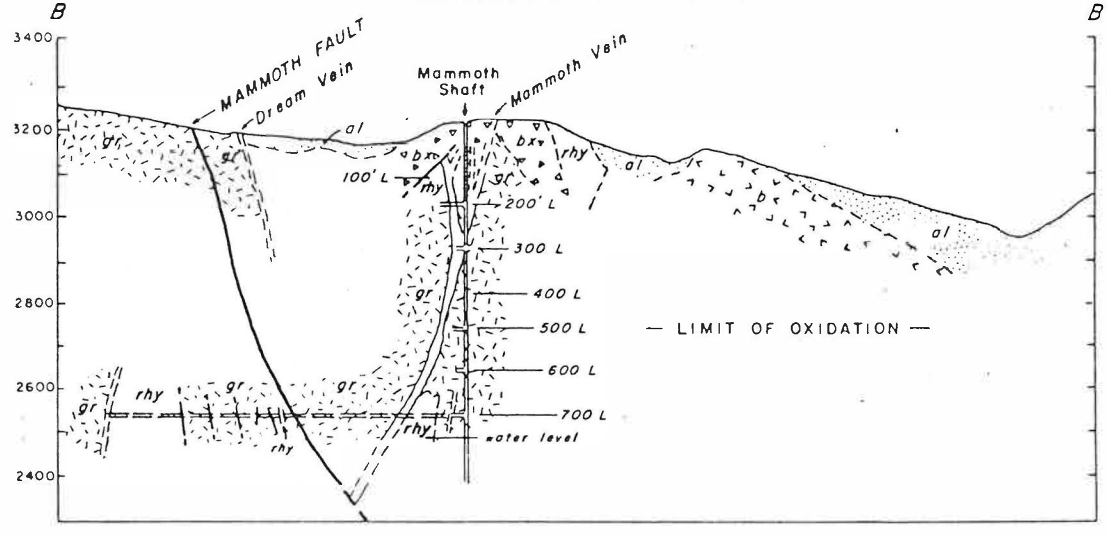
1:30 p.m. Location 2 -- Magma Copper Company "Open Pit"; examine exposures of Mammoth vein, wallrocks and rhyolite plug.

2:30 p.m. Location 3 -- Mammoth Fault; examine exposure of country rock and character of fault zone.

COLLINS VEINS



MAMMOTH VEIN



GENERALIZED CROSS SECTIONS

Tiger, Arizona Area

EXPLANATION

al	Alluvium and Gila Conglomerate
bx	Breccia (Intrusive breccia of Peterson)
rhy	Intrusive rhyolite
b	Volcanic rocks, chiefly basalt
gr	Oracle granite (Qtz monz in this locality)

━	Fault
┅	Vein

0 100 200 300 400 500 feet

After CREASEY, 1938

PRODUCTION FROM THE TIGER, ARIZONA AREA

Year	Location	Ore Mined Tons	Gold Ounces	Silver Ounces	Copper Pounds	Lead Pounds	Zinc Pounds	MoO_2 Pounds	V_2O_5 Pounds
1881-1947	All mines	1,889,375	397,201	983,918	3,456,121	74,730,289	48,272,654	6,314,822	2,540,842
1978	Mammoth Vein	100,000	3,000						

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Economic Geology
Vol. 63, 1968, pp. 645–654

Geology of the Kalamazoo Orebody, San Manuel District, Arizona

J. David Lowell

Abstract

An exploration project initiated by Quintana Minerals Corporation in 1965 has resulted in the discovery of the faulted segment of the San Manuel orebody. The project was based on a new interpretation of the geology of the San Manuel orebody which assumed that an original cylindrical orebody with concentric alteration zoning had been first tilted approximately 70°, then bisected by the flat San Manuel normal fault into the lower plate San Manuel orebody and an upper plate Kalamazoo orebody.

The deep drill holes of the Kalamazoo project provide an unusually good cross section of porphyry copper wall rock alteration. Vertical mineral and alteration zoning effects down the original vertical axis of the deposit are also exposed because the vertical axis is now nearly horizontal and within drilling depth of the ground surface.

Introduction

In the period 1943–1947, exploration projects were carried out in the San Manuel area by the U. S. Bureau of Mines and Magma Copper Company which resulted in the development of the San Manuel underground block-cave mine which is now in production at a rate of 41,000 tons per day.

Mining claims covering the area immediately west of the San Manuel orebody were staked in 1946 by Frank F. Salas, R. A. Buzan, H. G. Buzan, and W. C. Buzan of Mammoth, Arizona. These claims were optioned to Martha Purcell in 1946, and in the period of 1947–1958 seven churn drill holes ranging in depth from 1,400 to 2,950 feet were drilled by Mrs. Purcell. These holes did not intersect ore and no further deep exploration was attempted prior to the Quintana Minerals Corporation project which began in August, 1965, and which is described in this report.

The Kalamazoo deposit is in Sections 3, 4, 9, 10, T 9 S, R 16 E, Pinal County, Arizona, and it is seven miles east from Oracle, Arizona (Fig. 1).

The writer is indebted to Corbin J. Robertson and Ronald B. Thompson who participated in the exploration planning of this project and to a number of other individuals who contributed to its execution and management. Petrographic work by J. M. Guilbert was used as a basis for rock and alteration classifications.

A paper being prepared by the writer and J. M. Guilbert for publication in Economic Geology will compare the characteristics and genesis of the lateral and vertical alteration-mineralization zoning at San Manuel-Kalamazoo with those of a number of other porphyry copper deposits.

Acknowledgment is gratefully made to Quintana Minerals Corporation for permission to publish information developed during the Kalamazoo project.

Geology of the San Manuel District

The geology of the San Manuel area has been described by Steele and Rubly (1947), Schwartz (1953), Pelletier (1957), Creasey (1965), and Thomas (1966).

Precambrian quartz monzonite of the Oracle granite batholith in the San Manuel area was intruded in Laramide time by swarms of monzonite porphyry dikes and irregular monzonite porphyry masses. The rock classified as monzonite porphyry can be subdivided into a range of rock types including quartz latite porphyry, quartz monzonite porphyry, monzonite porphyry, biotite dacite porphyry, and probably other rock types. Some of these appear to be

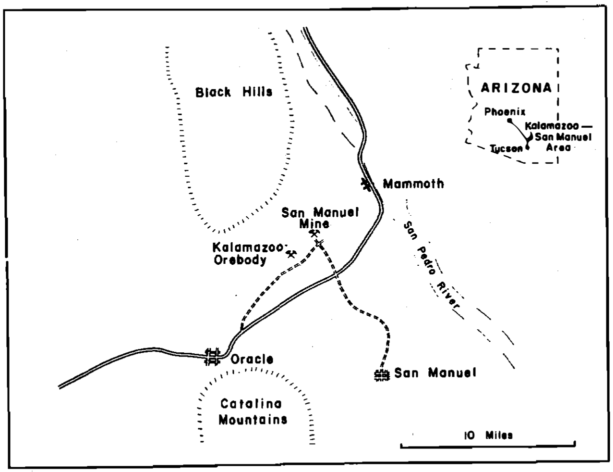


Fig. 1. Location map San Manuel District, Arizona.

slightly later than others, but all are closely related in time and all are apparently pre-ore in age. A few diabase dikes are also present in the Laramide-age dike swarms. Closely related in time with this Laramide intrusive activity was a pulse of porphyry copper-type mineralization that produced the San Manuel-Kalamazoo orebody and its associated concentric hydrothermal alteration zones. The axis of the hydrothermal flowage system seems to have been centered in the middle of one of the monzonite porphyry dike swarms.

Following emplacement of hydrothermal mineralization and alteration, district-wide structural displacements occurred that produced northeasterly tilting and probably resulted in relative elevation of the block which included the San Manuel-Kalamazoo orebody. Erosion cut into this block exposing a small corner of the orebody, and attendant supergene activity produced a thin chalcocite enrichment blanket. At this time the long axis of the orebody may have dipped at an angle of about 65° (Fig. 2). Subsequently, andesitic flows interbedded with detrital sediments and pyroclastics were deposited on this surface. Further igneous activity following the sedimentation resulted in the emplacement of andesite and rhyolite dikes.

The older Tertiary conglomerate unit in the Kalamazoo area has been correlated in published mapping (Creasey, 1965) with the Cloudburst formation of the Mammoth-St. Anthony area two miles to the northeast. The Cloudburst was considered by Creasey to be of post-San Manuel ore, but pre-Mammoth-St. Anthony ore age. Evidence for its post-San Manuel ore age in the Mammoth-St. Anthony area is not entirely convincing. However, the lowest conglomerate unit at Kalamazoo does appear to be of definite postore age; it is less well indurated than the Cloudburst formation and may be considerably younger. It may correlate (Watson, 1967) with the Pantano and Mineta formations of southern Arizona, which are considered to be late Oligocene or early Miocene.

Further tilting, averaging perhaps 15°, followed deposition of the lower conglomerate. It seems likely that tilting was accompanied by renewed elevation of the fault block since the block was again beveled by the erosion surface on which the Gila Conglomerate was later deposited. A third stage of about 30° of tilting moved the Gila Conglomerate into its present inclination and brought the long axis of the San Manuel-Kalamazoo orebody into a 20° west-dipping attitude. As seen on Figure 2, the San Manuel fault then diagonally bisected and offset the orebody into two pieces: the San Manuel and the Kalamazoo. It is uncertain whether the San Manuel fault displacement occurred before or after the last stage of tilting, but the fault has several characteristics commonly associated with low-angle faults including a thick gouge-breccia zone, a rolling fault plane surface, and braiding. It seems likely that the San Manuel fault displacement followed final tilting and that the present 25°–30° dip of the fault represents its original attitude. The fault divided the originally cylindrical San Manuel-Kalamazoo orebody into two mirror-image halves, and the upper (Kalamazoo orebody) half was moved in a down-dip, S55°W direction, about 8,000 feet. Imbricate displacements apparently occurred on overlying San Manuel fault strands which have resulted in one Kalamazoo ore section locally overriding another.

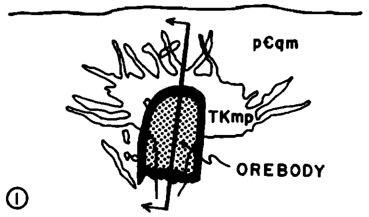
A system of high-angle, northwest-trending faults later produced relatively small, mostly normal fault displacements in both halves of the original orebody, and erosion stripped most of the Gila Conglomerate from the east end of the present San Manuel orebody. This erosion cycle developed extensive leaching and oxidation in the upper part of the San Manuel orebody with limited chalcocite enrichment beneath the oxidized zone. The lower portion of the San Manuel orebody and all of the Kalamazoo orebody were protected from oxidation by thick sections of capping. Erosion in the most recent cycle of erosion has exposed windows of pre-ore rock in the vicinity of both San Manuel and Kalamazoo (Fig. 3). A small area of the San Manuel orebody that had been exposed by erosion led to the original exploration of the area.

The original, unfaulted orebody, as defined by an 0.5% copper limit, has the general shape of a somewhat flattened or elliptical (in cross section) cylinder at least 7,700 feet in long dimension (along the axis of the cylinder) and from 2,500 to 5,000 feet in diameter. The top (east end after tilting) of the cylinder may have had a rounded shape with the bottom (west end after tilting) probably being somewhat irregular in shape. The orebody, like many porphyry copper deposits, had a poorly metallized core or "low-grade center." The wall thickness of the ore shell surrounding the low-grade center varied from about 100 to 1,000 feet. Mineralization and alteration form approximately coaxial cylindrical zones (Fig. 4).

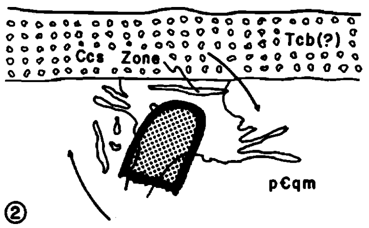
Figure 5 is a longitudinal geologic section of the Kalamazoo orebody and the overlying northeast-dipping Tertiary sediments. Figure 6 is a cross section illustrating the bisected hollow cylindrical shape of the orebody and shows a cross section of the mullion structure in the San Manuel fault zone.

Mineralization

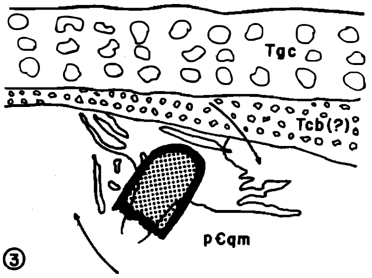
Ore mineralization is about equally distributed between coarse-grained Precambrian quartz mon-



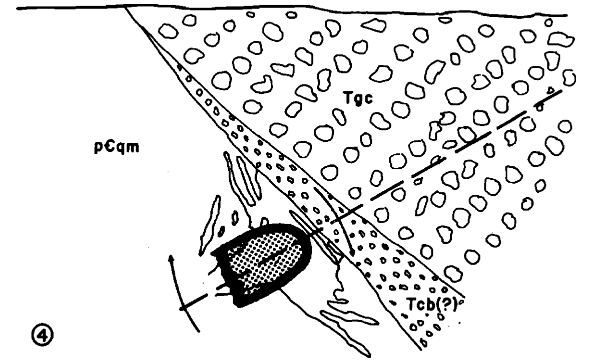
1. Precambrian quartz monzonite (pCgm) was intruded by a Laramide age monzonite porphyry (TKmp) dike swarm. A hollow cylindrical or pipe-shaped orebody with dimensions of approximately 8,000 × 3,500 feet was formed. It was probably nearly vertical and centered on the monzonite dike swarm. (Section line shows position of Figure 7.)



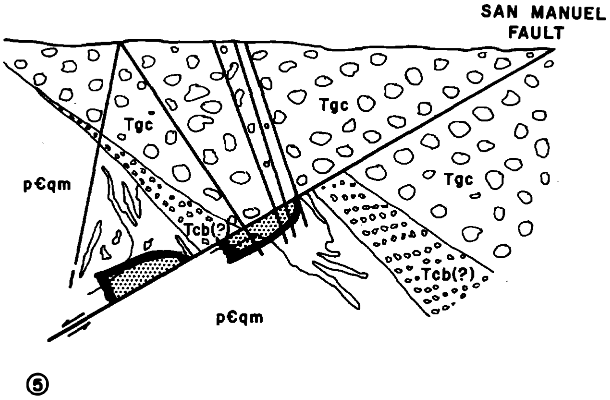
2. Tilting of the orebody was followed by erosion, then deposition of conglomerate and interbedded volcanics (Tcb?). A thin chalcocite blanket (Ccs) was formed at the water table.



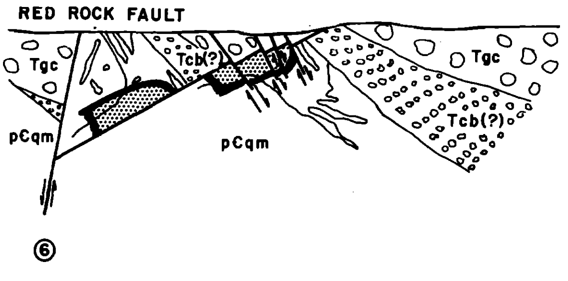
3. Continued tilting was followed by erosion of conglomerate and quartz monzonite and deposition of middle Tertiary Gila Conglomerate (Tgc).



4. Orebody is now at a flat angle due to continued tilting. An erosion surface is cut on the tilted quartz monzonite and Gila Conglomerate. Incipient San Manuel fault is formed.



5. Upper portion of orebody is displaced approximately 8,000 feet down the dip of the San Manuel fault. Some imbricate displacement may have occurred in the Kalamazoo segment.



6. High-angle normal fault displacements produced small offsets in the San Manuel orebody and a large displacement on the Red Rock fault west of the Kalamazoo orebody. Erosion exposed intrusive rocks and a corner of the San Manuel orebody and produced oxidation and limited chalcocite enrichment in the upper portion of the San Manuel orebody.

FIG. 2. Schematic drawings showing possible origin of Kalamazoo orebody.

zonite and Laramide monzonite porphyry host rocks. Ore in the Precambrian quartz monzonite tends to be slightly higher in grade.

Primary ore minerals in the San Manuel-Kalamazoo orebody are pyrite, chalcopyrite, molybdenite, and rare bornite. Oxide copper minerals, principally chrysocolla, have been developed in the upper portion of the San Manuel orebody. Chalcocite is common in the lower portion of the oxide zone and near the top of the chalcopyrite mineralization in the San

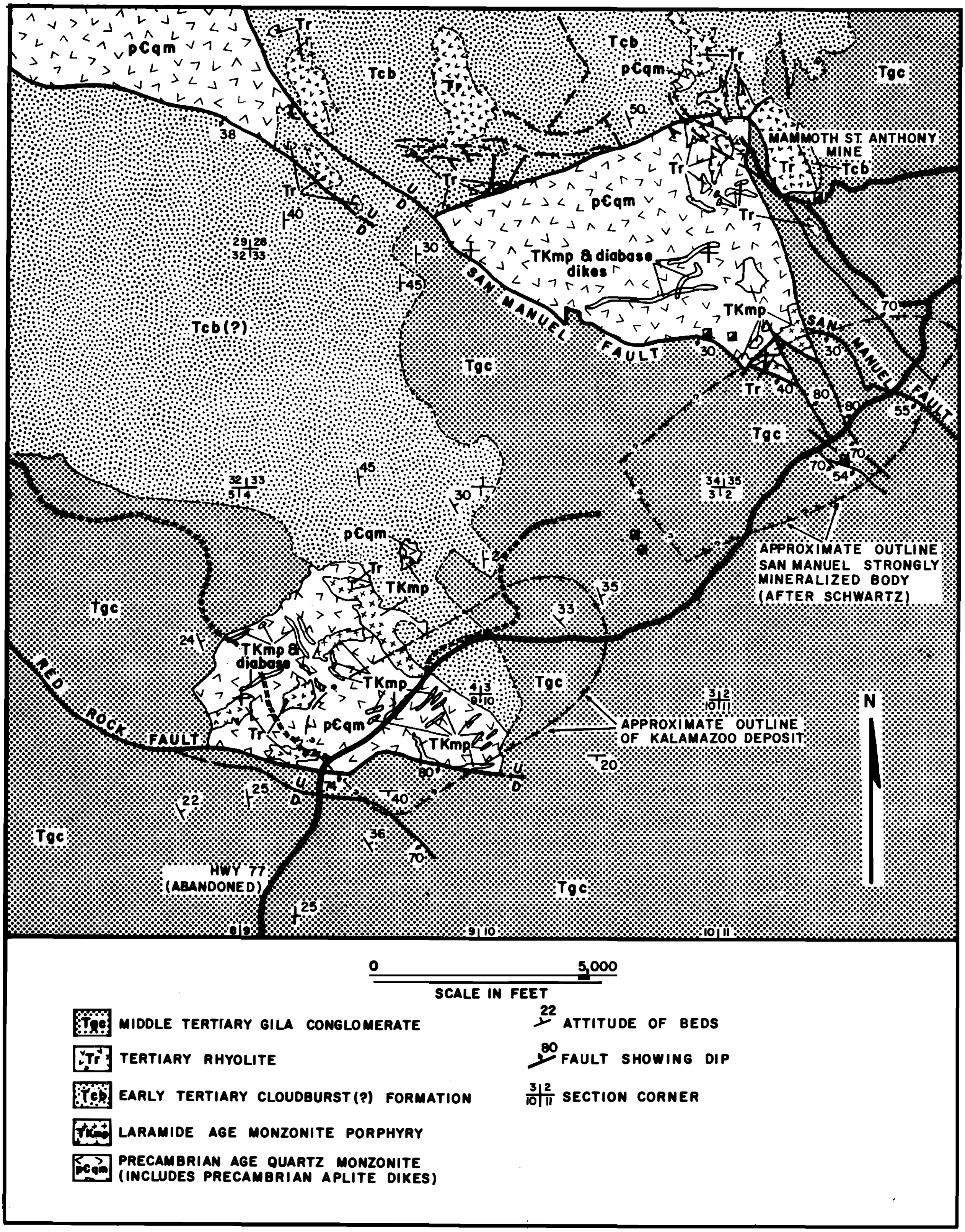


FIG. 3. Geologic map of the San Manuel area.

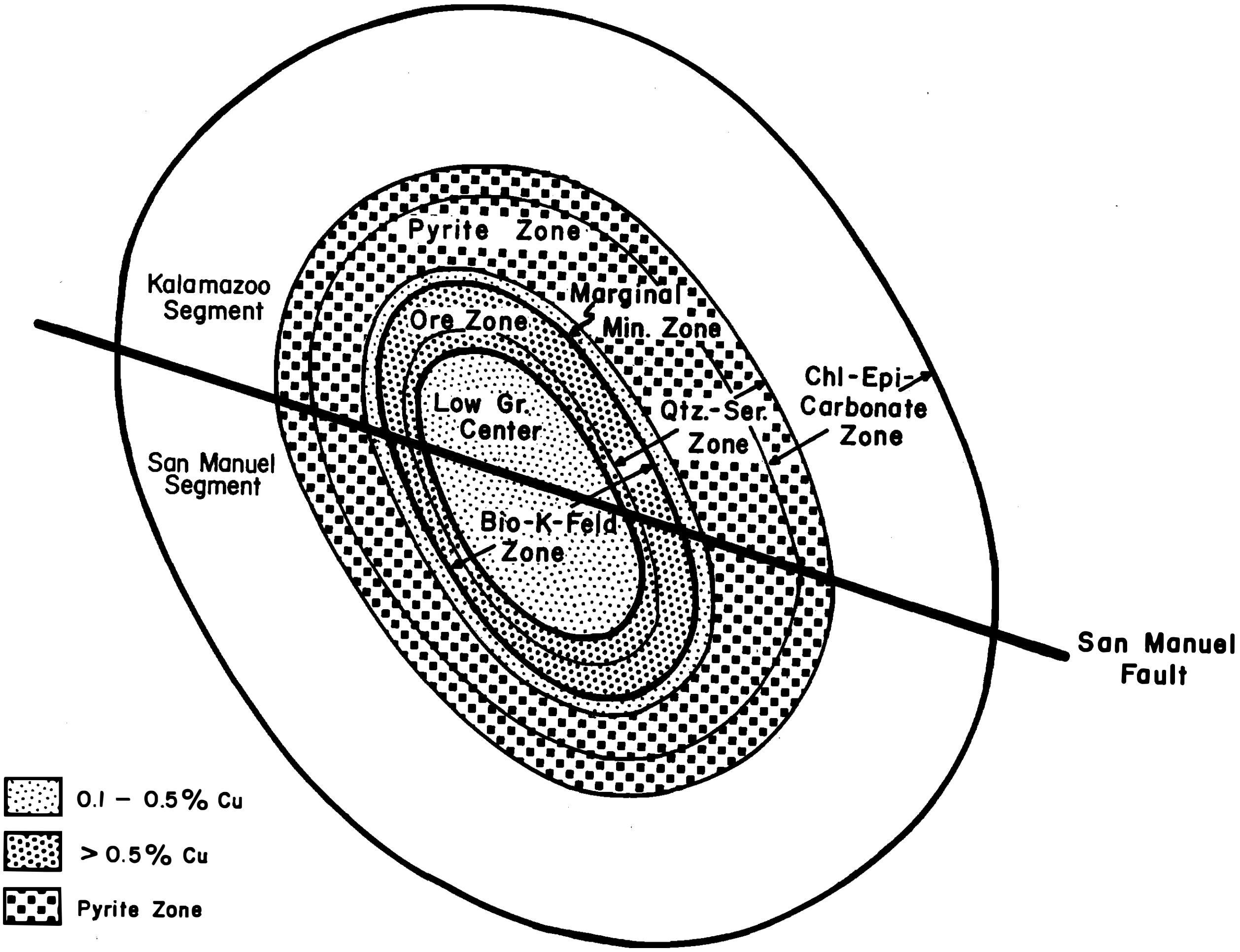


FIG. 4. Schematic horizontal plan showing alteration and mineralization zones.

Manuel orebody, but both chalcocite and oxide minerals are absent in the Kalamazoo.

Zones of Mineralization (*Fig. 4*).—1. The low-grade center zone averages about 2,600 feet in diameter and about 0.3% Cu in grade. Total sulfide content is low with a pyrite-to-chalcopyrite ratio of about 1 : 2.

2. The ore shell averages about 600 feet in thickness and ranges in grade from 0.5%–1.0% Cu. The pyrite-to-chalcopyrite ratio is about 1 : 1.

3. The marginal mineralization zone which surrounds the ore shell averages about 200 feet in thickness and ranges in grade from 0.1%–0.5% Cu. The pyrite-to-chalcopyrite ratio is about 10 : 1.

4. The pyritic zone that surrounds the marginal mineralization zone ranges in thickness from about 1,000–1,500 feet and ranges in grade from 0.01%–0.10% Cu, averaging about 0.03% Cu. It contains from 6%–25% pyrite by weight, averaging about 10% pyrite.

Total volume of sulfide minerals increases progressively from the center of the concentric mineralization-alteration system out to a point of maximum sulfide content in the inner portion of the pyritic zone. Outward beyond this point sulfide content progressively decreases. Copper content increases progressively from the center of the system out to a point of maximum copper grade in the center of the ore shell, then decreases by steps to the outer margin of the zone of marginal mineralization. Beyond this point copper rarely occurs as recognizable copper minerals, and the 0.01%–0.10% Cu content of the pyritic zone is probably included in the crystal structure of the pyrite.

Alteration

Alteration zones in this deposit, as in most porphyry copper deposits, are rather poorly defined and overlapping. Various host rocks respond in different ways to alteration solutions to produce

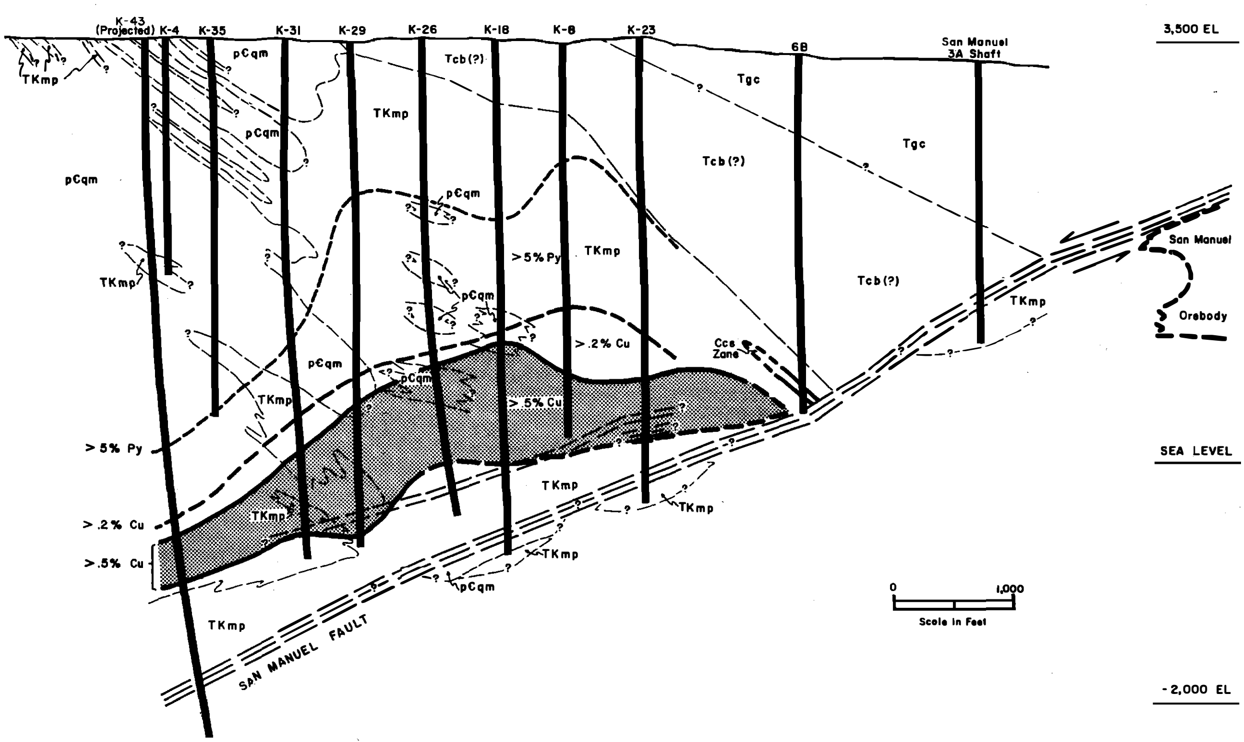


FIG. 5. Longitudinal section of Kalamazoo orebody looking northwest.

somewhat different alteration products within the same zone. Alteration zones are more clearly defined here than in most porphyry deposits, however, because the original San Manuel-Kalamazoo orebody had unusually uniform boundaries and a well-developed symmetrical configuration. This probably resulted from the fact that alteration and mineralization affected intrusive host rocks that were of generally similar chemical composition and of essentially isotropic fabric.

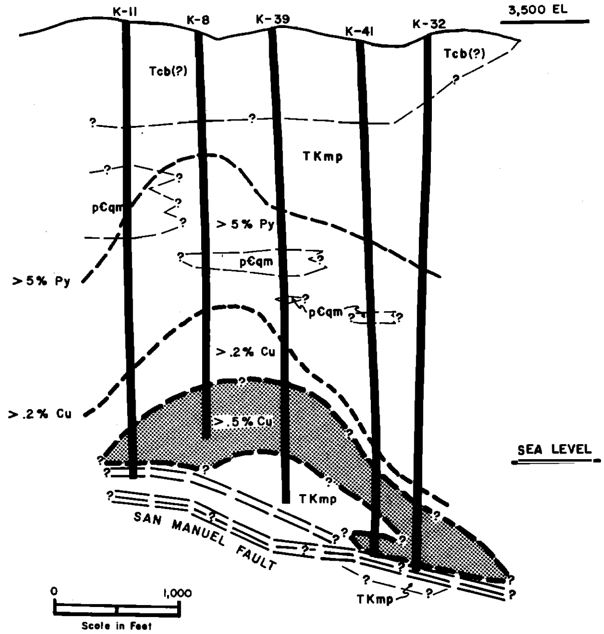


FIG. 6. Cross section of Kalamazoo orebody looking northeast.

Horizontal Alteration Zones.—These are zones distributed laterally in and around the orebody at a given depth at the time of ore formation. They consist of:

1. The inner alteration zone of the San Manuel-Kalamazoo orebody consists of biotite K-feldspar alteration (Fig. 4).

Several authors, especially Hemley and Jones (1964), have discussed the potassic alteration environment. Hemley and Jones delimit an environmental interface between K-feldspar and sericite stabilities consistent with late magmatic or early hydrothermal conditions in the K-feldspar-sericite-kaolin (pyrophyllite) system. Expansion of the system to include iron and magnesium should bring biotite, K-feldspar, sericite, and quartz into consideration, an assemblage increasingly often noted in porphyry copper deposits (Creasey, 1966) and assignable to the late magmatic-early hydrothermal "deuteric" environment. Such a biotite K-feldspar alteration assemblage with quartz, sericite, anhydrite, pyrite, chalcopyrite, and molybdenite generally constitutes the low-grade center and part of the ore shell of the Kalamazoo deposit. Conditions approaching those of wholesale remobilization of the porphyry concurrent with potassic alteration are suggested by coarsely vermicular and diffuse intrusive contacts between host rock and porphyry masses within the orebody.

It is certain in any case that this intense potassic alteration produced fresh-looking secondary minerals which led to the incorrect conclusion on the part of some previous workers that this alteration zone represented alteration weaker than that of the surrounding zones. The intense phase of biotite K-feldspar alteration tends to alter monzonite porphyry to a coarser-grained rock that somewhat resembles in texture the fresh Precambrian quartz monzonite. This alteration is not nearly as obvious as other alteration effects in the surrounding quartz-sericite zone which represent weaker hydrothermal conditions but more obvious destruction of rock textures.

At depth the biotite K-feldspar zone is partly replaced by a core of quartz-sericite-chlorite ± K-feldspar alteration as will be discussed later in this paper. This assemblage appears to represent a high-temperature environment in which sericite, chlorite, and minor carbonates appear.

2. A zone of quartz-sericite alteration generally includes all of the marginal mineralization and pyritic zones and overlaps the biotite K-feldspar alteration in the outer part of the ore shell. Sericite tends to be more abundant in the inner part of this zone with clay minerals and hydromica becoming more abundant towards the margins of the zone. In the inner portion of this zone, rock textures have been largely destroyed. The zone contains sections of spectacular, pervasive pyrite mineralization in which pyrite in some cases constitutes more than 20 percent by weight of the rock. Specularite is common towards the margins of the zone. A zone of hydrothermal magnetite mineralization appears to interfinger with and possibly replace this zone towards the west end (original bottom prior to tilting).

3. Surrounding and overlapping the quartz-sericite zone is a zone of propylitic alteration in which chlorite, epidote, and minor carbonates are developed. Pyrite content by weight averages 4 percent.

This zone gradually fades and may have a total thickness of 2,000 feet or more. The configuration of the alteration zone is apparently not related in detail to the distribution of monzonite porphyry bodies.

Vertical Alteration Zones.—The San Manuel-Kalamazoo orebody has unique genetic significance in the study of porphyry copper deposits because of the great length of the original vertical column of mineralization exposed. If the orebody has been tilted approximately 70° as postulated, then the west end represents ore mineralization which was originally about 8,000 feet deeper than the east end. Including mineralization in drill intercepts in the lower plate of the San Manuel fault below the Kalamazoo orebody, it is possible to partially reconstruct vertical mineral zoning changes over an original vertical column of 13,000 feet or more.

Figure 7 is a schematic section that illustrates vertical zoning relationships interpreted for the original San Manuel-Kalamazoo orebody. Concentric mineralization and alteration zones were roughly cylindrical in shape, but several zones appear to have converged upward, and the overall configuration of the system may have been beet shaped with a restricted root in depth. The hydrothermal magnetite and quartz-sericite-chlorite ± K-feldspar zones occurred only near the bottom of the orebody, and little is known regarding their configurations.

1. The core of the concentric alteration system or low-grade center mineral zone grades upward from quartz-sericite-chlorite ± K-feldspar alteration to biotite K-feldspar.

2. The ore-shell mineral zone progressively transgresses upward across the contact of the biotite K-feldspar and quartz-sericite zones. The upper portion of the ore shell is entirely within the quartz-sericite zone. Chalcopyrite mineralization appears to grade from predominantly bleb and veinlet type at the bottom to predominantly fine-grained disseminated at the top.

3. The zone of marginal mineralization surrounding the ore shell grades from chlorite-sericite-magnetite at the bottom to quartz-sericite alteration through most of the length of the orebody.

4. Magnetite substitutes for pyrite to a large extent in the bottom portion of the pyritic zone. Sericite content appears to decrease with the decrease in pyrite downward and to increase with the increase of pyrite content upward. The strongest pyrite mineralization was near the original top of the orebody.

5. Alteration surrounding the pyritic zone grades upward from disseminated and veinlet magnetite, chlorite, sericite, epidote at depth to chlorite, epidote, carbonate. Little is known of the general configuration of this zone because it has been partially destroyed by erosion and most of the present surface area is covered by postore formations. It seems likely that the overall configuration was beet shaped with a constricted root.

Geological Premises for Kalamazoo Project

The initiation of the Kalamazoo project was based upon the assumptions by the writer that (1) the San Manuel low-grade center and its potassic alteration represented the most, rather than the least, intense alteration zone present and, therefore, perhaps the

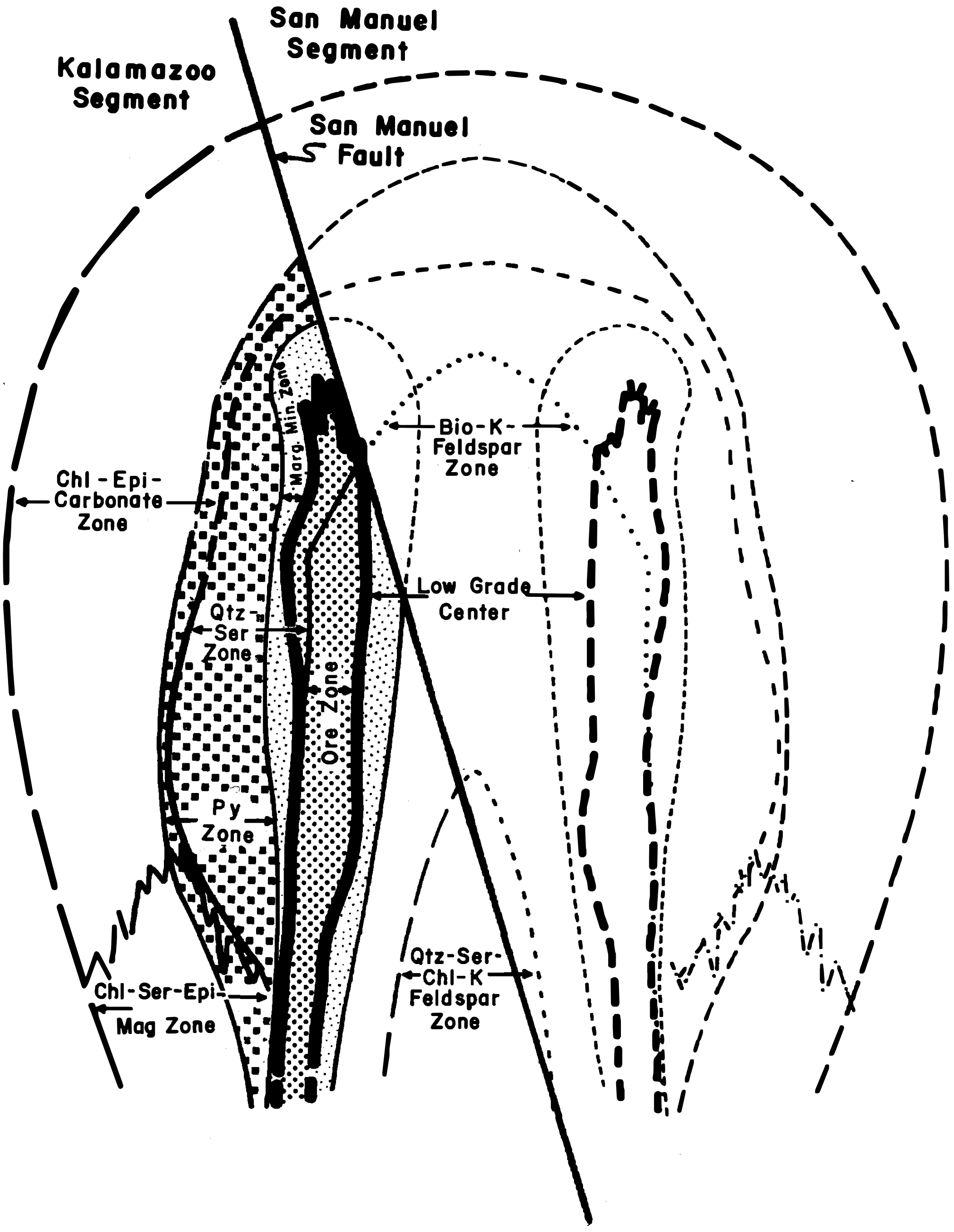


FIG. 7. Schematic section of San Manuel-Kalamazoo orebody showing vertical alteration and mineralization zones. Solid lines and shaded areas represent observed geology, and broken lines indicate extrapolated information. (See Fig. 2 for position of this section relative to final configuration of orebodies.)

core of an original cylindrical-shaped orebody, and that this original orebody would have had coaxial alteration and mineralization zones which would complete the cylindrical symmetry found truncated at San Manuel; (2) evidence existed for at least 45° of tilting of this cylindrical-shaped orebody and that it was reasonable to postulate additional tilting in pre-Cloudburst time so that the cylinder could have been originally in a near-vertical position typical of pipe-like porphyry copper deposits; and (3) the direction of displacement in the San Manuel fault could more logically have been in a down-dip direction as proposed by Steele and Rubly (1947) and Schwartz (1953) rather than having "had a domi-

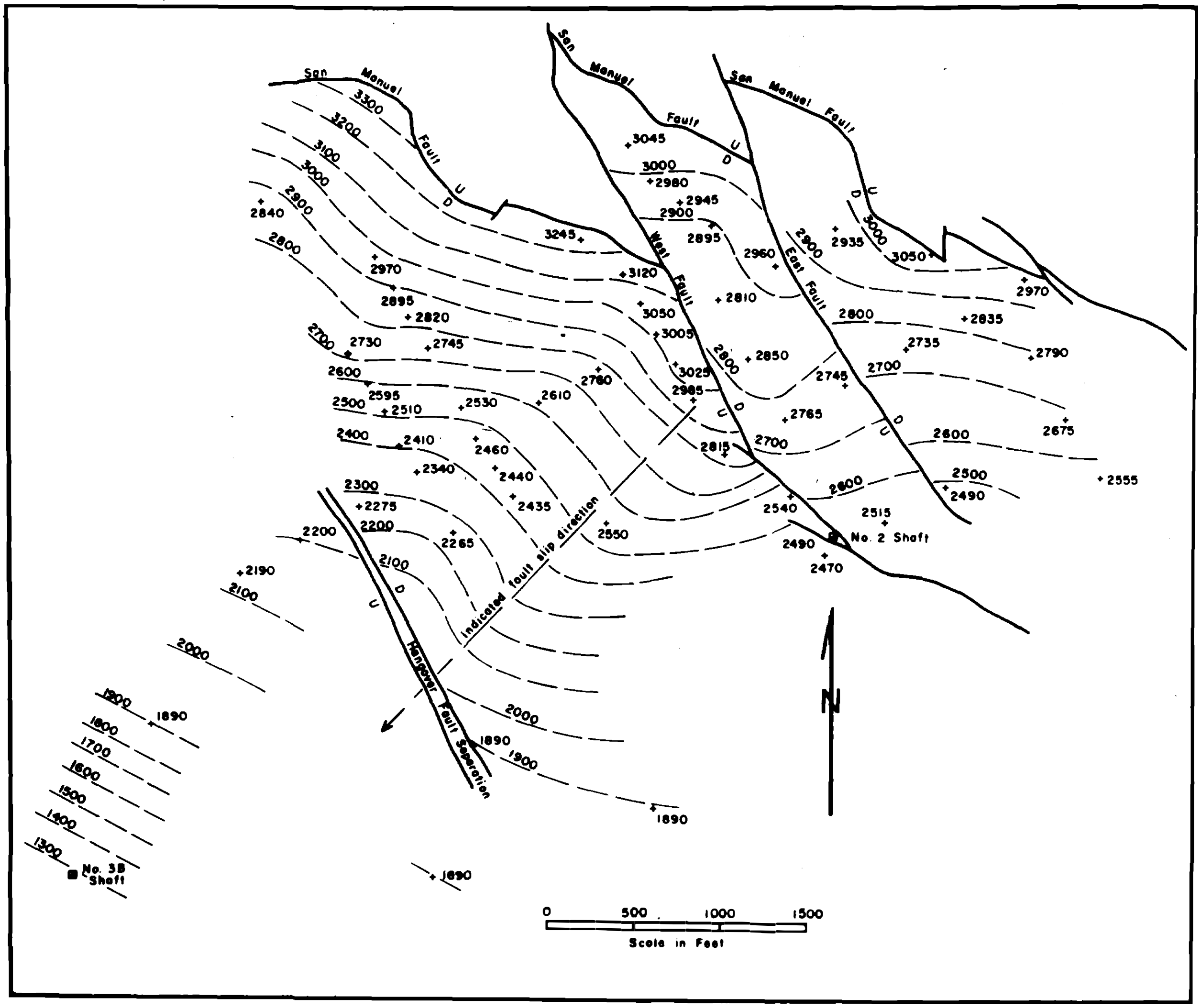


FIG. 8. Structure contour map of the San Manuel fault plane. Elevations are shown in feet above sea level.

nant component of right-lateral strike-slip movement" as postulated by Creasey (1965, p. 28) or having had reverse fault displacement as proposed by Wilson (1957) and Heindl (1963).

Kalamazoo Exploration Project

Initial investigation involved reviewing the geologic and assay logs and drill cuttings samples from the old Purcell drill holes. It was found that four of these holes apparently penetrated from weakly pyritic propylitic alteration into a strongly pyritic, quartz-sericite zone at depth, and one hole apparently bottomed in mineralization typical of the San Manuel marginal mineralization zone. The geometry of these intersections together with the projection of the San Manuel fault plane approximately determined the position of the cylindrical-shaped Kalamazoo pyritic zone.

A geochemical soil survey was carried out in the pre-ore outcrop area of the Purcell claims. This survey produced a moderately well-defined copper and molybdenum anomaly which was later found to overlie the Kalamazoo orebody. The anomaly probably represents the outcrop of a cylindrical shell of comparatively copper-rich (±0.04% Cu) propylitic alteration. Assaying the soil samples for total Fe produced a less well-defined anomaly approximately centered on the orebody which is thought to represent the outcrop of a shell of pyrite mineralization within the propylitic zone but outside the strong pyritic zone. The geochemical survey was not diagnostic in itself but did serve as additional evidence for the location of the faulted segment.

Elevations of intersections of San Manuel drill holes with the San Manuel fault were compiled from U.S.G.S. Professional Paper 256 and were contoured by W. F. Chester and the writer in a structure contour map of the San Manuel fault. This map (Fig. 8) showed large ridges and valleys in the fault surface which formed a large-scale mullion structure consistent with dip-slip normal fault displacement. The Kalamazoo orebody was located by the first drill hole that was spotted according to the normal faulting interpretation and the other evidence cited.

The first Quintana Minerals Corporation drill hole penetrated through Gila Conglomerate and Cloudburst formation into monzonite porphyry with, first, propylitic and then quartz-sericite alteration. The hole passed from the pyritic and marginal mineralized zones into ore-grade mineralization at about 2,500 feet. From structural considerations it appeared that the axis of the Kalamazoo orebody might have an orientation of N57°E. A 600-foot rectangular drill grid on a N33°W and N57°E orientation was laid out centered on the first drill hole. The unique opportunity for extrapolating geology and symmetry of mineral zones from the San Manuel deposit has made it possible to intersect the Kalamazoo orebody with every hole completed to date.

Typical holes in the project were drilled to a depth of about 3,000 feet by the relatively cheap rotary drilling method. The rotary cuttings were assayed using a field analytical method and, when the assays reached 0.2% copper, coring was begun. The final intercept of approximately 1,000 feet which contains the marginal and ore zones was completed with NX wireline core drilling by the same drill rig. No casing was used. Holes were drilled with oil field type rotary drill rigs equipped with 95-foot masts, automatic bit pressure controls, and geolograph recorders. Drill operations in the project were planned and managed by the Quintana Minerals Corporation drilling department.

The Kalamazoo orebody has the shape of an overturned canoe, and the first ore block mined will be the relatively wide and flat canoe bottom. This ore block will be overlain by the marginal mineralization zone so that block-cave dilution material will contribute some values to the mill heads. The ore lacks any chalcocite enrichment but is also free of oxide copper content. The molybdenum content falls in the same range as in the San Manuel orebody, and the ore contains a small recoverable amount of gold and silver. The rock in the Kalamazoo orebody appears to be suited to block-caving mining under conditions similar to those found in the nearby San Manuel mine.

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TUCSON, ARIZONA,
March 18; April 20, 1968

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FIELD NOTES AND SKETCHES

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