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'ewk file Porp Copper Arizona

Bill Kirtz

WELCOME

to the

SOCIETY OF ECONOMIC GEOLOGISTS

FIELD CONFERENCE

ON

TUCSON-AREA PORPHYRY COPPER DEPOSITS

April 3-6, 1979

Organizing Committee

Sal A. Anzalone
Richard E. Beane
Steven R. Davis
Frederick T. Graybeal
John M. Guilbert
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SEG FIELD CONFERENCE

Program Outline
(All at Ramada Inn, Tucson)

Tuesday afternoon, April 3

2:00-2:30 John M. Guilbert, University of Arizona, Porphyry Copper Deposits -- Definitions, Characteristics, Problems, and Progress.

2:30-3:00 Denis L. Norton, University of Arizona, Hydrothermal Processes Related to Porphyry Copper Deposit Formation.

3:00-3:30 Spencer R. Titley, University of Arizona, The Style and Progress of Mineralization and Alteration in Some Porphyry Copper Systems.

3:30-4:00 Richard E. Beane, University of Arizona, Geochemical Environments of Alteration-Mineralization.

4:00-4:30 Thomas L. Heidrick, Gulf Minerals Resources, Mesoscopic and Megascopic Fracturing and Diking in Barren and Productive Laramide Porphyry Systems of Southwestern North America.

4:30-5:00 Stanley B. Keith, Arizona Bureau of Geology and Mineral Technology, Porphyry Copper Districts, Whole Rock Geochemistry of their Plutonic Hosts, and Subduction Zone Geometries.

Tuesday evening, April 3

8:00-10:00 Introduction to the Silver Bell-North Silver Bell Deposit.

James A. Galey: ASARCO (now Fluor Min. & Met.), General Geology, Silver Bell District
Frederick T. Graybeal: ASARCO, Geology of the El Tiro Pit Area, Silver Bell
James A. Galey: Geology of the Skarn deposits, Silver Bell
Steven R. Davis: ASARCO, Geology of the North Silver Bell Area
Geoffrey H. Ballantyne: University of Utah, Thermal Gradients in the North Silver Bell Alteration Halo.

(Wednesday, 7:30 a.m. - 5:30 p.m. Silver Bell Mine)

Wednesday evening, April 4

8:00-10:00 Introduction to the Sierrita-Esperanza Deposit.

R. J. West, D. M. Aiken: Duval-Sierrita Corp. Mine Geology
S. R. Titley: University of Arizona, Alteration Petrology
F. M. Haynes: University of Arizona, Fracture Distribution
R. K. Preece: University of Arizona, Fluid Inclusions and Paragenesis
R. E. Beane: University of Arizona, Alteration Processes

(Thursday, 7:30 a.m. - 5:30 p.m. Sierrita-Esperanza Mine)

Thursday evening, April 5

Following banquet -- open-ended informal discussion of porphyry problems and progress.

(Friday, 7:30 a.m. - 5:30 p.m. North Silver Bell field area)

PLEASE!

When visiting the mines and their environs, remember, ABOVE ALL, SAFETY FIRST!

.Wear your hard hat and safety glasses at all times within designated areas.

.Wear steel-toed or protective boots.

.Stay on or near the toes of benches - don't climb up bench faces.

.Watch out for loose rock, bad footing, bench edges, production vehicles.

.Stay in designated stop areas in the pits - don't go off on your own without an okay.

.Obey all signs, your trip guides, and - common sense!

.Please 'go easy' on outcrops that are destructible - there're lots of collectable materials in the toes.

.Alcoholic beverages are stricly prohibited within pit limits, and therefore from our buses.

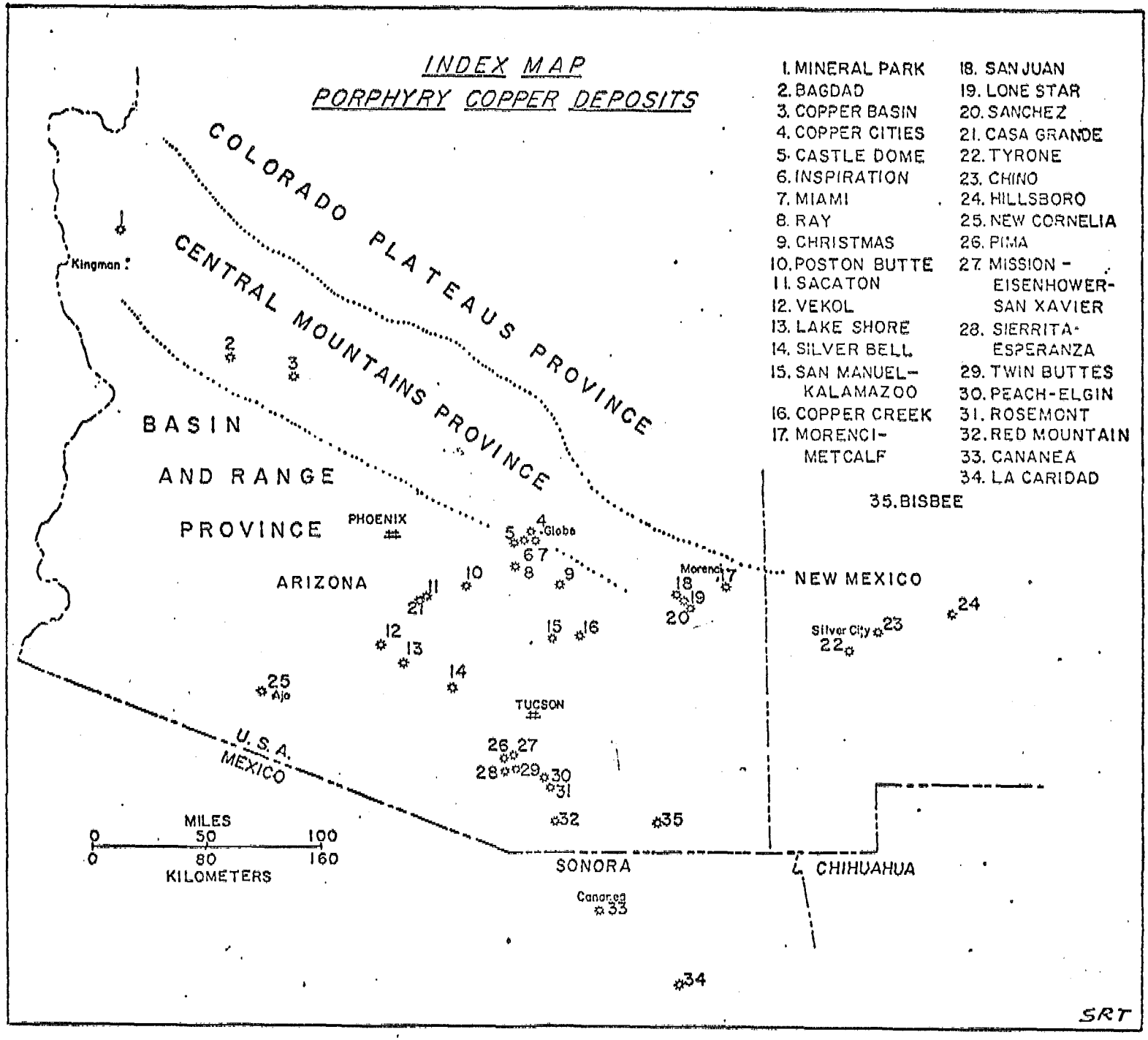
.Be wary of bench rims - it's a long fall, so stay back several feet.

S.E.G. FIELD CONFERENCE

SOUTHERN ARIZONA PORPHYRY COPPER DEPOSITS

INTRODUCTION

In excess of 35 named occurrences of porphyry copper mineralization occur in southeastern Arizona and adjoining regions. (Index Map, next page) These deposits, which are characterized, generally, by porphyry intrusion-centered, fracture-localized, zoned copper-molybdenum mineralization, occur in a variety of geologic settings within this restricted part of North America. These varied geologic settings have resulted in broad differences, in detail, of the style of evolution of the porphyry systems and, consequently, the manifestation of mineralization and alteration effects. Because we cannot, during the short period of a field conference observe and study all of the permutations of influence of variations in host rock, structure, alteration, mineralization, and supergene effects, we have selected two deposits in the vicnity of Tucson which reveal many extremes in the expression of these phenomena. These deposits, Sierrita-Esperanza and Silver Bell, (see area geologic map, following Page 7) reflect major differences in both their detailed and areal geology, in many respects which range from regional geometrical patterns, to different host rock and porphyry progenitor characteristics and finally, to striking differences in the habits of observed intrusion and hydrothermal effects.


INDEX MAP
PORPHYRY COPPER DEPOSITS
COLORADO PLATEAUS PROVINCE
CENTRAL MOUNTAINS PROVINCE
BASIN AND RANGE PROVINCE
ARIZONA
NEW MEXICO
SONORA
CHIHUAHUA
U.S.A.
MEXICO
Kingman
PHOENIX
Globe
Morenci
Silver City
TUCSON
Ajo
Cananea
MILES
0 50 100
0 80 160
KILOMETERS
1. MINERAL PARK
2. BAGDAD
3. COPPER BASIN
4. COPPER CITIES
5. CASTLE DOME
6. INSPIRATION
7. MIAMI
8. RAY
9. CHRISTMAS
10. POSTON BUTTE
11. SACATON
12. VEKOL
13. LAKE SHORE
14. SILVER BELL
15. SAN MANUEL-KALAMAZOO
16. COPPER CREEK
17. MORENCI-METCALF
18. SAN JUAN
19. LONE STAR
20. SANCHEZ
21. CASA GRANDE
22. TYRONE
23. CHINO
24. HILLSBORO
25. NEW CORNELIA
26. PIMA
27. MISSION - EISENHOWER-SAN XAVIER
28. SIERRITA-ESPERANZA
29. TWIN BUTTES
30. PEACH-ELGIN
31. ROSEMONT
32. RED MOUNTAIN
33. CANANEA
34. LA CARIDAD
35. BISBEE
SRT

Objectives

A basic objective of the conference is to provide the opportunity to examine the megascopic physical characteristics of the hypogene mineralization and alteration as they are revealed in these two deposits. A secondary objective is that of comparing broader aspects of geology of the two deposits in order that these details may be more fully and meaningfully understood and appreciated. From consideration of the comparisons of broad and detailed geology, a final objective will be that of examining manifestations of mineralogy and alteration and interpreting those features at the surface and in the zone of supergene effects.

SIERRITA - ESPERANZA AND SILVER BELL COMPARED

Both deposits reflect the results of mineralization related to multiple centers of porphyry intrusion. However, wall rocks to the intrusions differ in composition in the two deposits and the geometry of ore occurrence and alteration show similar disparity in style. These and other features are briefly discussed below.

Geometry

Sierrita-Esperanza consists of two, closely adjacent centers of mineralization about 0.3 km apart. The hydrothermal activity at each center has apparently produced overlapping of at least some features of hydrothermal origin. Silver Bell consists of multiple centers of mineralization which, by contrast, are separated by a distance of over 3.5 km along a northwest-trending axis.

Rock Types

Both deposits have hypogene copper mineralization centered on quartz monzonite porphyries. At Silver Bell, hosts to the porphyries which also carry copper mineralization, include dacite porphyry, alaskite, and sedimentary rocks of the Paleozoic section. At Sierrita-Esperanza, host rocks include a biotite-rich quartz diorite and a much older Jurassic body of mafic-rich quartz monzonite. In the Esperanza orebody, some mineralization is also hosted by volcanic rocks. Each rock type in each setting reveals its own characteristic type of mineralization and alteration.

Alteration Styles

Igneous mineralogies of the host rocks at Sierrita-Esperanza are apparently reflected in the alterationmineral assemblages. Pervasive, selectively pervasive, and vein-veinlet alteration mineral assemblages are those of igneous rocks. Potassium silicate or iron-magnesium-silicate minerals, together with zeolites, anhydrite, and minor carbonate veining present there, are characteristic of centrally-restricted parts of "potassically-altered" parts of other porphyry systems where igneous rocks of intermediate or more felsic compositions predominate. Although widely distributed, quartz-sericite alteration products on veins are subordinate to other types of alteration assemblages. The presence of relatively magnesium-rich diorite and granodiorite among the host rocks has apparently been responsible for development within the zone of potassic alteration, chlorite and epidote, the

characteristic minerals of propylitic assemblages, as major alteration products. Except for parts of the Esperanza orebody where sulfide content was apparently high, the metal assemblage at Sierrita-Esperanza is low total sulfide (2-3% volume) and the cpy-py ratio is relatively high. The body lacks the significant quartz-sericite alteration overprinting observed at Silver Bell.

The diverse mineralogies of host rocks at Silver Bell have given rise to magnesium and calc-silicate alteraion types in carbonate-bearing rocks of the Paleozoic, and the variation in this mineralogy reflects these variations in host rock composition. In addition to the "typical" potassium silicate and propylitic alteration of the quartz monzonite porphyry, dacite porphyry, and the alaskite, much of Silver Bell reflects profound and widespread development of quartz-sericite alteration in the igneous rocks. This late stage of alteration, masks much of the earlier potassic and propylitic types. The copper is part of a higher (than Sierrita) total sulfide assemblage - probably 4-6% volume, which results chiefly from addition of pyrite by the result of late stage development of quartz-sericite alteration.

Supergene Effects

Silver Bell is characterized by widespread development of secondary sulfide enrichment especially where the quartz monzonite, dacite porphyry or alaskite, altered to quartz-sericite, were present. Except for a small but important tonnage of secondary

enrichment ore which was mined initially at Esperanza, the Sierrita-Esperanza ore bodies are especially noteworthy because of the absence of secondary sulfides. Hypogene chalcopyrite was present in some rock types at Sierrita at the grass roots. Although there may be many additional reasons for this difference, the presence or absence of abundant pyrite and fracture permeability is seen as one potentially important reason for this difference.

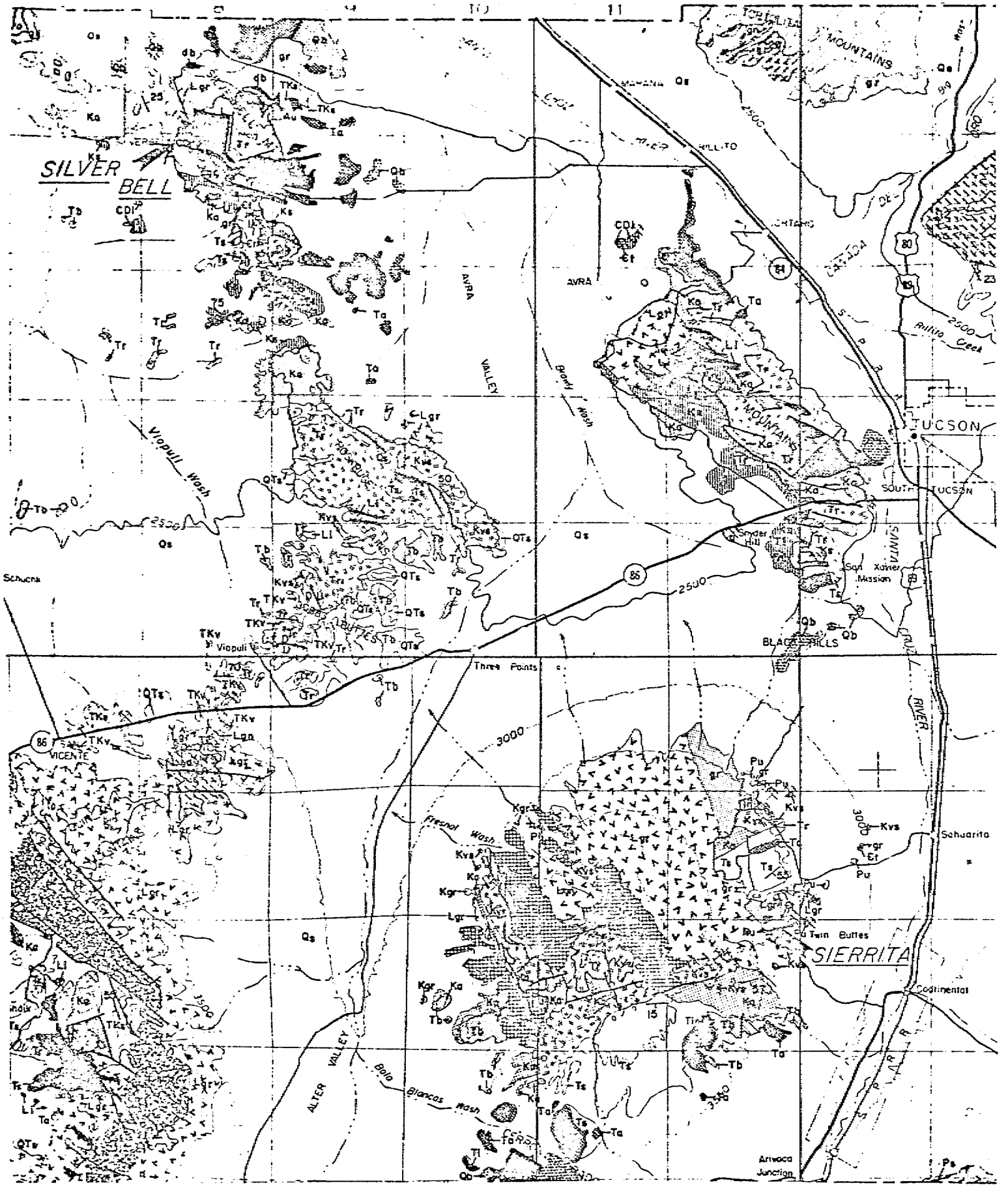
The different styles of alteration result in different manifestations of mineralization at the surface. Silver Bell has been enriched through several cycles of oxidation and leaching. The result is a capping developed in rocks originally strongly modified by hypogene alteration that, from place to place, shows the residual products from destruction of old chalcocite blankets. The result is a comparatively spectacular surface with hues from hematitic goethitic and jarositic limonites. Jarosite is exposed on some higher benches. Where sulfide contents are lower and the rocks have not been strongly modified by hypogene processes, capping is less spectacular and at Sierrita, is characterized more by goethitic or goethitic-jarositic oxidation products, strongly localized in and near the veins from which they have been derived. Much of the North Silver Bell capping reflects low hypogene inheritance, although better zones of hematitic limonites will be pointed out.

ANNOTATED EXPLANATION FOR REGIONAL GEOLOGIC MAP

(From: Geologic Map of Pima and Santa Cruz Counties, Arizona: Ariz. Bur. Mines; E. D. Wilson, R. T. Moore, and R. T. O'Haire, 1960)

Grid Scale is 6 miles (9.6 km)

Qs	Quaternary sediments	- basic fill cover
Qb	Quaternary Basalt	- At least some exposures of this unit may be mid-Tertiary in age - from results of post-mapping radiometric age dating.
Ti Lgr	Tertiary Intrusions	- mapped in the Silver Bell Mountains and the Sierrita Mountains. Mostly Laramide in age. See separate summaries for respective ages.
Tr Ta	Tertiary andesite rhyolite	- most exposures shown are known or inferred to be Upper Cretaceous-Laramide and pre-ore. In the Roskruge Mountains, some ages of about 100my have been measured.
Ks	Lower Cretaceous strata	- mostly arkoses and sandstones of Amole affinity (Tucson Mountains) or Angelica Arkose (Sierrita Mountains)
Kvs	Cretaceous volcanics and sedimentary rocks	- mostly mapped in the Roskruge Mountains and includes Mesozoic volcanics of possibly older age.
Pu	Paleozoic undivided	- carbonate and clastic sedimentary rocks.
Ps	Permian sedimentary rocks undivided	Includes the Rain Valley Formation and the Naco Group
CDi	Carboniferous and Devonian rocks undivided	Includes the Escabrosa Limestone and Martin Formations
Ct	Cambrian strata	Includes here the Abrigo Limestone and Bolsa Quartzite.
gr	Precambrian granite	On this map, mostly in the Sierrita Mountains.


SILVER BELL
TUCSON
SOUTH TUCSON
SANTA CRUZ RIVER
Snyder Hill
San Xavier Mission
BLACK HILLS
Three Points
VICENTE
Viopuli
Viopuli Wash
Brady Wash
AVRA VALLEY
Fresnal Wash
ALTER VALLEY
Bolo Blancos Wash
Sahuarita
Twin Buttes
SIERRITA
Continental
Arivaca Junction
Schuchi
Rillito Creek
MOUNTAINS
2500
3000
3500

REGIONAL GEOLOGY

The economic porphyry copper deposits of southeastern Arizona were formed during the Laramide interval (ca 55-75 my ago), a notable single exception being that of Bisbee which is Jurassic in age. That they are now exposed is apparently the result of geologic accidents associated with evolution of Basin and Range landforms which occurred during the mid-Tertiary. The reason or reasons for such great numbers of deposits in this region remain obscure and matters for speculation. Similarly, reasons for their great flourishment during the Laramide are also unknown, but continuing analysis of the effects of plate interaction and geometries during the Laramide is providing some answers. A necessary step to solution of these problems, however, will have to include the development of further understanding of the pre-Laramide and Laramide geologic settings.

The oldest basement rocks known in this southeastern part of Arizona are those of the Pinal Schist which is about 1700 my old. These rocks, together with intrusions of about 1420 my old compose the basement platform for rocks of younger Precambrian and Phanerozoic age and comprise the basement traversed by the porphyries. A pronounced and potentially important characteristic of the Precambrian is a northeast-trending structural grain which, at least locally as in the Globe Miama area, can be seen to be associated with alignment of separate centers of intrusions. The older Schist-granite basement was covered with a relatively thin column of much younger Precambrian sedimentary rocks in central Arizona, perhaps was more extensive than is now

recognized. This sedimentary column and Precambrian diabase which invaded it are present in the altered rock systems at Ray, Christmas, Globe-Miami, and some other deposits of this area.

During the Paleozoic, the southwestern half of Arizona composed a cratonic sedimentational environment between the Mesocordilleran geosyncline to the northwest and the Pedregosa Basin and its antecedents to the southeast. The Paleozoic column thickens perceptibly to both the northwest and southeast but in most of the southeast Arizona region, the column has a thickness of about 5000 feet (1500m). of rocks which are dominantly carbonate with minor interbedded clastic rocks. These rocks represent sediments of shallow shelf environments and include evaporites and shallow water limestone. In many deposits, rocks of this part of the section compose important hosts to porphyry copper mineralization. Noteworthy examples are Morenci, Silver Bell, Santa Rita, Twin Buttes, Mission, Pima, Vekol, and Lakeshore. Altered and mineralized units of the middle and upper Paleozoic will be seen at Silver Bell.

The style of geology which evolved during the Mesozoic reveal the effects of periodic or continuing geologic unrest if contrasted with the Paleozoic. In southeastern Arizona, there remain volcanic and volcaniclastic rocks of probable Triassic and Jurassic ages. The thickness and most widespread exposures are south of a line marked by an old and profound fault that strikes northwestward through the Sierrita Mountains. It was

during this lower part of the Mesozoic that the ores at Bisbee evolved, but no rocks of these ages are known to have survived in that area and the deposit was covered by upper Mesozoic strata after its evolution and oxidation. Rocks of the lower Mesozoic are present in and near both the Sierrita-Esperanza and Silver Bell deposits.

During the lower Mesozoic, the southern part of Arizona was largely emergent and structurally high with respect to the region of the Colorado Plateaus province. Volcanic and clastic debris was shed northward from southern Arizona during this time. However, during the Cretaceous, subsidence of southeastern Arizona once again took place and seaways encroached along the same paths taken by the older seaways of the Paleozoic. Southeasternmost Arizona was covered during the Lower Cretaceous by at least 12,000 feet (3,500m) of clastic sedimentary rocks in what was apparently the northwesternmost part of the Sonoran Embayment. Only thinned parts of probable uppermost Lower Cretaceous strata remain in the region of the porphyry systems and most interpretations suggest that thick sedimentation of this age did not extend much further northwest that about the vicinity of Tucson. Although sedimentation continued into the lower part of the Upper Cretaceous, not much remains of these strata and if they were at all widespread, they were stripped by erosion prior to the events of the uppermost Cretaceous.

This evolution of the porphyry copper systems of the Laramide was apparently heralded by widespread volcanism over much

of the region. This activity resulted in deposition of andesitic to rhyolitic, calc-alkaline volcanic rocks and interbedded clastic and volcaniclastic sequences. Some of these strata remain in and near the mineralized centers and the units are present at both Silver Bell and in the vicinity of the Sierrita-Esperanza intrusive centers. In both locations they reveal at least weak effects of the hydrothermal processes, and are generally unequivocally pre-ore in age. Where present, however, they appear to be the most youthful of pre-ore rocks, and they have been crosscutt by intrusive progenitors of the porphyry copper deposits.

The immediate pre-ore setting for most of the region of the porphyry copper deposit occurrence may thus be summarized as follows: A Precambrian basement of Schist and granite, with local thin units of Precambrian sedimentary strata compose the oldest rocks involved with the porphyry emplacement and hydrothermal processes. These rocks were covered by some 5000 feet (1500 m) of largely epicontinental Paleozoic strata. Although thick sections of Mesozoic strata are known in southeastern Arizona, there is fairly good evidence that such thicknesses (possibly as great as 20,000 feet - 6000 m) either did not extend into or were not deposited upon the region in which the porphyry copper deposits presently known evolved. (There may be a few exceptions to this generalization such as Rosemont-Helvetia.) Most of the stocks, for which the record remains, apparently crosscut virtually the entire pre-ore rock column, locally as great as 10,000 feet (3000 m) of Phanerozoic strata

and volcanic units, some of which may be genetically related to the intrusive event. At Morenci, for example, the intrusion crosses a thinned Paleozoic column (750 feet, 250 m) and the overlying Upper Cretaceous (Pinkard fm - Mancos?) section, a total of about 1500 feet (500 m).

The tectonic style of the Laramide has been deduced for the southeasternmost corner of the state. The style is characterized by compression-induced uplift of basement blocks, the boundaries of which are marked by northwest-trending pre-Laramide faults. Along those lines, northeast-directed folding and southwest-directed thrusting took place. Although the work from which these deductions have been made was carried out in the southeast corner of Arizona, it is reasonable to suggest that the same style persisted into the nearby regions. Both Silver Bell and Esperanza-Sierrita appear to have evolved near the edges of such basement blocks.

Following emplacement of the porphyries, uplift, erosion, and at least some oxidation and enrichment of the copper systems took place. These events, which probably took place during the early Tertiary, cannot yet be rigorously documented as to timing. The presence, however, of oxidized fragments of ore in dated mid-Tertiary deposits leads indirectly to such a conclusion. It is further inferred that some base level of oxidation was reached during this early Tertiary time which slowed and stopped the process, an inferrence based upon the fact that there was insufficient erosion to remove the deposits.

The next geologically and economically important event was that of mid-Tertiary Basin and Range mountain building. This event, preceded and accompanied by volcanism, appears to have resulted in placing a protective volcanic cap on top of the deposits, uplifting some and downdropping others. We view them at present time as accidents of erosion and of mountain building which has exposed them to view. They are locally undergoing continued oxidation, leaching and secondary enrichment, and are in the process, left to themselves, of being further eroded.

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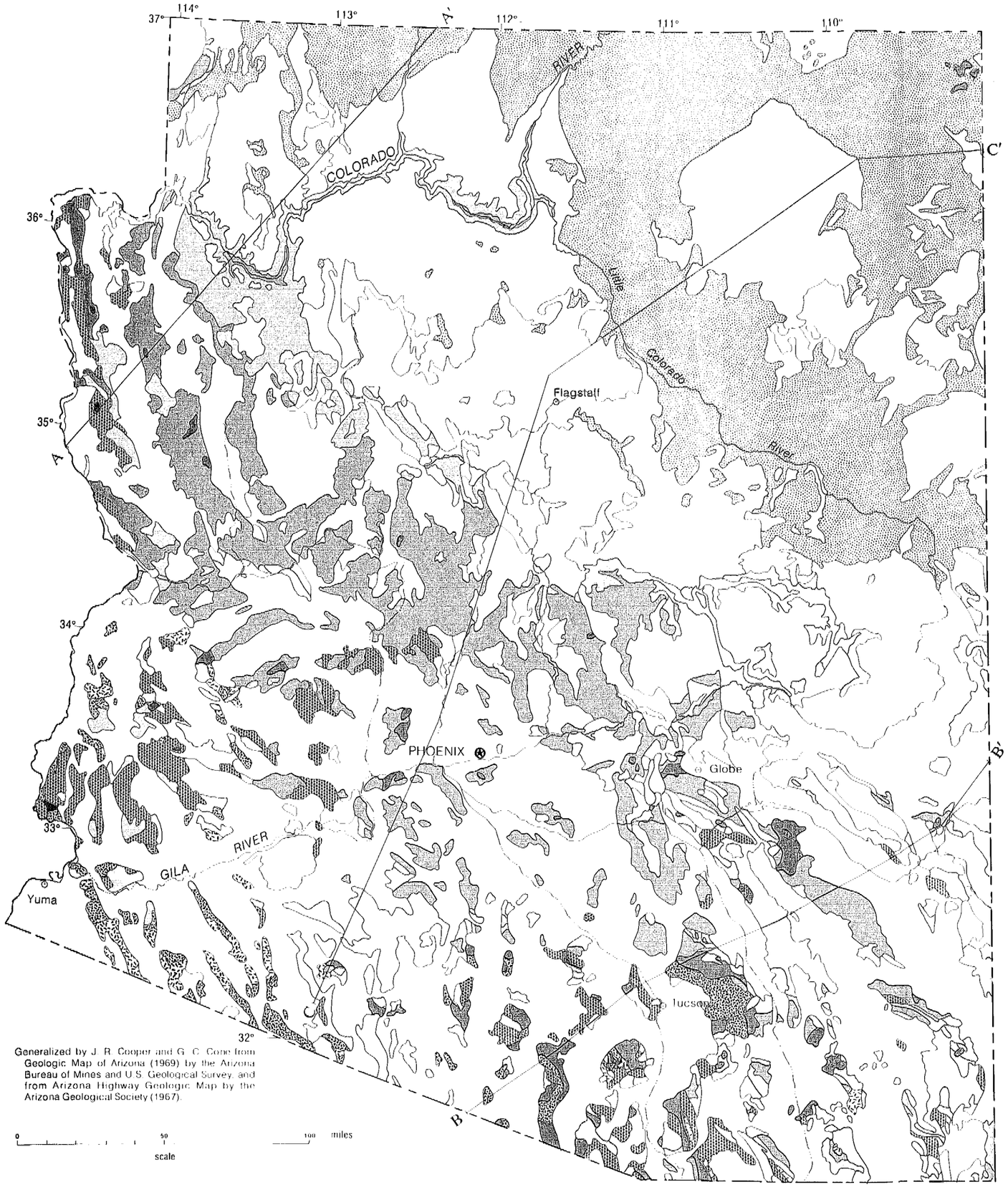

Generalized by J. R. Cooper and G. C. Cone from Geologic Map of Arizona (1969) by the Arizona Bureau of Mines and U.S. Geological Survey, and from Arizona Highway Geologic Map by the Arizona Geological Society (1967).

EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

CENOZOIC

QTs — Quaternary and upper Tertiary (Pliocene) sedimentary rocks, mostly unconsolidated; includes scarce lava and silicic tuff

QTv — Quaternary and upper Tertiary volcanic rocks, mostly basaltic in composition

Ts — Middle Tertiary (Miocene and Oligocene) sedimentary rocks; locally include lava and tuff

Tv — Middle Tertiary volcanic rocks of silicic to basaltic composition; includes related intrusive rocks

MESOZOIC

Ks — Cretaceous sedimentary rocks

TRv — Lower Tertiary to Triassic volcanic rocks; includes some sedimentary rocks

JTRs — Jurassic and Triassic sedimentary rocks

Mesozoic sedimentary rocks

PALEOZOIC

PIPs — Permian and Pennsylvanian sedimentary rocks; shown only on Colorado Plateau

M€ / Pz — Mississippian through Cambrian sedimentary rocks on Colorado Plateau; all Paleozoic sedimentary rocks in Basin and Range province

PRECAMBRIAN

Yp€ — Younger Precambrian sedimentary rocks and intrusive diabase

Op€ — Older Precambrian rocks of all types, including schist, gneiss, and fine- to coarse-grained igneous intrusive rocks

OTHER METAMORPHIC AND INTRUSIVE IGNEOUS ROCKS

Tertiary and Upper Cretaceous intrusive igneous rocks

Post-Paleozoic gneiss and schist

Mid-Cretaceous to Triassic intrusive igneous rocks

GEOLOGIC MAP and CROSS-SECTIONS of ARIZONA

Porphyry Copper Deposits - Definitions, Characteristics, Problems, and Progress

(Abstract)

by
John M. Guilbert
Department of Geosciences
University of Arizona

PCD definitions since Parsons (1933) have ranged between engineering (bulk, low grade) and geologic emphasis. Recent geologic definitions have ranged from purely descriptive to process-genesis emphasis. As more is discovered about PCD's, the group appears to widen in many senses - for example to include the sodic alkalic deposits of British Columbia and the SW Pacific. As P-T studies of the type to be described at this conference mount up, classifications such as Sutherland-Brown's plutonic-volcanic-phallic and Cheney's batholithic-epizonal will be resolved. Meaningful definitions still emphasize the word 'porphyry' - the implication of porphyritic texture is clearly consistent with porosities, permeabilities, mineral stabilities, and alteration reactions of epizonal environments, and porphyritic, intermediate-composition intrusive rocks are still universally associated with PCDs. A workable 1979 definition is 'a large, low to medium grade deposit primarily of copper as chalcopyrite and molybdenum as molybdenite in which sulfide and silicate zoning spans alkali, principally potassic, and hydrolytic metasomatism, and which is spatially and temporally related to intermediate to felsic porphyritic epizonal intrusive rocks'.

Since 1966 the (Titley-Hicks volume), 1967 (the Barnes volume), 1968 (the Penrose Conference and Graton-Sales volume), and the notable publications of the early seventies, great strides in field and laboratory studies have been made. Excellent and numerous deposit descriptions have established the importance of zoning, for example, and have served in part to explain it and deviations from it. But field studies coordinated with intensive laboratory work, the thrust of this Conference and exemplified by progress over the years at, for example, Butte, hold great promise in resolving current problems.

Problem areas now under most intensive study in field and laboratory (and about which more will be said today) are:

Zoning. The geochemical and temporal relationships of alteration-mineralization phases is complex and is being increasingly perceived as generally involving many subassemblages and phases, each buffered by wall rock plus fluid characteristics. Phyllic alteration has always been recognized as post-potassic, but its wide recognition as also post-propylitic, and the recognition of deposits like Sierrita and El Arco with almost no quartz-sericite-pyrite, have prompted evaluation of retrograde 'phyllic overprint' onto earlier potassic-propylitic continua. Careful study of distribution of assemblages and individual phases, and of cryptic zoning (solid solution variation) within them, permits activity-activity diagram representation and sensitive mass distribution modelling.

Fluid mechanisms and sources. Recent isotopic studies, computer-modelling of cooling plutons, and fracture distribution studies have demonstrated that non-magmatic waters must have circulated through these PCD volumes, and the natures of physical and chemical gradients along which they moved are to be considered a prime Conference subject. The ratio of juvenile-meoteoric contributions at different times and places within PCD systems is one of the frontiers.

Metal sources and distributions. Hand in hand with fluid transport dynamics is the problem of the ultimate source of metals and non-metals, cations and anions, in the fluids and hence the deposit, with emphasis ranging from essentially total wall-rock derivation to dominantly or totally magmatic; evidence for both, again, will be heared during the Conference.

Solution Geochemistry, Geothermometry, and Geobarometry. This area, the focal point of fluid inclusion - phase composition studies, is providing insight at a whole new level. Precise information on solution types, salinities, physical state (boiling vs condensed), and temperatures, coupled with contemporaneous silicate-oxide sulfide data, affords chemical-thermal paragenetic inference not hitherto available.

Structure and structural control. The evolution of fractures in PCD systems is vital to their understanding. The quantitative, qualitative, and spatial distribution of fractures, microveinlets, veinlets, and veins with time in P BMD systems is eloquent of external tectonic influence (the 'strain gauge' concept), internal P-T evolution, and rock mechanics and behavior. Quantitative study of fractures, alteration-mineralization, and paragenesis is another fulcrum of the Conference.

Areal-regional distribution and occurrence. Ultimately, the explorationist in all of us seeks to know what localizes PCD systems in particular tectonic-geochemical-temporal settings. Continued application of the field and laboratory approaches mentioned, and their integration with regional tectonics, plate tectonic concepts, geochronology, and geochemistry, will improve our insight.

I have essentially - though not intentionally - outlined today's program, including much that will be developed in the evening sessions and at field stops. I may have outlined the next few year's progress. In any event, the rate of progress appears to be accelerating in many subject areas to be considered in this SEG Field Conference.

Hydrothermal Processes Related to Porphyry Copper Deposit Formation

by

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The sequence of events that formed hydrothermal mineral deposits have been reconstructed by economic geologists from comprehensive field and laboratory data accumulated over several decades. These data suggest that the typical porphyry copper system occurs in close proximity to stock-like intrusions, but extends for several kilometers into surrounding host rocks, and that the porphyry, skarn, and lithocap zones in these systems formed as a consequence of extensive fluid circulation, Figure 1.

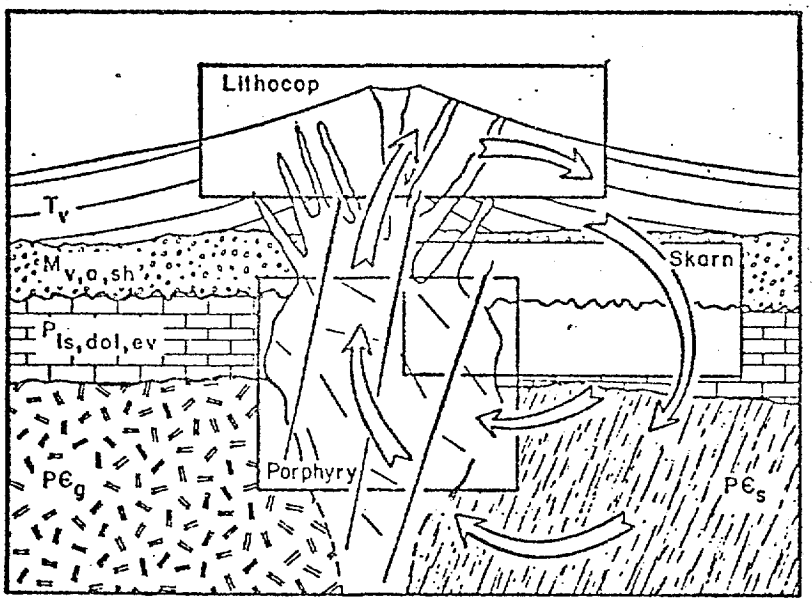


Figure 1. Schematic cross section of pluton-volcanic complex in host rock analogous to Arizona-New Mexico porphyry-copper province. Arrows represent hydrothermal circulation characteristic of permeable pluton and host rock environment. Mineral deposit zones are depicted by large boxes which locate porphyry, skarn, and lithocap zones within a complete system. Continuous transition in mineral and chemical alteration is observed between various zones.

The purpose of this communication is to discuss the results of studies that have applied the principles of transport theory to the problem of determining the geologic history of magma-hydrothermal systems. These studies have been supported by the National Science Foundation, Research Corporation, Department of Energy, Occidental Petroleum, Westingouse, and the University of Arizona,

and represent contributions by R. Knapp, T. Gerlach, R. N. Villas, B. Moskowitz, J. Knight, R. Capuano, K. Bladh, J. Quick, E. Noah, and D. Bird.

These studies indicate that the necessary and sufficient processes for the formation of porphyry copper type ore deposits involve: 1) emplacement of a thermal energy source (magma) into brittle rocks, 2) transport of thermal and mechanical energy away from the source, 3) rock deformation in the form of fractures that increase rock permeabilities, 4) hydrothermal fluid flow from sourceregions through permeable rock units along pathlines and transport of ore-forming components, and 5) reactions between fluids and minerals along the walls of flow channels, formation of hydrous-silicate alteration phases, and concomitant deposition of transition-metal sulfide minerals. These processes are diagrammatically represented in Figure 2.

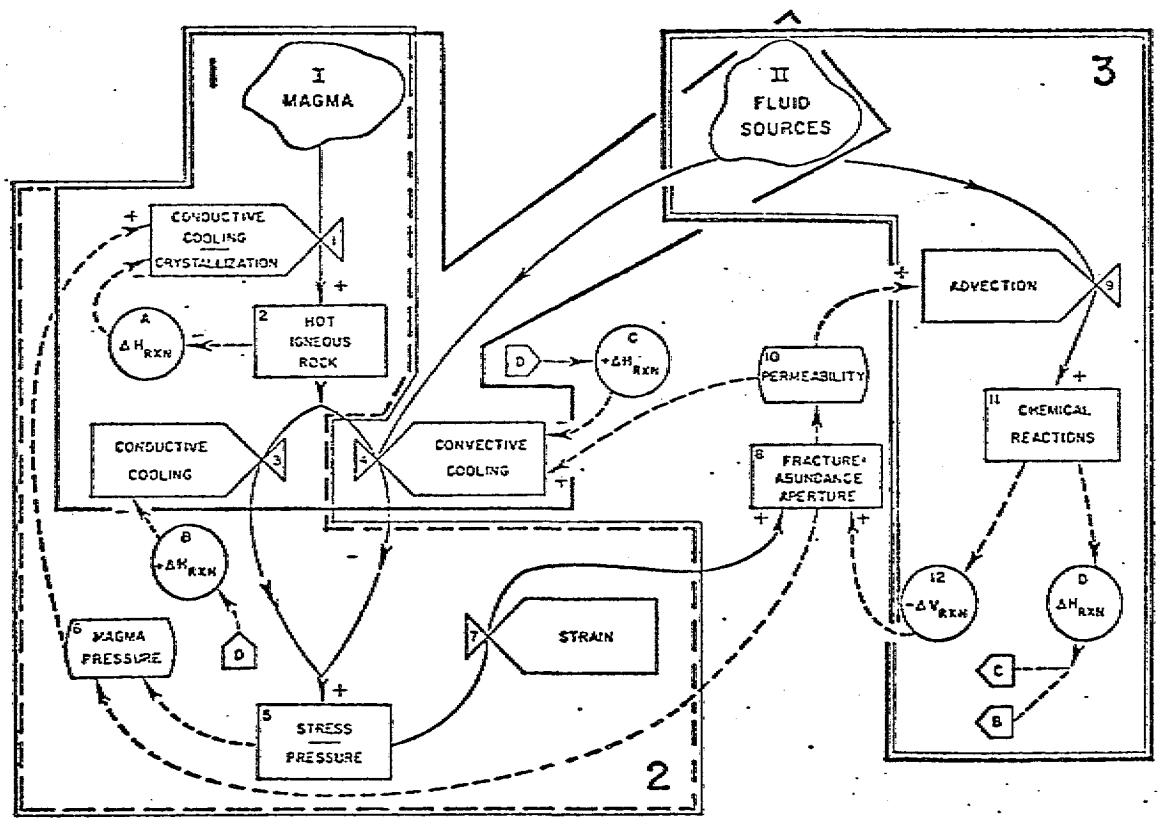


Figure 2. Dynamics of hydrothermal systems, relating thermal, mechanical, and chemical processes. Rectangular boxes with valves represent rates, rectangular boxes represent levels, circles indicate feedback from level to rate, and positive signs indicate that feedback augments rate. Regions 1, 2, and 3 represent subsets of overall processes which coincide with decoupled equations. Where dashed lines cross subset boundaries, feedback is approximated by arbitrary functions which estimate magnitude of effects. Analyses of processes in the respective subsets include: Region 1 - Norton, 1972; Ribando and Torrance, 1977; Norton and Knight, 1977; Cathles, 1977; Norton and Knapp, 1977; Norton, 1978; and Norton, 1979a. Region 2 - Knapp and Norton, 1979; and Roberts, 1970. Region 3 - Helgeson, 1971; Norton, 1972, 1978, 1979b; Norton and Taylor, 1978; and Henley and McNabb, 1978.

Computer evaluation of equations that represent processes in regions 1, 2, and 3 of Figure 2 effectively simulate the geologic history of magma-hydrothermal system. Sequential computations of; 1) the thermal history, region 1, defines temperature, pressure and fluid velocities, 2) mechanical history, region 2, defines the stress conditions, strain rates and failure events, and 3) chemical history, region 3, defines the extent of hydrothermal alteration and consequently the abundance and location of ore zones.

Numerical simulation of the thermal history of magmas from the time of emplacement to decay of the hydrothermal system have produced quantitative models of the ore forming processes. The features of these models that are likely to be significant in their natural analogs are:

The potential for hydrothermal-fluid flow is an inevitable consequence of the occurrence of magmas in the crust, but the magnitude and style of the flow is a function of rock permeability. The transfer of energy by fluid convection is significant in those regions where rock permeabilities are $\geq 10^{-3}$ millidarcy. Temperature, pressure and fluid flux conditions are dependent on rock permeability and the transport properties of the hydrothermal fluid. Because these fluids are dominantly composed of H_2O, and transport properties of phases in the H_2O and related salt-H_2O systems are characterized by extreme values in the supercritical region, temperatures in the 300-500°C range are common in the skarn and porphyry zones and 200-300°C are common in the lithocap zones for a major portion of the systems history.

Sourceregions for hydrothermal fluids conincide with permeable rocks and the fluids are redistributed along pathlines that cross through regions of relatively large permeability. The sourceregions in systems with small permeability plutons ($<10^{-3}$ millidarcy) are entirely composed of host rocks. Even in systems with large permeability plutons ($\sim$10 millidarcy) the host rocks account for 95% of the fluid that circulates through the pluton. Typical porphyry copper systems

in Arizona and New Mexico were very likely formed by fluids that flowed from regions as far as 5 km away from the pluton and incorporated fluids from carbonate, evaporite, pelitic, metamorphic and volcanic rocks. Corresponding statements regarding the sources of ore forming components are in the process of being developed.

Fracture permeability in magma-hydrothermal systems is a consequence of stress conditions caused by three distinct processes after inflation of the magma chamber: 1) Crystallization of volatile rich magmas increases the magma pressure sufficiently to produce tensile failure in the crystalline portion of the magma and host rocks, and to produce multiple magma chambers within the magma. 2) Differential thermal expansion of the host rocks as they are heated and of the pluton as it cools, causes tensile and shear-failure, and 3) thermal expansion of pore fluids contained in the residual porosity of the host rocks results in tensile failure over a broad zone above the pluton, including the lithocap zone. The fractures generated by variations in magma pressure are dependent on the volatile content and are largely restricted to regions within the pluton or close to host rocks close to its contacts. Therefore the extent of hydrothermal alteration within a pluton is expected to be a direct consequence of the initial volatile content of the magma and its crystallization history.

Reactions between hydrothermal fluids and minerals occur along the fluid pathlines as the fluids flow from their respective sourceregions. The composition and abundance of mineral products is a direct consequence of the competing rates of change in fluid composition caused by: 1) advection of components by fluid flow, 2) nonequilibrium reactions between minerals and fluids flowing between different environments, and 3) local equilibrium between the aqueous solution and alteration product minerals. Relative rates computed for simple systems indicate that within the <u>porphyry zone</u>: 1) during the early high temperature phase

(500-900°C) the aqueous solution and minerals equilibrate because of the relatively rapid nonequilibrium reaction rates, and produce alteration products similar in composition to the original igneous minerals, 2) at intermediate temperatures (400-500°C) the three rates are nearly equal and local conditions such as proximity to contacts with rocks of contrasting composition determine the style of alteration, and 3) at low temperatures (<400°C) the advection and equilibrium rates cause the production of relatively large quantities of hydrous alteration minerals, e.g., epidote, muscovite, paragonite, kaolinite, and montmorillonite.

The closely coupled nature of the thermal, mechanical and chemical history, as shown in Figure 2, appears to be the cause of the complex variations and temporal and spatial distribution of alteration effects. The theory and calculations indicate that the dispersion of thermal energy away from the pluton is the fundamental cause of the alteration effects. Because this transport of thermal energy produces a sequence of tensile and shear-failure events in the rocks and these events produce fractures with various orientations, variation in vein-alteration types within a single outcrop is expected. These variations are also consistent with the fact that fluid compositions are likely to change because of the diversity of sourceregions and the travel time of fluids from their sourceregions to your favorite outcrop.

The Style and Progress of Mineralization and Alteration in Some Porphyry Copper Systems

S.R.Titley

Abstract

The manifestations of alteration and mineralization in many porphyry copper systems are the result of complex mechanical and hydrothermal processes. Rocks of these deposits indicate that they have been repeatedly cracked and that the physical-chemical conditions of deposition of ore and alteration minerals have changed during the life of the process. The result of these changes in conditions and of continuous fracturing of rocks has been to produce rock volumes in which complex vein relationships exist. This complexity is characterized by cross-cutting veins and veinlets with different and distinctive stable alteration assemblages. The paragenesis as deduced from studies of veins indicates that in felsic igneous host rocks, the progress is commonly that of a change from biotite-stable (sometimes epidote-chlorite-stable) alteration assemblages through feldspar-stable assemblages, to quartz-sericite-stable assemblages. Variations in this sequence or in the stable assemblages may be present in different deposits and in rocks with differing compositions. Nonetheless, as a result, the definition of discrete zones characterized by single specific stable alteration assemblages is not ordinarily possible unless paragenesis is also considered. The type of veinlet alteration can not ordinarily be used as a guide to the type of alteration affecting the rock as a whole, because of the superposition of alteration types.

Chemical and mineralogical composition of the host rocks exerts a profound control on alteration minerals produced under changing thermochemical conditions. Similarly, mechanical properties of the rock, together with compositional characteristics, influence the evolutionary style of alteration and mineralization. Viewed mesoscopically, alteration assumes

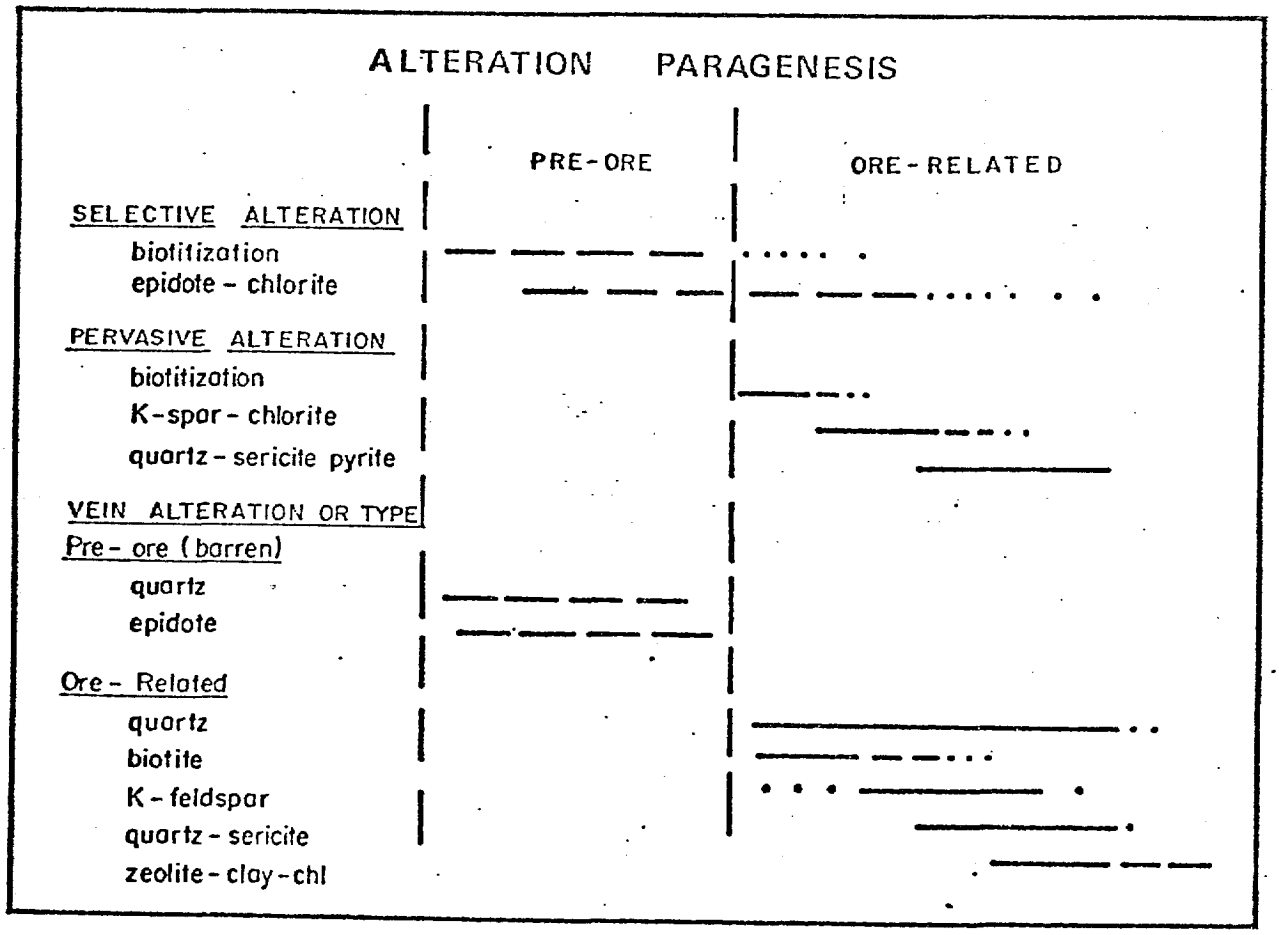
three typical habits. These habits, described further, consist of selectively pervasive alteration, pervasive alteration, and vein-veinlet alteration.

Selectively pervasive alteration has affected specific minerals of rocks and a common result is enhancement of rock texture. The alteration type is commonly observed peripheral to centers of systems although it is likely that its effects, early in the process, were ubiquitous. The most common manifestation is the selective conversion of igneous hornblende to biotite. Other manifestations include argillic alteration of feldspar phenocrysts, replacement of feldspar by epidote minerals, and, in late hydrothermal stages, selective conversion of biotite to chlorite.

Pervasive alteration results in destruction of original rock textures. As considered here, it is not now obviously vein-related although it may have progressed from alteration along closely-spaced veins. It occurs on a scale that involves from tens to thousands of cubic meters of rock. The process that produces this alteration has often been described as "flooding." Included is the complete alteration of large rock volumes to silica and alunite, to orthoclase or more rarely to biotite, and, in carbonate rocks, to calc-silicates. These alteration types evolve rocks which are hosts to ore and they are therefore products of early hydrothermal processes. Late pervasive alteration is commonly that of development of quartz-sericite. Finally, supergene effects which have produced large volumes of acid may overprint and destroy many of the effects of all hypogene types.

Vein-Veinlet alteration attends deposition of ores. In most deposits in igneous rocks and in many evolved inskarns, sulfide deposition can invariably be shown to be related to fractures. These fractures range in size from large obvious features down to micro-veinlets. A variety of veins and veinlets, each with their own characteristic alteration selvage is usually present within the central parts of porphyry copper systems. The progression,

as revealed from cross-cutting veins relat onships, is from biotite-stable alteration products with sulfide, to orthoclase-stable alteration products with sulfide, to quartz-sericite-stable assemblages with sulfide, to, finally, clay-chlorite-zeolite stable assemblages which may or may not be attended by sulfide deposition. Quartz or quartz-feldspar (either orthoclase or albite) with reaction products may locally be interspersed, but at different times and places in different deposits. In the veins of calc-silicate deposits, progression may reflect systematic changes in ratios of iron, magnesium, and calcium together with changes in hydrated to anhydrous minerals, with or without sulfides. As in the veins of igneous rock, however, alteration mineralogy is strongly wall rock controlled. A generalized paragenetic sequence for alteration types in felsic igneous rocks is shown below.



Time-space relationships of alteration can only be generalized, noting that many combinations can be seen from deposit to deposit, variations which can, in part be the result of the level at which a deposit is viewed. For example, "late argillic" alteration (silica-alunite flooding, clay stable) may have evolved at high levels in some systems but if so, is now absent at the level viewed. In numerous old deposits of the American southwest, the alteration phenomena described here can be interpreted as having evolved, at the level viewed, in the following way:

The system is the entire volume of rock involved in the hydrothermal process - the copper deposits occupy a much smaller volume within the altered mass of rock. The deposits appear to occur within an aureole of selective biotitic alteration that defines the limit of the system. Biotitic alteration may have subsequently been modified by superposition of much younger "propylitic" alteration which, among other changes, selectively alters early biotite to chlorite. This progression and style results in the interpretation of peripheral propylitic alteration, when, in fact, earlier and widespread biotite-stable alteration was present. Veinlet alteration may "wax and wane", gonerned by the progress of evolution of fracture permeability. It is not uncommon to find at least some orthoclase stable alteration at the periphery of the volume of fractured rock and, further, not uncommon to find volumes of more densely fractured and quartz-sericite-altered rock closely restricted to the center of such systems.

It is becoming increasingly clear that many aspects of alteration zoning are complex and clearly time-related as well as space-related. The results of the studies reported here and other studies of these phenomena have, as one major purpose, the correct interpretation of the isolated outcrops of fractured rocks in the context of their relationship to hidden or unrecognized porphyry copper systems.

GEOCHEMICAL ENVIRONMENTS OF MINERALIZATION AND ALTERATION

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Introduction

Lindgren (1933, p. 212) established a class of mineral deposits generally referred to as hydrothermal whose "origin (was) dependent upon the eruption of igneous rocks" and which were formed "by hot ascending waters of uncertain origin, but charged with igneous emanations". Igneous emanations may, of course, consist of both heat and matter. But in subsequent years hydrothermal solutions were generally considered to have been generated from, rather than by, magmas in spite of the fact that the presumed igneous progenitor for the fluids was not observed at numerous deposits. Lindgren, however, refused to make this universal genetic correlation.

Alteration minerals formed in the class of deposits known as "porphyry copper" have been described by Lowell and Guilbert (1970) and Rose (1970) to occur in a systematic coaxial arrangement from interior potassic through progressive phyllic and argillic to marginal propylitic, and in many instances are seen centered upon a stocklike mass of mineralized quartz monzonite (Fig. 1). Experimental investigations of the system K_2O-Al_2O_3-SiO_2-H_2O by Hemley and coworkers (Hemley, 1959; Hemley and Meyer, 1967; Montoya and Hemley, 1975) which defined mineral stabilities in terms of the temperature and composition of an aqueous phase

(Fig. 2) were used to explain the "typical" alteration zoning in porphyry copper deposits listed above by calling upon cooling of an aqueous phase as it moved from the presumed quartz monzonitic source into cooler rocks (cf., Rose, 1971) as shown by the arrow AB, Figure 2.

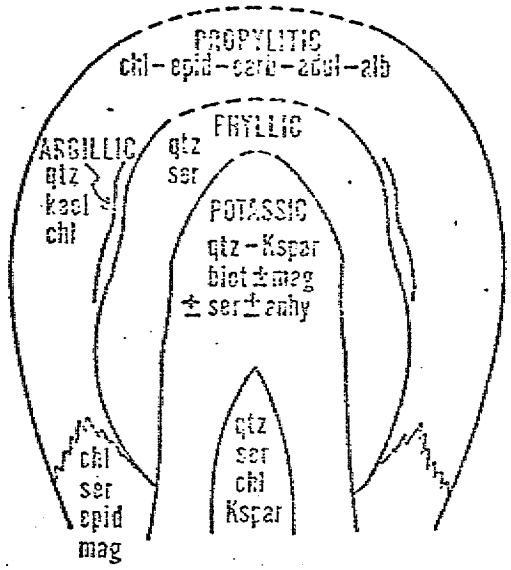

Figure 1. Schematic drawing of alteration zoning in a typical porphyry ore deposit (from Lowell and Guilbert, 1970). Vertical cross section.

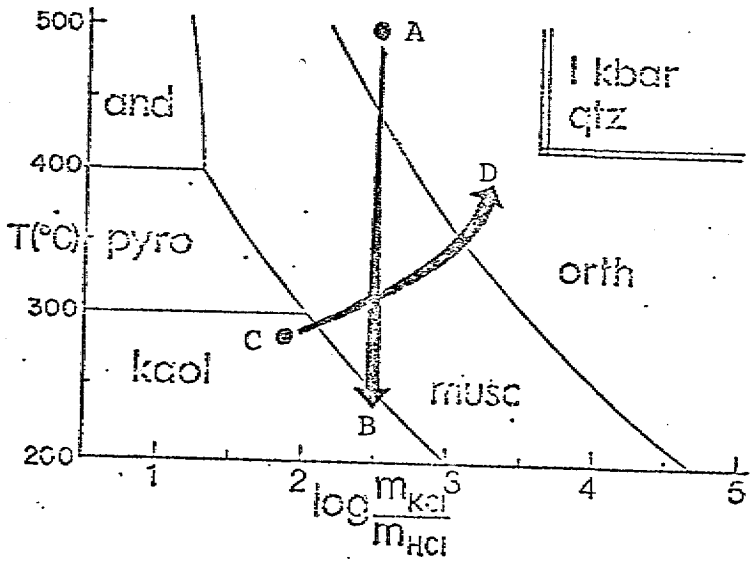

Figure 2. Stability relations of phases in the system K_2O-Al_2O_3-SiO_2-H_2O as a function of temperature and solution composition at 1 kbar pressure and quartz saturation (modified from Montoya and Hemley, 1975). Path A-B corresponds to cooling and path C-D represents progressive reaction of originally acidic fluid with orthoclase.

Stable isotope studies of alteration minerals in several porphyry copper deposits led Sheppard, Nielsen and Taylor (1969, 1971) to propose that two genetically distinct fluids were involved at different times in porphyry copper deposits, the earliest being of magmatic parentage and the later of meteoric origin. As a consequence of this work, the concept of convective circulation of non-magmatic fluids became generally familiar (cf., Norton and Knight, 1977) to geologists working with porphyry copper deposits and this general mode of convective circulation has been modelled numerically. At essentially the same time the isotope relations were defined, Helgeson and co-workers (1969, 1970a, 1970b) developed a means of numerically simulating the consequences of irreversible reactions between hydrothermal solutions and minerals with which they were not in equilibrium. From these simulations came the suggestion that the progression of alteration phases in porphyry copper deposits could beproduced by reaction between an initially acid solution and K-feldspar at constant temperature as shown by arrow B-C, Figure 2. The spatial arrangement of alteration types (Fig. 1), however, indicated that the reacting solution might be moving inward toward the intrusive center corresponding for example, to the lower portion of a convection cell, rather than away from it as suggested by the hypothesis of fluid-cooling.

Studies in recent years have documented the presence of two isotopically and chemically distinct fluids in porphyry copper deposits, and the ensuing topic of debate has become

the correlation of either the magmatic or the meteoric fluid with sulfide transport and deposition (cf., Gustafson and Hunt, 1975; Gustafson, 1978). The apparent association of sulfide mineralization with both of the fluid types at El Salvador were interpreted by Gustafson and Hunt (1976) to indicate that sulfides originally deposited from early magmatic fluids were remobilized by later circulation of meteoric waters. Over the last 3 years a research project has been in progress at the University of Arizona to examine the thermal and chemical characteristics of hydrothermal solutions in the porphyry copper environment by studies of fluid inclusions. Two of the primary purposes of this research funded by the National Science Foundatin and the State of Arizona have been to correlate alteration and sulfide minerals with properties of accompanying fluids, and to define chronologic relations between fluids having differing properties. The general methods used to establish chronologies using fluid inclusions are the same as those employed by a field geologist to establish a relative time sequence of geologic events and may be illustrated using Figure 3. Because a primary inclusion

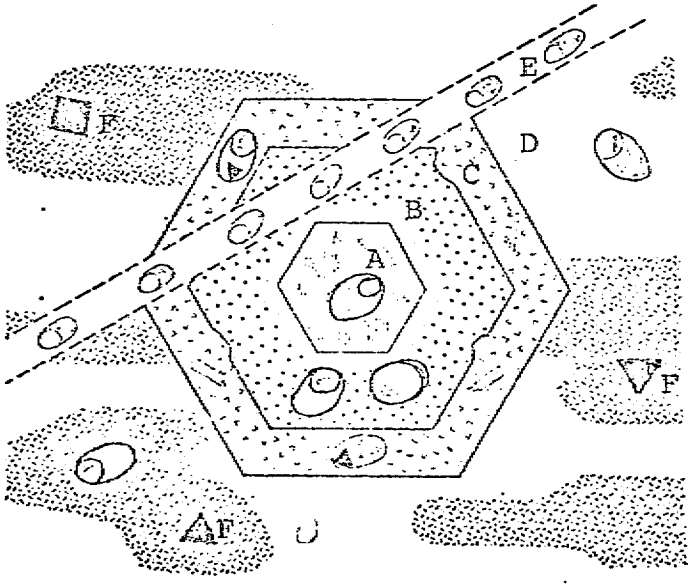

Figure 3. Schematic diagram of some features which may be used to establish chronologic relations among fluid inclusions. A quartz crystal exhibiting three growth zones (A,B,C) is engulfed in a later generation fo quartz (D) and all are cut by a plane of secondary inclusions (E). Various other mineral phases (F) enclosed in quartz are correlated with primary fluid inclusions.

traps a fluid coexisting with the enclosing mineral (quartz in this example), relations such as superposition of growth zones in single crystals (A→B→C, Figure 3), unconformities between two generations of a mineral or minerals (interface C-D) and crosscutting planes of secondary inclusions formed along fractures in the host mineral (E) define the time sequence of fluids A through E from early to late, respectively. Solid inclusions trapped in (or coprecipitated with) the host mineral (various phases F) may frequently be related to primary fluid inclusions which permits alteration and sulfide minerals to be correlated with fluids having certain temperatures and salinities. Minimum temperatures of entrapment are indicated by homogenization temperatures of fluids, and in many instances, particularly in systems at relatively low pressures, these may provide close approximation to actual filling temperatures corresponding to mineral deposition. Fluid inclusion may contain only a liquid and a vapor phase and homogenize to one or the other. In certain instances, two adjacent fluid inclusions may each homogenize to one of the two endmembers, liquid and vapor, and if they do so at the same temperature they may indicate boiling of the hydrothermal fluid in which case the homogenizaion temperature is identical to the filling temperature. Inclusions trapping concentrated fluids may contain one or more daughter minerals deposited from solution upon cooling. Among those daughter minerals tentatively identified during this study based on optical

and crystallographic properties are: halite, sylvite, hematite, magnetite, pyrite, chalcopyrite, anhydrite, calcite and tourmaline. With the exception of phases considered to have formed by post-entrapment leakage of the H_2 gas (hematite, anhydrite), the daughter products generally dissolve upon heating at temperatures less than that at which the fluid homogenizes to the liquid phase. Fluid inclusion studies have been carried out on several deposits of porphyry copper affinity at various positions in the overall cross-sectional environment shown in Figure 4 modified from Norton, et al (1975).

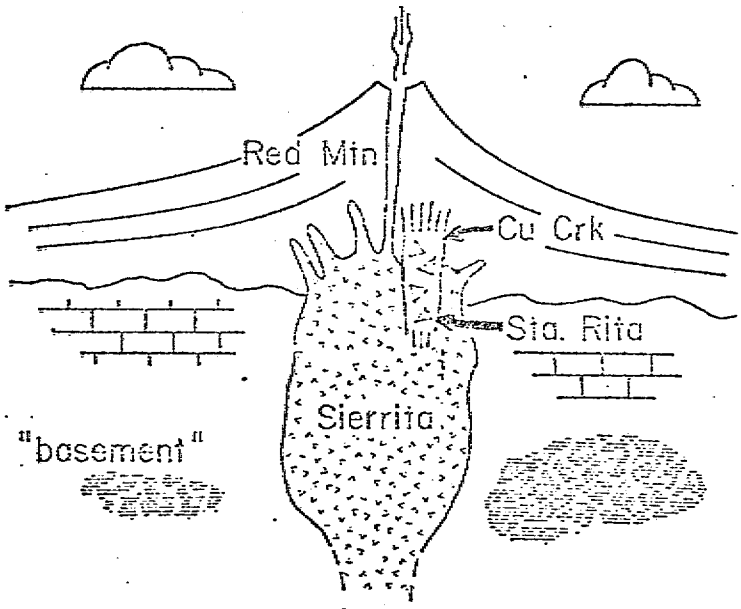

Figure 4. Generalized cross section of a porphyry copper system showing the central intrusive body, overlying stratovolcano, and intruded basement. Located on the cross section are probable positions of the four deposits described in this communication.

Among these are included:

1) A vertical column of approximately 1500 m in pre-ore volcanic rocks considered to overlie a buried pluton at Red Mountain, Arizona (Bodnar, 1978; Bodnar & Beane, 1977).

2) Two breccias pipe localities, one of which is directly associated with the porphyry copper deposit at Santa Rita, N. M. (Reynolds, 1979) and the other at Copper Creek, Arizona where such mineralization has been inferred by

Gilmore (1977),(Walker, 1979).

and

3) From within the Duval-Sierrita open pit in the heart of a mineralized system (Preece, 1979; Preece & Beane, 1979).

The breccia pipes, and in particular the Whim Hill at Santa Rita, plus a nearby vein, were selected for study because of the mode or origin suggested for such by Norton and Cathles (1973). According to their hypothesis, the Whim Hill formed by collapse of overlying rocks into a void occupied by exsolved magmatic fluids, and the resulting breccia would have been bathed by the escaping fluids (Fig. 5). Subsequently, meteoric waters in convective circulation would have been concentrated in the pipe owing to its high permeability. Thus this structure may have seen both magmatic and meteoric fluids in chronologic succession.

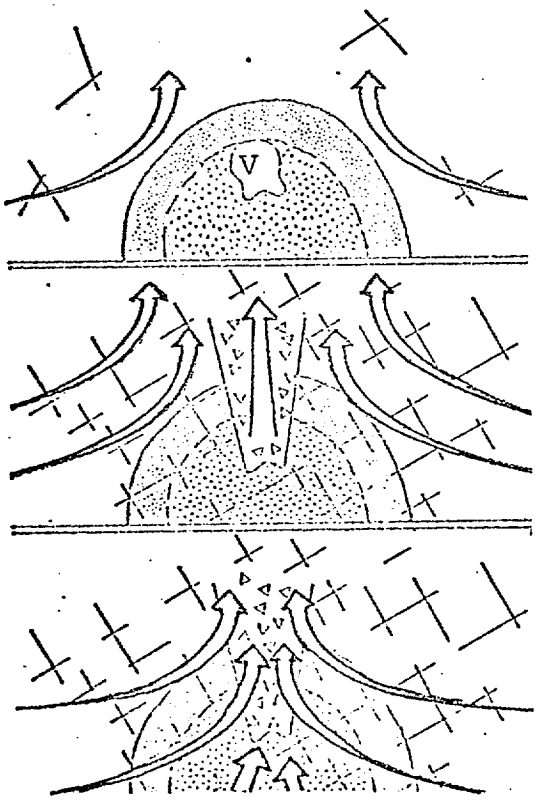

Figure 5. Proposed sequence of fluid flow patterns attending formation of the Whim Hill breccia Pipe, Santa Rita, N.M., based on the model described by Norton and Cathles (1973).

a) Trapped vapor bubble in hood of stock
b) Collapse of rock column and escape of magmatic fluid
c) Late influx of meteoric fluids

Red Mountain

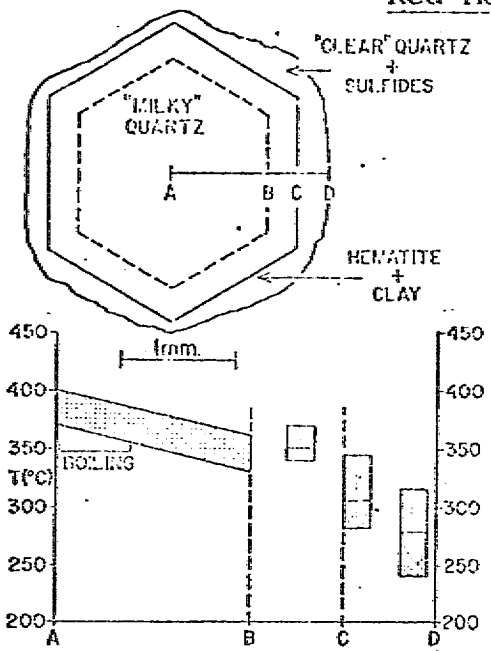

Figure 6. Typical spatial and temperature relationships in a single vein at Red Mountain, Ariz (Bodnar & Beane, 1977).

1. Early cloudy quartz crystal overgrowths formed from low salinity fluids which showed initial boiling near 400°C.
2. Later clear quartz overgrowths showing saline fluids and sulfide inclusions.
3. General temperature decrease with time.

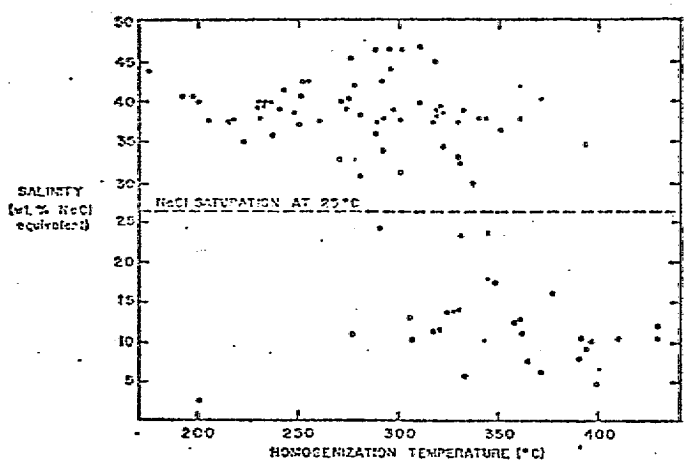

Figure 7. Two types of fluids present (Bodnar & Beane, 1977).

1. Early low salinity
2. Late high salinity with metallization
3. General temperature correspondence of the two fluids
4. All less than 450°C

Temperatures are in good agreement with those predicted by computer modelling (Norton & Knight, 1977). Single veins may show reopening or continuous filling with intermittant growth.

Whim Hill Breccia Pipe, Santa Rita, N. M.

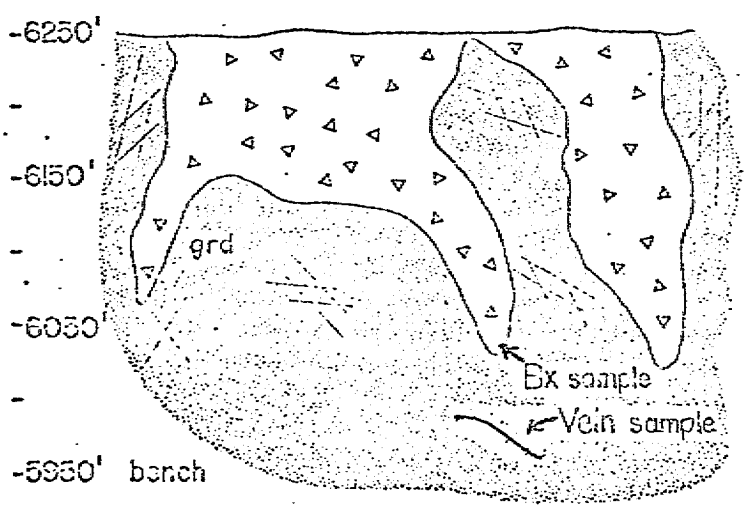

Figure 8. Sample locations at Santa Rita (Reynolds & Beane, 1979).

1. Qtz+orth+biot (chl)+apat vein indicated by isotope studies to be of magmatic origin-no primary metallization.
2. Qtz crystals showing overgrowths in the breccia pipe associated with orth+biot/chl+py+cpy.

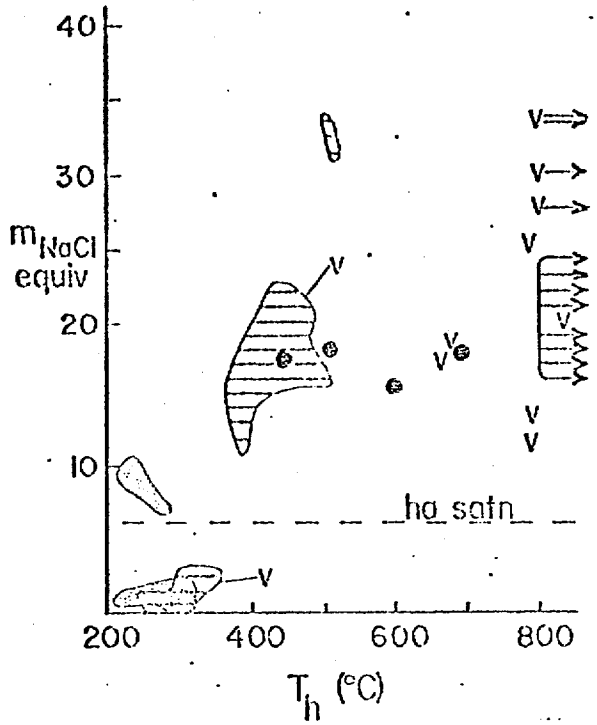

Figure 9. Three distinct fluids (Reynolds & Beane, 1979)

1. Early hypersaline at magmatic temperatures-vein
2. Intermediate hypersaline at moderate temperatures-vein and pipe
3. Late low salinity at moderate temperatures-vein and pipe. Associated metallization in pipe.
4. Very few inclusions of intermediate character.

The earliest fluids from the vein are considered to be magmatic. The highest temperatures in the breccia pipe are from a quartz substrate on which crystals grew. Mineralization appears to be associated only with a specific stage of late, low salinity fluids in the pipe, although Cu was present in high salinity fluids as evidenced by daughter products in some inclusions.

Breccia Pipes at Copper Creek, AZ

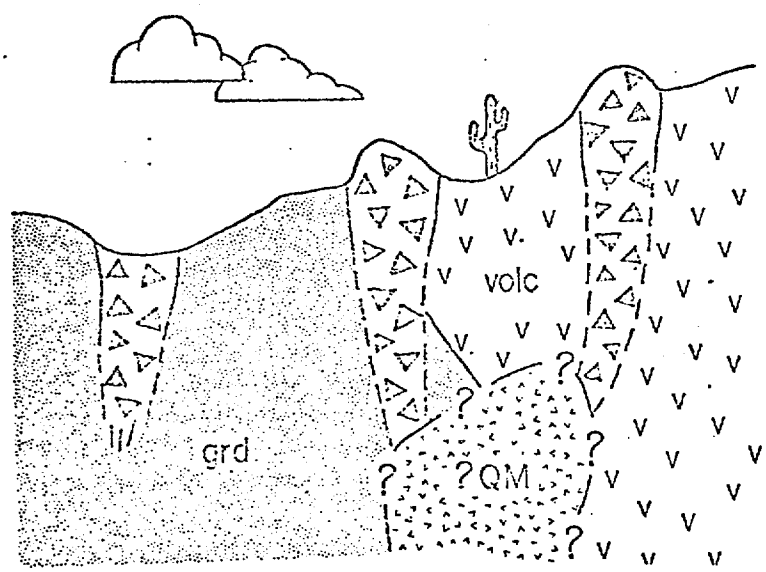

Figure 10. Sample locations at Copper Creek

1. In granodiorite, intruded Glory Hole volcanics and on the contact between the two.
2. Weak sulfide mineralization (cp, py, mo)
3. Question of buried, mineralized intrusive.

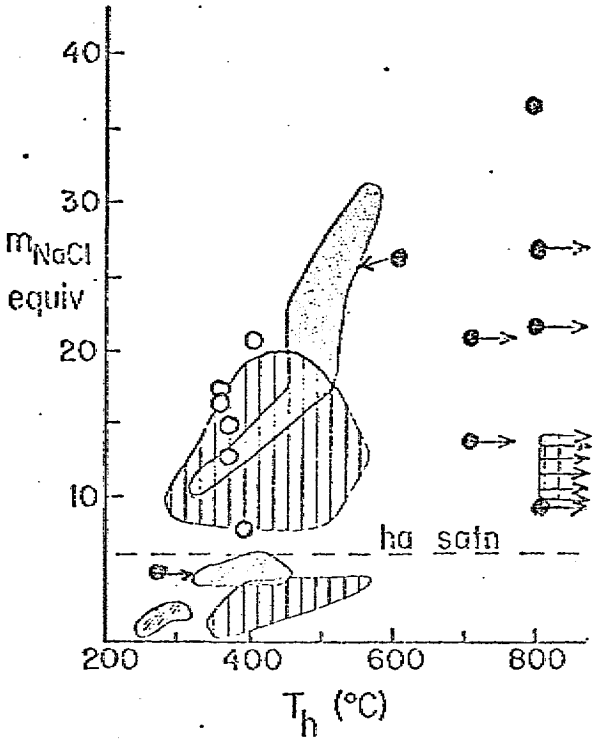

Figure 11. Three distinct fluids

1. Early hypersaline boiling at magmatic temperatures not present in all pipes.
2. Intermediate hypersaline at moderate temperatures-cpy, py daughter minerals-not present in all pipes.
3. Moderate temperature, low salinity-py, cpy in rock-present in all pipes.
4. Very few intermediate temperatures and salinities.

(Walker, 1979)

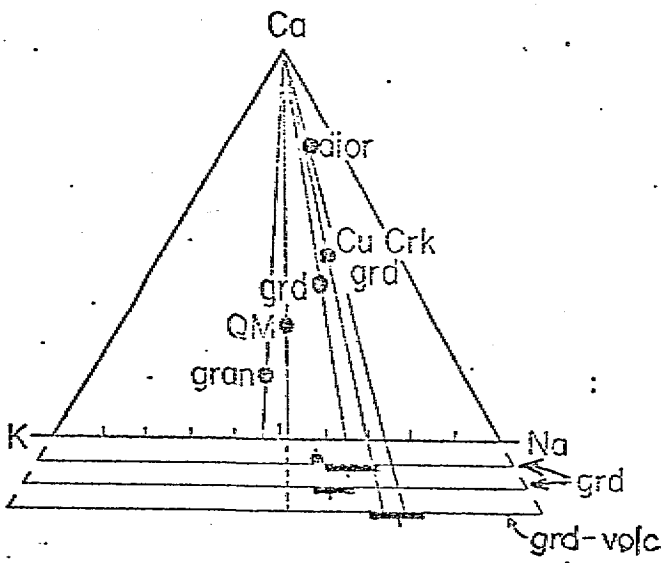

Figure 12. Correlation of fluid Na:K ratios with rock types.

1. General correspondence with enclosing rock type or slightly more potassic differentiate.
2. Could correlate with quartz monzonite.
3. Same for Santa Rita.

(Walker, 1979)

Boiling magmatic fluids occur as earliest stage, followed by cooler but equally saline fluids, and finally low salinity but very little temperature change. Na:K ratios in saline fluids generally correspond to nearby igneous rock types.

Sierrita in Harris Ranch QMonz and Biot Qtz Diorite

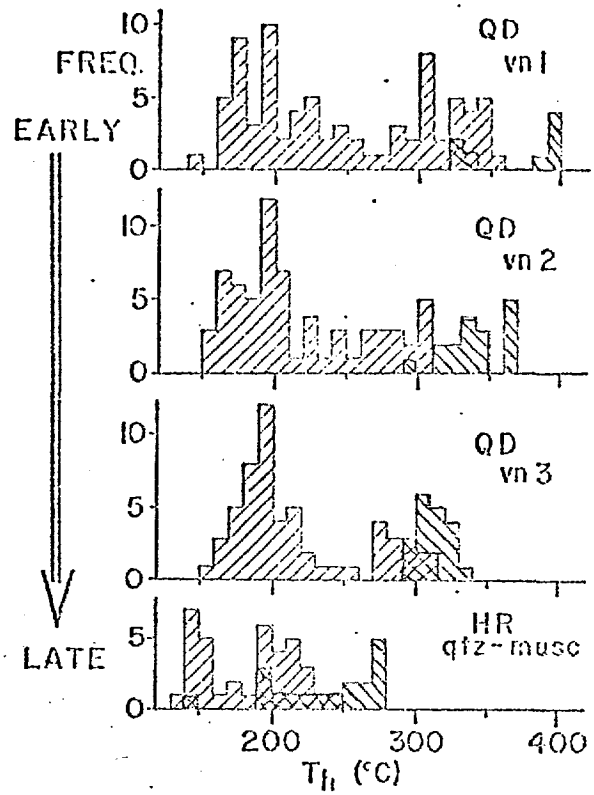

Figure 13. Primary and secondary inclusions

1. Characteristic primary inclusions.
2. Repeated reopening forming secondary inclusions.
3. Correlate with alteration and mineralization.

(Preece & Beane, 1979)

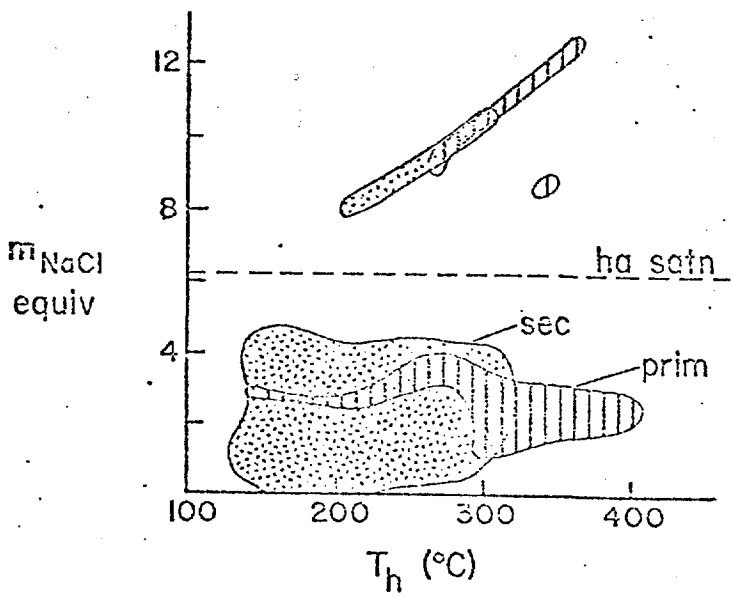

Figure 14. Two types of fluids

1. Early saline - rising temperature.
2. Several stages of later fluids with decreasing temperature, boiling at ~420° and constant low salinity.
3. Sulfides at 300-350°C and 140° from later, low-salinity fluids.

(Preece & Beane, 1979)

An early saline fluid was followed by low salinity fluids with which sulfides are associated. Different alteration assemblages can be correlated across rock types using fluid properties. No high temperature fluids are seen thus far. These relationships will be discussed in detail by Preece (this vol.).

Summary

1. Three types of fluids are seen and can be distinguished chronologically. Very little evidence of transition between successive fluid types are recorded by fluid inclusions.
2. Early hypersaline fluids, sometimes boiling, are seen at magmatic temperatures in the breccia pipes.
3. Both the early high and later moderate temperature saline fluids from breccia pipes may contain sulfides as daughter products, but except in the case of molybdenite, no sulfide minerals are deposited in enclosing rocks.
4. Mineralization in the breccia pipes and Sierrita is associated with late, low salinity fluids at moderate temperatures.
5. Only at Red Mountain are sulfides associated with hypersaline fluids, but here the low salinity fluids are earlier.
6. Na:K ratios of hypersaline fluids appear to correspond with enclosing rock types.

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MESOSCOPIC AND MEGASCOPIC FRACTURE AND DIKE PATTERNS ASSOCIATED WITH LARAMIDE PORPHYRY SYSTEMS OF SOUTHWESTERN NORTH AMERICA

Tom L. Heidrick

Studies integrating the temporal, petrochemical, and structure-tectonic character of Late Cretaceous-early Tertiary (Laramide) igneous activity in southwestern North America (Heidrick, 1975; Heidrick and Titley, 1976) suggest that at circa 80 m.y.BP, Andean- or mature island arc-like magmatism spread rapidly inboard across the American Southwest to the present Rocky Mountain front (Figs. 1 and 2). In the wake of this expanded arc orogen, 75-50 m.y.BP epizonal calc-alkaline plutons repeatedly experienced requisite physical and chemical conditions conducive to the localization and preservation of porphyry Cu-Mo alteration-mineralization. Although many details concerning the structure-tectonic control of porphyry copper localization remain obscure and a much debated issue, the inescapable conclusion of most workers in the American southwest is that the entire area experienced a major tectonic transition concurrent with the surge of Campanian, Maestrichtian, and Paleocene Cu-Mo-Zn-Pb-Ag metallization (Fig. 1). Unambiguous detail of this remarkable transition are discernable through tedious local and regional analyses of mesoscopic and megascopic structural elements spatially and temporally restricted to intrusive centers scattered throughout the Laramide arc orogen.

Results of our preliminary structural analysis of mesoscopic joint sets, veins, dikes, and faults in eight nonproductive Laramide stocks and three porphyry copper deposits in Arizona were reported earlier (Rehrig and Heidrick, 1972). This preliminary analysis entailed the statistical treatment of about 15,000 high-angle mesoscopic structures employing conventional Schmidt equal-area projections and resultant strike histograms. More recently, Heidrick (1974, 75) expanded this data set to include 7 additional strategically located nonproductive and ore-related systems in Arizona and New Mexico bringing the total number of mesoscopic elements examined to over 50,000. These data are summarized in synoptic fashion according to nonproductive, ore-related, and productive (pits) on Figure 3(a-i). The importance of these data and a few of the more salient conclusions concerning the nature of the Laramide framework and which elements of that frame influenced the preferential localization of Laramide Cu-Mo metallization throughout the province include:

1. Mesoscopic dikes and unmineralized fracture sets within nonproductive and ore-related Laramide plutons are systematically oriented in a relatively simple motif. This motif is dominated by a subvertical system of orthogonal fractures and dikes striking ENE$\pm 20^{o}$ and NNW$\pm 20^{o}$ (Fig. 3a, b). Although not shown on Figure 3, the NNW$\pm 20^{o}$ maximum is statistically a double maxima with discrete sets striking N10^{o}W$\pm 5^{o}$ and N30^{o}W$\pm 5^{o}$.

2. Mesoscopic mineralized fracture sets within both nonproductive and ore-related plutons are systematically oriented in a statistically monotonous pattern dominated by subvertical double maxima striking N60^{o}E$\pm 5^{o}$ and N80E$\pm 5^{o}$. These double maxima are particularly apparent on the synoptic strike frequency rosettes shown on Figure 3 (d,e).

3. Subordinate but statistically real subverical joints sets with maxima of N70°W (Fig. 3a,b,d) and N20°E (Fig. 3a,b) are likewise locally significant.

4. In marked contrast to the above, our mesoscopic fabric analysis of three porphyry copper deposits (Sierrita, Bagdad, and Mineral Park) delineates a somewhat diffuse NNW±15° maximum for unmineralized joint sets (Fig. 3c) while mineralized joint sets are dominated by a subvertical orthogonal system striking ENE±10° as well as NNW±10° (Fig. 3f).

5. Synoptic plots for veins, multiple veins, fault-veins, and faults show maxima of N70°E±10° (dominate) and N75°W±10° (moderate) in the six nonproductive plutons examined. In contrast, ore-related plutons show the monotonous repetitive ENE-trending double maxima (Fig. 3h), while the porphyry copper deposits are pervaded by fault and veins dominately trending ENE±10°, with subordinate maxima of N70°W±5° and N10°W±10°.

6. As frequently emphasized in the literature, rocks of porphyry copper deposits are typically broken on a very fine scale. Our Schmidt plots and strike histograms demonstrate convincingly that fracture sets within the productive plutons have a definite tendency to "box-the-compass" in a somewhat more haphazard fashion than those found in barren and ore-related plutons (cf. Fig. 3d,e,f). This implies that fractures of local derivation do exist and are superimposed as radial and concentric patterns on the more regional bidirectional systems.

7. A review of published accounts by other authors provides supporting evidence for similar structure in many other Arizona and New Mexico porphyry copper deposits. In most instances, the ENE±20° set(s) has exerted by far the dominant influence over ore localization at mesoscopic levels of observation. Clearly, this repetitious orthogonal ENE and NNW fracture system is regional in extent, and not restricted temporally or spatially to specific plutons or local domains within the province.

8. Temporal control provided by radiometric dating of each studied pluton indicates that the regional motif of mineralized fractures and dike swarms developed in response to a widespread stress field that persisted for at least 25 m.y. (viz. 75-50 m.y.BP). Continued reactivation of the fundamental bidirectional elements of the Laramide frame throughout this time period, explains the preferential ENE and NNW elongation of composite intrusions across the arc orogen.

9. Field relationships typically preclude the quantitative definition of strike, dip, or oblique slip components along measured mineralized and unmineralized elements. However, as noted elsewhere, the repeated presence of horizontal to subhorizontal slickensides along elements of ENE-trend were evident in every pluton studied (Rehrig and Heidrick, 1972, p. 211). In this context, the persistent double maxima of N80°E±5° and N60°E±5° strike and their contained subhorizontal slickensides, are certainly in part a direct product of conjugate shearing under conditions conducive to the development of small dihedral shear angles (20-25°).

10. The near perfect distribution of mutually perpendicular mineralized joint sets (Fig. 3f) and dikes (Rehrig and Heidrick, 1972), prohibits a conjugate shear origin for this brittle (extensional) fracture system.

11. Wholesale NNW-SSE-directed extensional stresses were the rule during crystallization, cooling, and mineralization of each respective Laramide pluton examined. The most obvious product of this extension is mirrored by the repetitious pattern of near vertical ENE±20°-trending

dilatant structural elements including mineralized joint sets, veins, multiple veins, dike swarms, and fault-veins. This plane of maximum extension fixes the minimum principal stress (σ_3) as horizontal and oriented NNW$\pm$20^o throughout main stage porphyry copper metallization (75-50 m.y.BP, Fig. 1). This orientation of σ_3 in turn fixes the maximum principal stress (σ_1) within a vertical plane striking ENE$\pm$20° during the orogeny.

12. A review of brittle fracture criteria, experimental and theoretical rock mechanics, and the physical character of mineralized continuous planar structures suggest that most of these elements represent the dynamic consequence of hydraulic fracturing by fluid-saturated residual calc-alkaline magmas (Heidrick, 1974).

13. Application of the effective stress laws governing failure by hydrofracturing mechanisms in concert with recognition of the N60^{o}E and N80^{o}E double maxima as products of conjugate shearing of very small dihedral angle (extension), and presence of bidirectional-orthogonal directions of coeval extension (ENE$\pm$20^o and NNW$\pm$20°) leads one to a unique and unambiguous definition for the orientation of σ_3 and the plane containing σ_2 and σ_1.

14. Provided the mesoscopic intra-plutonic structures mirror larger scale elements of the Laramide framework and established dynamics of faulting hold, wrench tectonics should pervade the porphyry province when σ_2 is vertical. During those periods when σ_1 is vertical, differential vertical uplift and normal faulting tectonics should dominate. Low-angle compressional thrust faulting is not expected under the proposed Laramide stress field, unless driven laterally as a secondary consequence of convergent wrenching, differential uplifting (upthrusting), or propelling off prominent uplifts under the influence of gravity.

Additional documentation of the proposed stress field, its regional character, and relevance in localizing porphyry systems throughout the Southwest is provided by our synthesis of megascopic structures temporally and spatially associated with 24 Laramide districts scattered throughout Arizona and New Mexico (Fig. 4). Details of veins, dikes, elongate plutons, and fault-veins measured, construction procedures utilized, and other geologic details for 10 of the resettes included on Figure 4 are provided elsewhere (Rehrig and Heidrick, 1976). Each respective element measured was divided into 1,000 ft. strike segments, each segment's strike averaged, grouped into 10° class intervals, and plotted on percentage strike frequency rosettes. In total, these synoptic rosettes constitute over 1,250 miles of Laramide elements in Arizona and 725 miles in New Mexico.

A comparison of patterns delineated on Figure 3 with those evident on the synoptic strike frequency rosettes for high-angle megascopic elements (Fig. 4), show that both sets of data quantitatively share the same maxima in great detail. In particular, megascopic strike maxima show a marked statistical preference for NE to E strikes over an area measuring tens of thousands of square miles. Regional control over Laramide intrusive emplacement, the localization of productive systems, and the orientation of metallized structures therein, is apparent at all scales of observation. This is likewise apparent provencially in that most known porphyry copper systems are systematically distributed either along the axis of the NNW-trending Southwest arc orogen or sympathetic to transverse dilatant porphyry-mineral belts of ENE strike (Fig. 5).

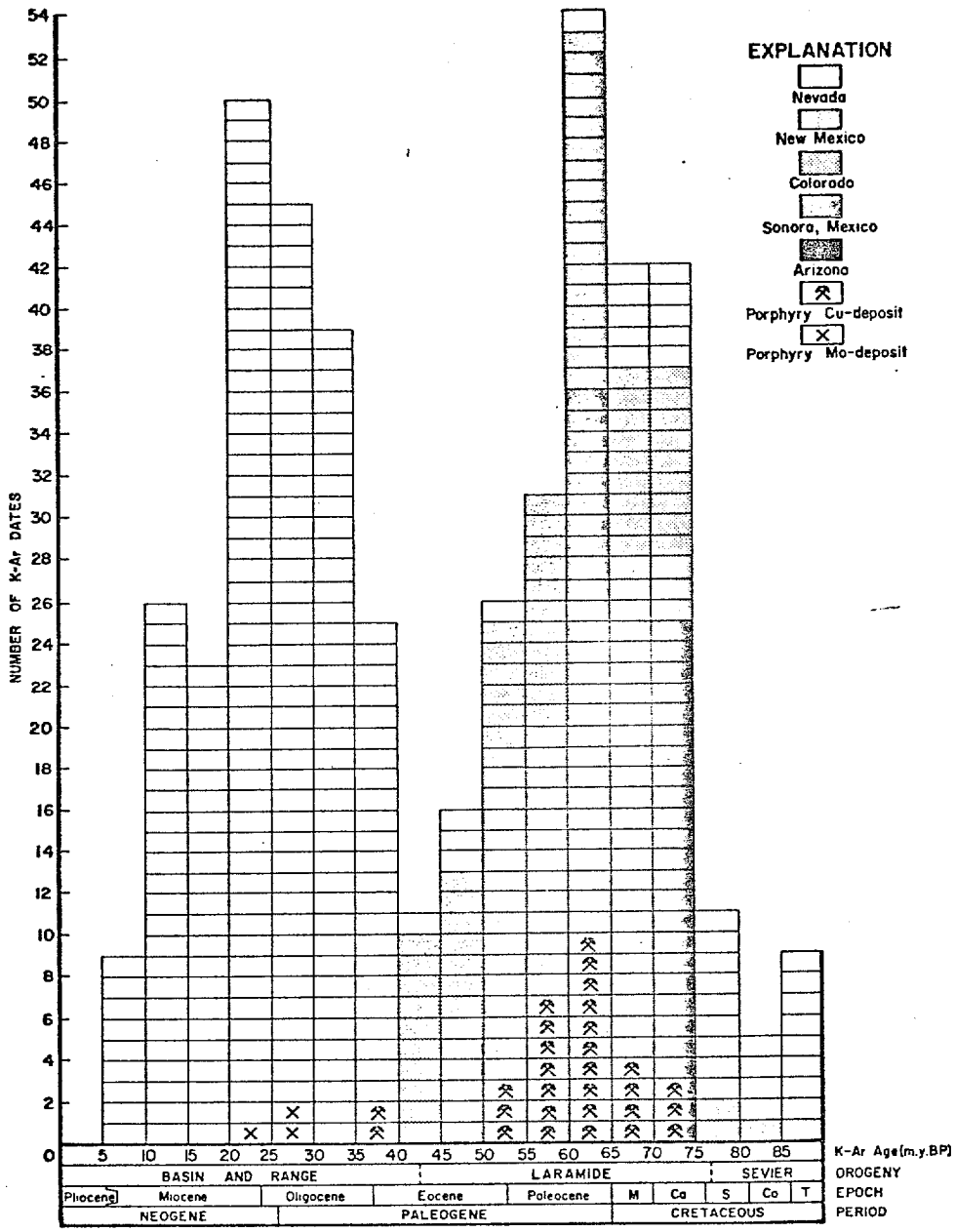
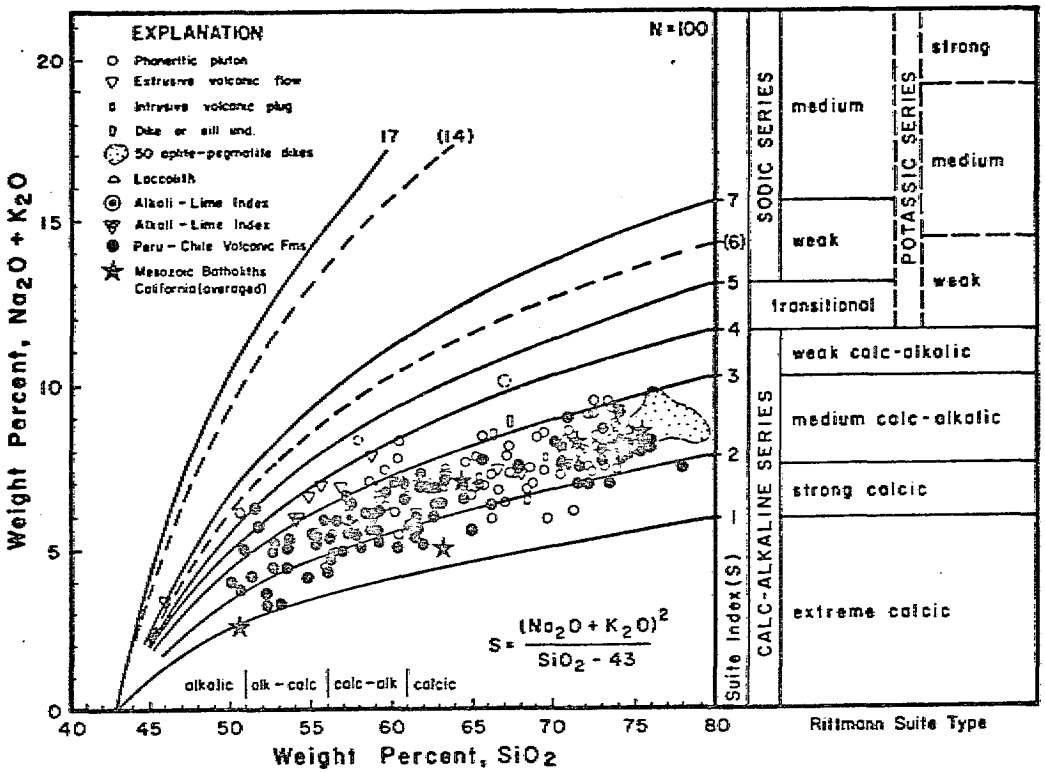
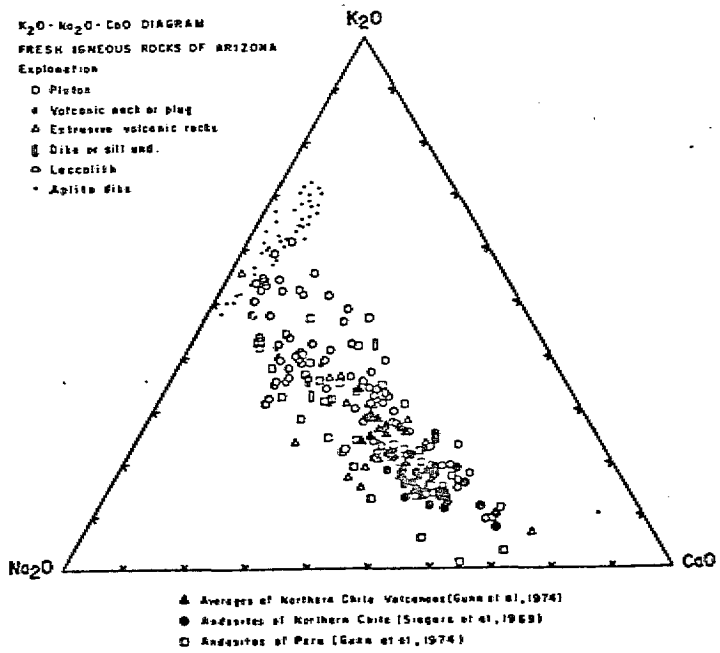


Figure 1. Histogram of K-Ar Ages from Igneous Rocks, American Southwest. -- Plotted data are from hypabyssal plutons and volcanic rocks or their hydrothermally altered equivalents. The post-40 m.y. BP portion of the histogram is after Damon (1971).



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).

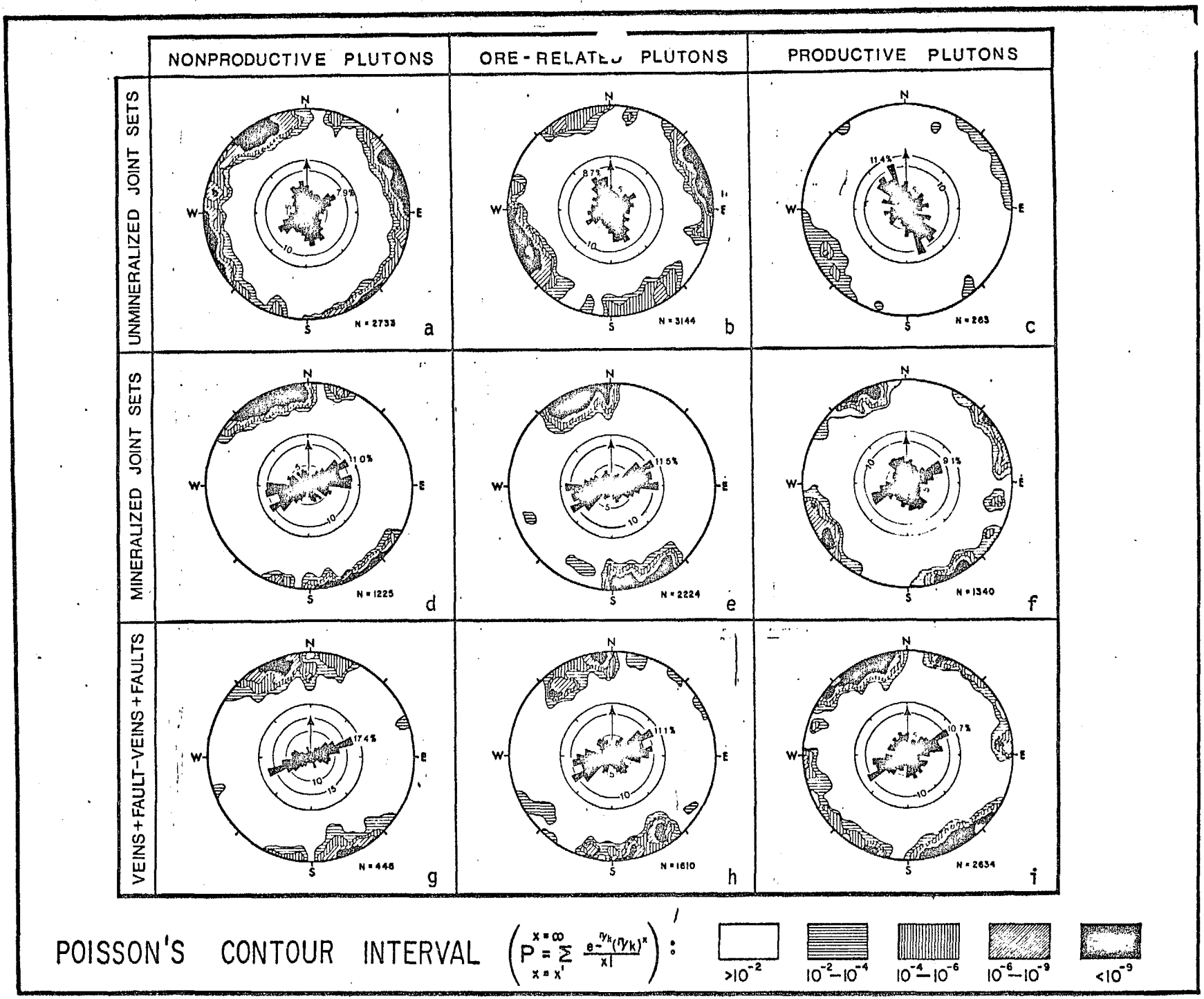
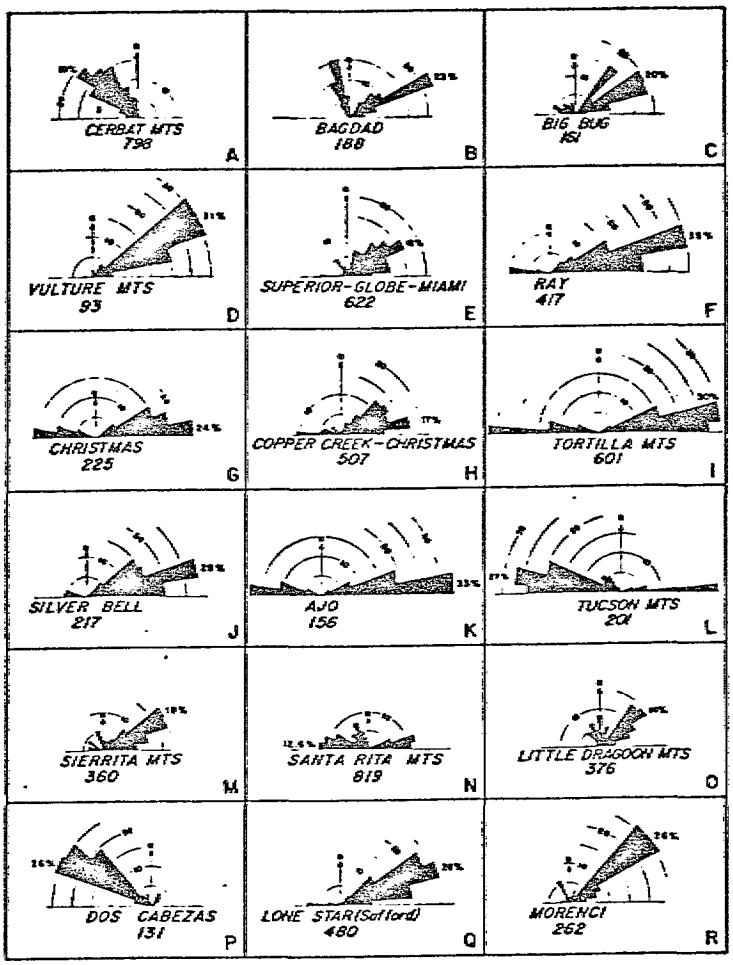


Figure 3. Synoptic lower hemisphere Schmidt equal-area nets and strike histograms of total joint sets (unmineralized, a-c; mineralized, d-f) and veins, fault-veins, and faults (g-i) measured in 6 non-productive, 9 ore-related, and 3 productive Laramide plutons in Arizona and New Mexico.

ARIZONA



NEW MEXICO

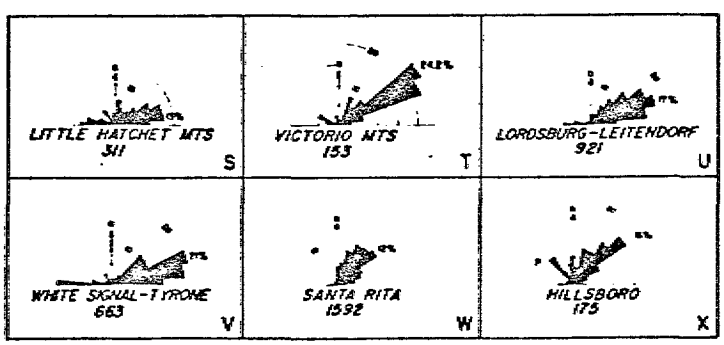
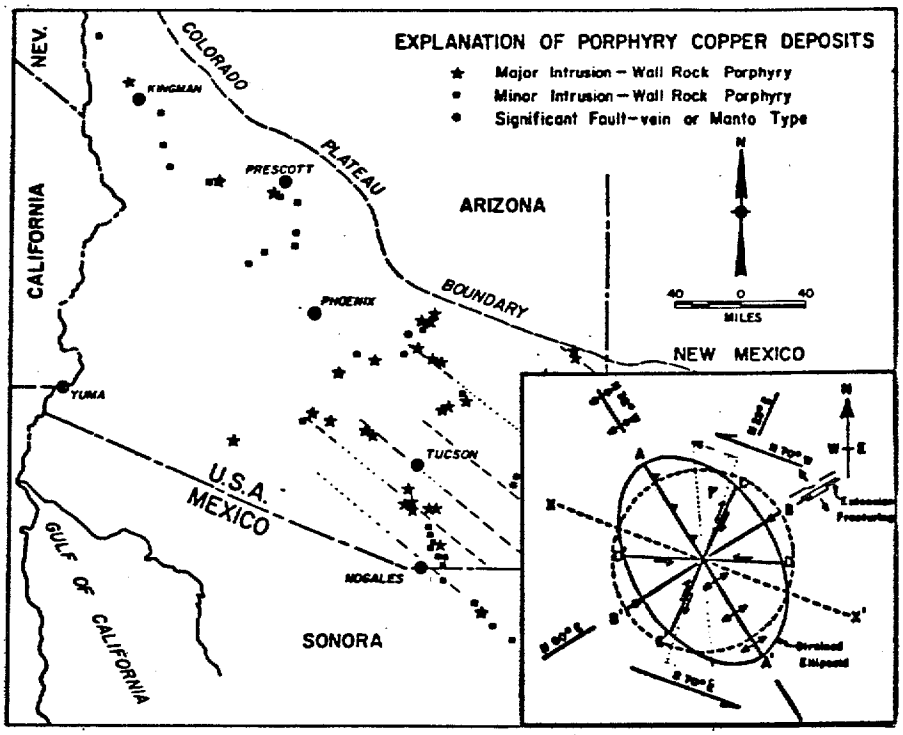
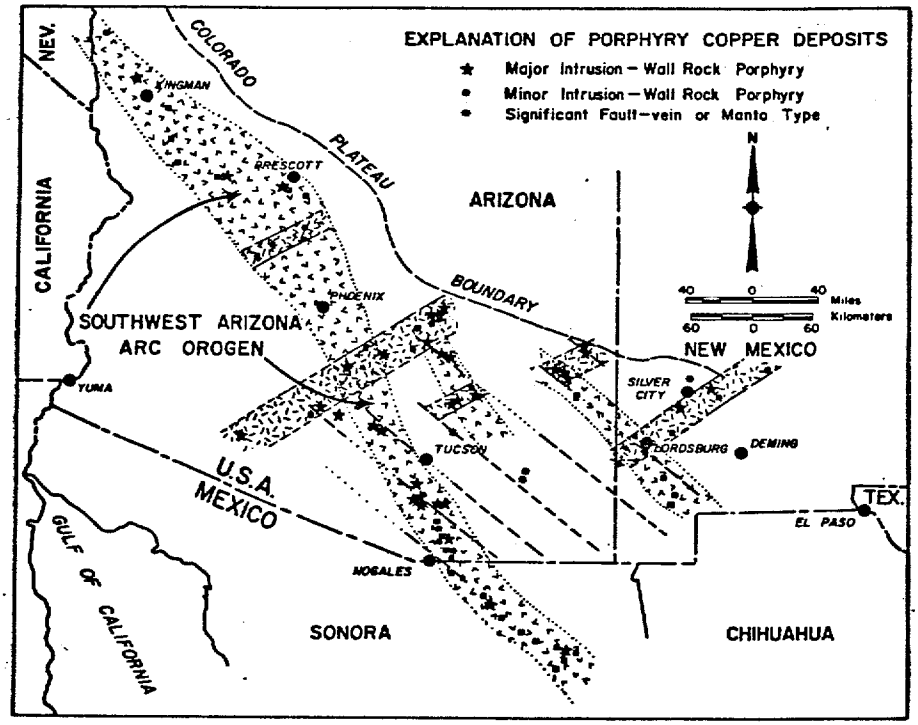


Figure 4. Arizona and New Mexico strike rosettes for Laramide dikes, elongate plutons, veins, and fault-veins. Rosette bars are constructed for 10^{0} class intervals. Length of strike bars are proportional to percentage of total elements measured. The number of elements plotted is indicated beneath each respective plot.



5a.



5b.

Figure 5. Laramide volcano-tectonic framework of southwestern New Mexico and southern Arizona showing the distribution of major and minor porphyry deposits (5a), derived intermineral paleostrain field (5a, inset), position of inferred composite Andean arc orogen, and several transverse ENE-trending porphyry breaks (5b). The NW-trending linear discontinuities are adapted from Titley (1976).

more lead and gold rich, and, to some extent, silver rich. Similar data treatment of fluorine contents in igneous biotites reveals an increase in fluorine content of biotite with increasing alkalinity of the rock suite that contains biotite. Significantly, fluorite is a common gangue mineral in mineral deposits associated with alkalic rocks.

In this respect, southeast Arizona-southwest New Mexico copper porphyries (and copper porphyries in general) are part of a metallogenic spectrum which is sensitive to alkalinity of the associated magmatic rocks. This suggests that major and trace-element chemistry of magmas and metal chemistry of associated sulfide systems may be interrelated and that magmatic rocks might be a source of metal. To test this hypothesis, I am currently assembling trace metal data in igneous rocks of various alkalinities. Data in Table 3 are selected chemical data on igneous rocks taken from Turekian and Wedepohl (1961) and arranged according to increasing potash content. It is clear from the table that trace metal contents of igneous rocks are qualitatively similar to those of higher concentration in sulfide systems associated with magmas of the same general chemistry (compare data of Table 2 and 3). This strongly implicates magmas as a source of the metals. Also implied is that metal chemistry, like potassium chemistry of magmas, is systematically related in depth to an inclined seismic zone. Thus, in any given subduction complex where suitable chemical and metallogenic data are available, specific trench-parallel, magma geochemical belts and metallogenic belts may be defined.

In southwestern North America, Keith (1978) showed that during Laramide orogeny in the southwestern Cordillera, a continentward shift of magma geochemical belts occurred (Figure 1a). Within the area of the porphyry copper cluster in southeast Arizona and southwest New Mexico, a lead-zinc-silver belt, associated with high potassium calc-alkalic magmas, swept eastward through the area of the future porphyry copper cluster between 80 and 70 m.y. ago (Table 4). The belt returned in a westward sweep between 30 and 20 m.y. ago. In the interim (70 to 50 m.y. ago), the region was occupied by cal-alkalic plutonism and associated copper porphyries. The magmas mentioned above, intruded the same host-rock geology. However, the magmas were associated with sulfide systems of distinctly-different metallogenic characters, another indication of the strong chemical correlation between magma and metal chemistries.

Another aspect that the southeast Arizona-southwest New Mexico porphyry cluster shares with other high-metal volume, clustered sulfide systems is its occurrence in a plate tectonic setting of flattening underthrusting oceanic slabs. This is suggested chemically by examination of chemical changes of magmatic rocks within a given region over time. As shown by Keith (1978), magmas become more calcic with time within any given district of the porphyry copper cluster. This suggests that the depth to the inferred locus of magma generation progressively shallowed with time, and strongly implies a flattening oceanic slab under Arizona-New Mexico continental lithosphere between 80 and 50 m.y. ago. Analysis of suitable chemical data in other subduction settings (Greater Antilles, Solomons Arc and western New Guinea) reveals strikingly similar patterns. In each case an early "barren", more alkalic phase of magmatism preceded porphyry copper mineralization, which is consistently associated with more calcic igneous rocks. Age data for the British Columbia cluster shows an eastward sweep of magmatism from 80 to 55 m.y., very similar to the continentward march of plutonism in the southwest Cordillera through Arizona and New Mexico. Age data for younger Miocene-Pliocene age plutonism in New Guinea also shows a continentward sweep of plutons away from an inferred trench along the northern coast of New Guinea. Thus, chemical, spatial and age data suggest that porphyry clusters in British Columbia, southwestern United States the greater Antilles, Solomon arc and western New Guinea are all associated with regimes of shallowing subduction.

Spatial, Temporal, Chemical and Structural Evolution of the Southeast Arizona-Southwest New Mexico Porphyry Copper Cluster.

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The southeast Arizona-southwest New Mexico porphyry copper cluster is one of the great metallogenic regions on earth. Production and potential reserves (extrapolated to .2%) are over 170 x 10^6 tons of copper metal, making the province the greatest copper concentration on the planet. Naturally, such an anomalous metal concentration demands explanation and the literature is replete with virtually every scenario imaginable. The porphyry copper province is unique and requires a unique explanation. This paper represents yet another attempt to find explanation by synthesis of spatial, temporal, chemical, structural and plate tectonic observations about the southeast Arizona-southwest New Mexico province and its copper porphyries. It will be argued that the porphyries resulted from a unique coincidence of tectonic and chemical conditions which served as antecedent conditions for the porphyry copper occurrence. Once the coincidence of these antecedent conditions was achieved, the porphyries were inevitable. Without these conditions, the porphyries would have been impossible. The porphyries are, in effect, a plate tectonic accident which occurred in a small area of the southwestern North American Cordillera about 65 m.y. ago during the climax of the great Laramide orogeny.

The southeast Arizona-southwest New Mexico copper porphyries share several similar traits with other porphyry copper clusters and perhaps clustered sulfide systems in general. Like other porphyry coppers, those of southeast Arizona and southwest New Mexico are exclusively associated with calc-alkalic rocks as defined in Table 1. The southeast Arizona-southwest New Mexico porphyry coppers are emplaced into Precambrian sialic continental crust and are generally associated with slightly more alkalic calc-alkalic magmas ($K_{57.5}$ = 1.6 to 2.5) than counterparts in island arcs built on comparatively young oceanic crust (most are from 0.4 to 2.0). Both porphyry copper sulfide systems and associated magmas occur in plate tectonic settings where subduction of oceanic crust is directly demonstrable or strongly inferable.

It has been recognized for years (particularly in Japan) that magmatic arcs in subduction settings become progressively more alkalic (specifically more potassic) and less calcic with increasing distance away from the trench. The increasing potash content of these magmas has been correlated empirically with depth to the inferred seismic zones by Dickinson and Hatherton, 1968 and Dickinson, 1975. The rock classification in Table 1 attempts to take the depth correlation into account. If the correlation is valid, major implications for magma genesis (and metal genesis) are suggested.

Comparison of production and reserve data for sulfide systems associated in space and time with magmas of a specific alkalinity (denoted by the $K_{57.5}$ index among others) strongly suggests that metal ratios in a given sulfide system might change with the alkalinity of the rock suite. Table 2 is a preliminary summary based on comparison of sulfide system metal ratios with the alkalinity of spatially and temporally-associated magmatic rocks where suitable age, metal-abundance data and chemistry were available for subduction-related mineral deposits. Generally, zinc and copper content decreases with increasing alkalinity, while lead and gold content increases with increasing alkalinity. Silver may increase and then decrease with increasing alkalinity. Changes in ratios seem particularly evident near $K_{57.5}$ = 2.5. Below 2.5 copper and zinc predominate while sulfide systems above 2.5 are distinctly

Supplementary figure - S.B. Keith Abstract
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Figure 1'

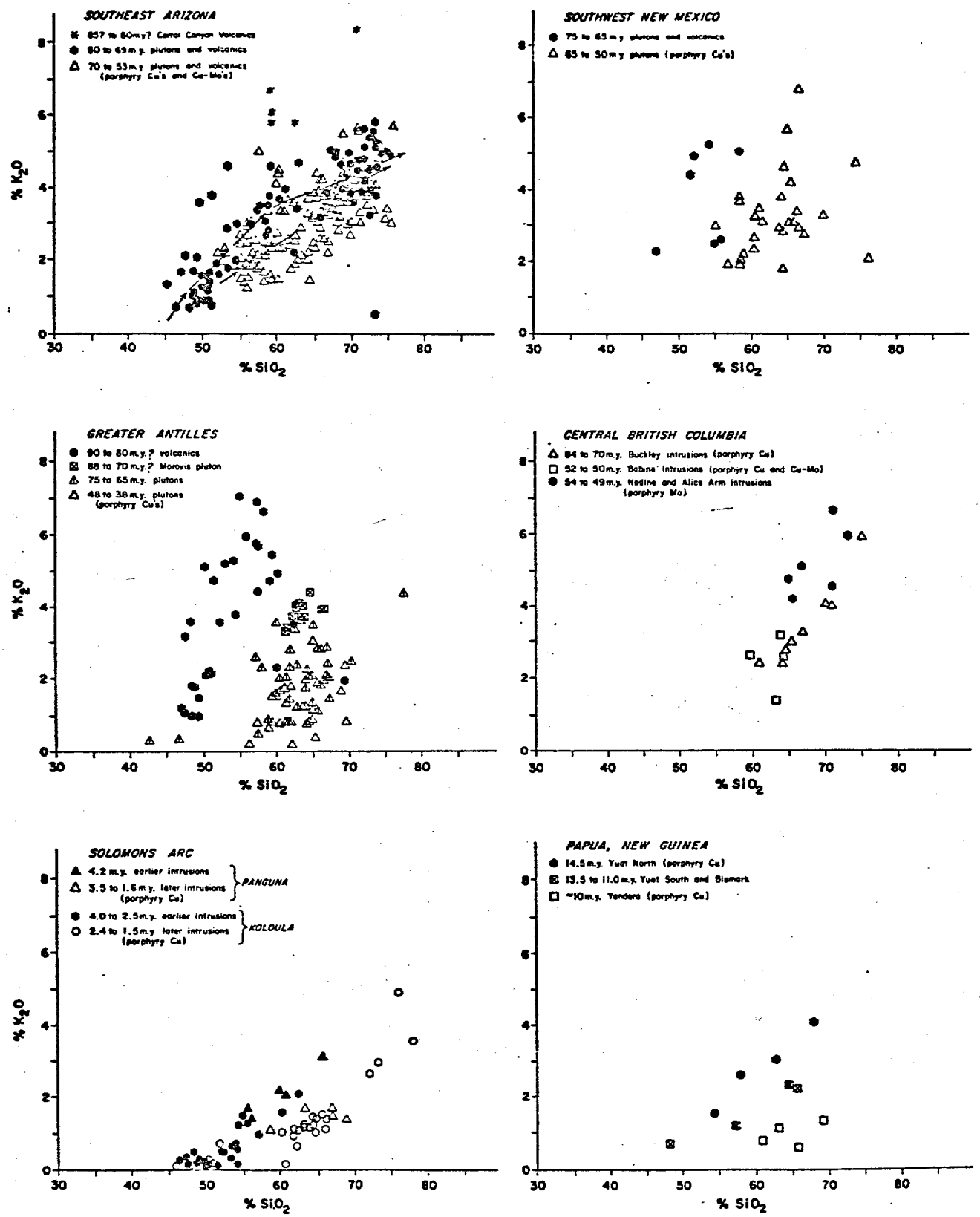

Figure 1': K_2O/SiO_2 Harker variation diagrams for igneous rocks associated with porphyry Cu-Mo deposit clusters.

If Benioff zone dips are related to convergence rates in the manner of Luyendyk (1970), i.e., shallow dips imply higher convergence rates, then porphyry clusters (and perhaps sulfide clusters in general) are related to subduction zones where high convergence rates occurred. This would be logical in that higher convergence rates imply higher magma (and metal) generation rates. It is significant that the greatest volume of metal emplacement in Arizona and New Mexico (see Table 4) occurred when convergent rates were anomalously high (about 14 cm/yr, if the analysis of Coney (1976), is correct). Indeed, 80 to 40 m.y. ago, orogenic belts throughout the world were mineralized on an unprecedented scale.

What sets the southeast Arizona-southwest New Mexico porphyry copper cluster apart from other porphyry clusters is its unique structural setting. Like many of the South American porphyries, those of Arizona and New Mexico are found entirely within Precambrian continental crust. The cluster itself is entirely contained within the notorious and unique Texas zone which is at least 1,200 m.y. old (Swan, 1976). Analysis of structural developments within the Texas zone from 90 to 40 m.y. ago reveals that complex, shifting tectonic patterns took place. These are depicted schematically in Figure 2. From 120 m.y. to 90 m.y. ago plutons and tectonism remained west of the porphyry cluster. Plutonism was centered in the coastal batholith complex of southern California and gradually crept eastwards in a regime of constant dip subduction (Keith, 1978). Approximately 90 m.y. ago, convergence rates began to increase, and plutonism and deformation swept eastward at a progressively-accelerated pace as the subduction zone began to flatten. In southeast Arizona the eastward march of tectonism and plutonism (which moved eastward at different rates) was marked by rapid retreat of the Bisbee sea, a former early to mid-Cretaceous marine ~~incursion~~ INCURSION. In the wake of the marine regression east-west and west-northwest-aligned basement-cored or wedge style uplifts arose along reactivated west-northwest and east-west striking structural elements of the Texas zone 90 to 75 m.y. ago. The uplifts were achieved under the influence of NNE-SSW compression. Uplift of the basement cores was accompanied by fluvial deposition of coarse, well-rounded conglomerates and the accumulation of local fresh-water ponds in basins immediately adjacent to the uplifts. During the later part of this stage, high potassium alkali-calcic and high potassium calc-alkalic magmatism appeared. The magmatism was marked by widespread fields of pyroclastic trachyandesites and ignimbritic ash flow welded tuffs, indicating that the volcanic expression of this magmatism was very violent and could reflect high amounts of tectonic overpressure in and near surface magma chambers. Sulfide systems co-eval with this magmatism were lead-zinc-silver rich (Table 4).

From 80 to 65 m.y. ago, deformational fabrics indicate regional, compressive stress changed from NNE-SSE to ENE-WSW. The reason for this change is unclear, but it may have had something to do with changing-plate motions which occurred on a global basis nearly 80 m.y. ago (Coney, 1972). The change in regional compressive stress evolved basement-cored uplift tectonic styles into wrench fault tectonic styles. Elements of the Texas zone, which formerly had moved in reverse slip, later moved in oblique slip and, by 65 m.y. ago, were moving in left slip. ENE-WSW regional compressive stress in southern Arizona-southern New Mexico after 65 m.y. ago was distributed across a diffuse 300 to 400 km-wide zone of WNW to E-W striking faults. The net effect was to subject the province to a regionally-distributed left shear. In many places, the lithosphere failed in tension rather than shear. Regional deep-seated tension fissures opened up and provided areas of low tectonic pressure which were rapidly filled by dikes and metal-bearing volatiles.

The shift to left shear, wrench-style tectonism near 65 m.y. ago in southeast Arizona (near 55 m.y. ago in southwest New Mexico) had a decided effect on pluton geometries. Prior to 65 m.y. ago, plutons tended to assume a laccolithic shape.

The general mode of emplacement was for a pluton to ascend a west-northwest-trending fault which commonly had pre-pluton vertical offset. When the pluton encountered preserved, down-thrown stratigraphic layers, it moved laterally rather than vertically, resulting in a large laccolithic sill with a dike-like root which presumably tapered downward. Outstanding examples of this style of intrusion are found in the Catalina Mountains immediately north of Tucson. After 65 m.y. ago, dike forms predominated. Individual dike swarms may be up to 60 km long and may be traced through a vertical profile of over five km in areas where strong post-Laramide block rotation around sub-horizontal axes has occurred (see subsequent discussion).

From 75 to 65 m.y., the subduction zone continued to flatten, and magma, metal and volatile generation rates greatly increased. Successively, more calcic and copper-rich batches of parent magma rose from zones of partial melting at the subduction zone-asthenosphere interface (Figure 2a). Higher than normal strontium isotopes (.706 to .708) suggest these magmas may have mixed with more radiogenic sialic crust in another zone of partial melting at the base of the continental lithosphere. It is possible that the sialic crustal component may have modified the metal contents slightly by adding more molybdenum and diluting the gold content. Pursuant to these mixing modifications at the base of the continental lithosphere, the magmas moved into the middle crust and evolved metal-bearing hydrothermal fluids. Evolution of these fluids induced freezing of the magma in the mid-crust while the metal-bearing fluids ascended into the upper crust to ultimately become the great porphyry copper deposits between 65 and 50 m.y. ago. 'Drier' plutons rose higher into the crust and formed many of the plutons we see today. While these plutons had the same chemistry as the presumed 'wetter' counterparts which had crystallized at deeper levels in the crust, they were not the direct source of the metals.

From 55 to 45 m.y. ago, continued slab flattening ultimately occluded further magmatism, but not before a unique assemblage of peraluminous muscovite granites was produced. These granites are common within the crystalline cores of the recently-recognized metamorphic core complexes (Crittenden and others, 1978). Higher initial ratios (.711 or more) suggest that at least twice as much sialic and radiogenic crust was involved in formation of the muscovite granite. The lack of any more mafic inclusions, border phases, or intrusive phases also suggest a higher crustal contribution. Intrusion of the peraluminous granite suite marked the end of the great copper metallogenic event. No significant metallization of any kind has been proven to be related to these unique intrusions. Immediately after intrusion the oceanic crust is inferred to have been in direct contact with the overriding continental lithosphere. Hence, the muscovite granites were intruded when convergent rates were approaching their highest value. In this context it is reasonable to suggest that the continental crust was under very high regional compressive stress. The pervasive low-angle mylonite fabrics, which invariably are extensively developed in areas of muscovite granites may record this compression. Heat from the intruding plutons triggered a pervasive regional mylonitic shearing. The omnipresent shallow-plunging ENE-WSW lineation phenomena present in the mylonite gneisses records the direction of regional compressive stress present in the crust when the muscovite granites intruded.

Several facets of the chemical and historical narrative just presented are relevant to debates about porphyry copper genesis. First, the systematic relationship of production and reserve data for economic sulfide systems to specific igneous chemistries suggests that magmas are sources of metals. This is further supported by trace metal data in magmatic rocks which parallels that of higher metal concentrations in economic deposits. Second, clusters of high metal concentrations seem to be found in subduction plate tectonic settings of high convergent rates where underthrusting slabs seem to flatten. Both of the above points emphasize the broader vital role that subduction has to play for porphyry copper genesis, in particular, and cordilleran styles of metallogenesis, in general. This author

knows of no economic base or precious metal sulfide system which has proven links to Basin and Range-related basalt-rhyolite magmatism, i.e., magmatism not thought to be the result of subduction.

A third consideration is that metals present in porphyry coppers in southeast Arizona (and perhaps epigenetic sulfide systems in general) seem to have come from large plutons which crystallized in the mid-crust at depths of eight km or more. Two lines of evidence support this. First, Laramide age, vein and dike swarms in the northern Tortilla Mountains, 80 km north of Tucson, can be tracked several kilometers into the Precambrian basement. Here, a strong case can be made for post-Laramide eastward rotations of up to 90° around subhorizontal axes so that the current exposures are, in effect, a cross-section of the upper five km of the earth's crust. The tension cracks, filled by dikes and veins, indicate that the top (and perhaps up to eight km of Arizona crust in this area) was pervaded by open space cracks with apertures of up to ten meters. The second line of evidence is that calc-alkalic plutons, which appear at the level of the exposed sulfide systems, are not generally large enough to be direct sources for the high amounts of metal found in closely-associated sulfide systems. If it is assumed that the metals are related to the magmas, then a larger body which crystallized in the mid-crust is a logical source of metal (as in Figure 2). If these speculations are correct, then the metal portion of sulfide systems was transported by hydrothermal fluids which evolved in the mid-crust well below the interface with meteoric water. This, in turn, raises questions about the role of meteoric water and the development of the phyllic and argillic alteration assemblages which are common but not universal in the porphyry copper systems (Sierrita-Esperanza is an example where little or no phyllic alteration occurs). Possibly, phyllic alteration in many cases represents the independent superposition of a convection-driven meteoric geothermal system upon an earlier metal-bearing potassically propylitically-altered sulfide system. Possibly, some phyllic alteration is produced independently by convection circuits related to nearby drier plutons which intruded to the same high level as the sulfide system. Thus, phyllic alteration is not necessarily linked in a causal way to potassic alteration which is almost universally-associated with the copper mineralization. Indeed, many geothermal systems related to Basin and Range basalt-rhyolite magmatism may have extensive areas of phyllic and argillic alteration without any obvious evidence of base metal mineralization.

In the southern Arizona-southern New Mexico case, dry plutons and metal-bearing hydrothermal fluids had access to the same plumbing system. It is important that magmas originating under continental areas must have some sort of structural plumbing system to facilitate their upward passage. In this connection, an intriguing theory is that magmas might have risen from a subduction zone to the base of the crust under a comparatively structureless Colorado Plateau. Lacking an adequate plumbing system, they might have coalesced at the base of the lithosphere without ever ascending further. Thus, the conditions under the Colorado Plateau may have been similar from a subduction and magma point of view. However, lack of a deeply-penetrating system of basement flaws prevented the occurrence of any high-level magmatism and metallization that was so abundant along the southern margins of the Plateau province.

The regional geographic aspect of the dike and sulfide system also raises questions about the role of hydro-fracturing. While hydro-fracturing may be important in the cooling history of a given pluton, it is questionable that the earth's crust surrounding that pluton is systematically fractured by the same mechanism. The large area occupied by the dike and vein swarms suggest that a more regional tectonic force was at work, a force which may have involved diffuse left-shear wrenching of the earth's crust over the width of the Texas zone.

In summary, the following set of unique antecedent conditions coincided to create the great copper metallogenic event in southeast Arizona-southwest New Mexico 65 to 50 m.y. ago.

1) Subduction was present.
2) Increased convergent rates induced slab flattening and increased strain rates in the continental lithosphere.
3) The shallowing slab produced calc-alkalic copper-bearing magmatism under the region from 70 to 50 m.y. ago.
4) Preexisting WNW-trending Texas zone basement flaws reached through the brittle zone of continental lithosphere.
5) Left shear wrench-fault tectonics created deep-seated tension cracks to tap volatiles in the mid-crust 65 to 50 m.y. ago.

As a result of that fortunate sequence of events, the region's inhabitants find themselves with a very precious resource indeed.

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TABLE 1. NOMENCLATURE AND SELECTED CHEMICAL AND MINERALOGICAL PARAMETERS FOR ROCKS DISCUSSED IN THIS PAPER

Suite type this paper	Depth to inclined seismic zone in Km	K_2O slope character @ 40-65% SiO_2	$K_{57.5}$ index*	θ index*	S index*	K_2O/Na_2O @ 40-60% SiO_2	$Na_2O + K_2O$ @ 50-60% SiO_2	Peacock (1931) alkali-lime index	Iron enrichment (on AMF diagram)	Al_2O_3 content	Selected normative mineralogy	Selected model minerals
Calcic	80-120	0.0-.3% K_2O per 5% SiO_2	0.4-1.2	43-53	0.65-1.5	0.25	2.5-4.5	52-68 (calcic)	strong	high (14-18%)	Moderately quartz normative @ 50-60% SiO_2	Hornblende and biotite rare; no feldspathoids
Calc-alkaline	120-220	0.3-.8% K_2O per 5% SiO_2	1.2-2.4	39-49	1.3-3.0	0.25-.7	3.5-6.5	58-62 (calc-alkalic)	little or none	high (15-19%)	Moderately quartz normative @ 50-60% SiO_2	Biotite, hornblende, and orthopyroxene no feldspathoids
High-K calc-alkalic	220-260	0.5-.8% K_2O per 5% SiO_2	2.4-3.0	38-44	2.4-3.2	0.6-.9	4.5-7.5	57-59 (calc-alkalic)	little or none	high (15-19%)	Weakly quartz normative	Clinopyroxene and orthopyroxene; biotite
Alkali-calcic	260-390	>0.8% K_2O per 5% SiO_2 @ 45-55% SiO_2; at 55-60% SiO_2 slope may flatten and approach 0; at 60% SiO_2 slope may be 0 or negative	3.0-4.4	31-43 generally <39.5	1.8-6.0 generally >2.3	generally near 1.0; may vary between 0.3-2.0	4.5-9.0	52-58 (alkali-calcic)	generally none	high and variable (14.5-20%)	commonly olivine normative; some are nepheline normative @ 50-60% SiO_2	common; leucite common; trachytes contain sanidine
Alkalic	>390	very steep; near 1.0% K_2O per 5% SiO_2; near 60% SiO_2 slope commonly reverses and is negative	4.4-6.0	25-34	6.1-14+	0.3-1.0 generally <0.8	5.5-13.0	45-52 (alkalic)	moderate	variable (5-20%)	Olivine and/or nepheline normative at less than 60% SiO_2	Clinopyroxene; biotite rare; nepheline or analcime; trachytes contain anorthoclase

* $K_{57.5}$ index = potash content at 57.5% silica in a K_2O/SiO_2 Harker variation diagram; θ index = $SiO_2 - 47 \frac{(Na_2O + K_2O)}{Al_2O_3}$ from Sugimura (1968); S index = $\frac{(Na_2O + K_2O)^2}{SiO_2 - 43}$ from Rittman (1960).

Table 2: Comparison of Metallogenic and Chemical Data for Sulfide Systems and Their Associated Coeval Igneous Rocks

Sulfide System	Associated Igneous Rocks	$K_{57.5}$ of Associated Igneous Rock	Depth to Inferred Locus of Partial Melting in km	Zn:Pb	Cu:Pb+Zn	Cu:Au	Ag:Au
Syngenetic banded Iron Formations	Calcic	0.4-1.37	50-130 km				
Epigenetic zinc-copper stringer ore below massive sulfides	Calcic to Calc-alkalic	0.4-1.8	50-180 km				
Syngenetic zinc-copper massive sulfides		0.4- 1.8	50-180 km	3:1 to >100:1	1.5:2 to 1:40	>10,000:1	About 750:1
Epigenetic porphyry copper (± Zinc; significant Zinc present if carbonate section present)	Calcic to Calc-alkalic	0.4-2.5	50-230 km	>3:1	>4:1	>9,000:1 (in island arcs) >50,000:1 (continental arcs)	Generally >50:1 Commonly >100:1
Epigenetic Epithermal Silver-gold veins	Calc-alkalic	1.5 to 2.5	150-240				50:1 to greater than 200:1
Epigenetic Lead-zinc silver veins and replacements	High K Calc-alkalic to Alkali-calcic	2.5-4.0	240-360	<1:1.5 usually <1:3	<1:10	<1,000:1 Generally <500:1	>40:1 commonly >100:1
Epigenetic Tin-Tungsten veins replacements, and porphyries	Alkali Calcic	3.2?-4.4?	280-400				
Epigenetic porphyry molybdenums	Alkali Calcic to Alkalic						
Epigenetic gold-lead-zinc (minor silver)	Alkali calcic	3.6-4.2	320-380	<1:1.5	<1:10	<600:1	<25:1
Porphyry gold copper (± lead-zinc-molybdenum-silver)	Alkali calcic	3.5-4.5?	310-410	<1:2	3:17	<50,000:1; commonly <200:1 (Canadian)	<20:1 commonly <5:1 (Canadian)
Epigenetic gold-silver telluride deposits	Alkali calcic (olivine normative)	3.8-4.3	340-390				<20:1; commonly <3:1

Table 3: Selected Major and Trace Element Data in Igneous Rocks*

Element	Basaltic Rocks	Granitic Rocks High Calcium	Granitic Rocks Low Calcium	Syenites	Trend
Potassium	8,300	25,200	42,000	48,000	Increasing
Calcium	76,000	25,300	5,100	18,000	Generally decreasing
Silicon	230,000	314,000	347,000	291,000	Generally increasing
Sodium	18,000	28,400	25,800	40,400	Generally increasing
Aluminum	78,000	82,200	72,000	88,000	No trend
Magnesium	46,000	9,400	1,600	5,800	Generally decreasing
Iron	86,500	29,600	14,200	36,700	Generally increasing
Lead	6	15	19	12	Generally increasing
Zinc	105	60	39	130	Generally decreasing
Copper	87	30	10	5	Decreasing
Gold	.004	.004	.004	.00X	No trend
Silver	.011	.051	.037	.0X	Increasing, then decreasing
Barium	330	420	840	1,600	Increasing
Molybdenum	1.5	1.0	1.3	0.6	No trend
Titanium	13,800	3,400	1,200	3,500	Generally decreasing
Nickel	130	15	4.5	4	Decreasing
Vanadium	250	88	44	30	Decreasing
Chromium	170	22	4.1	2	Decreasing
Sulfur	300	300	300	300	No trend
Flourine	400	520	850	1,200	Increasing
Chlorine	60	130	200	520	Increasing
Zn:Pb	17.5:1	4:1	2:1	11:1	Generally decreasing
Cu:Pb+Zn	1:1.3	1:2.5	1:5.8	1:28	Generally decreasing
Cu:Au	21,750:1	7,500:1	2,500:1	—	Decreasing
Ag:Au	2.75	12.75	9.25	—	Increasing, then decreasing??

*Data are expressed in parts per million and are from Turekian and Wedepohl, 1961, Table 2.

TABLE 4: Comparison of Magmatic Chemistry and Metallogenic Aspects of Late Cretaceous, Late Cretaceous-Early Tertiary (Laramide) and Middle Tertiary Sulfide Systems Within the SE Arizona-SW New Mexico Porphyry Copper Cluster*

Age	Magmatic Chemistry ($K_{57.5}$)	Copper ($K_g x10^6$)	Lead ($K_g x10^6$)	Zinc ($K_g x10^6$)	Gold ($K_g x10^6$)	Silver ($K_g x10^6$)	Zn:Pb	Cu:Pb +Zn	Cu:Au	Ag:Au	Number of Districts
Mid-Tertiary (30-20 m.y.)	2.5 to 4.0	7.556	85.55	61.16	0.0261	1.045	1:1.4	1:20	290:1	40:1	12
Laramide (70-50 m.y.)	0.7 to 2.5	22,253.	273.8	1,292.	.1256	5.96	5:1	14:1	180,000:1	47:1	26
Late Cretaceous (80-70 m.y.)	2.6 to 4.4	7.655	48.69	17.13	.0124	1.197	1:3	1:9	620:1	96:1	11

Age	Total Base Metals ($K_g x10^6$)	Total Precious Metals ($K_g x10^6$)	Total Metal ($K_g x10^6$)	Emplacement Rate (K_g per year)
Mid-Tertiary (30-20 m.y.)	154.3	1.0711	155.34	15.5
Laramide (70-50 m.y.)	23,819.	6.09	23,825.	1,190.
Late Cretaceous (80-70 m.y.)	73.5	1.21	74.7	7.5

*Notes: Data is based on a compilation of production data for 39 districts within the porphyry copper cluster where a sulfide system could be recognized. In most cases each district constitutes a single sulfide system. That is, sulfide system data includes all mines within a district which have produced from epigenetic vein systems which can be linked spatially and temporally to a single igneous event. Thus, production data was composited from all mines considered to be in the district zoning picture; not simply the mines thought to be at the center of the district. Emphasis is thus on total metal emplaced over an entire sulfide system which is district wide in its dimensions and is a composite of several or many smaller deposits. Data in Table 2 is based on 1900-1975 production data. The 1900-1975 U. S. Bureau of Mines yearbooks are the primary data source. This source was augmented by Arizona Bureau of Geology file data and annual company reports.

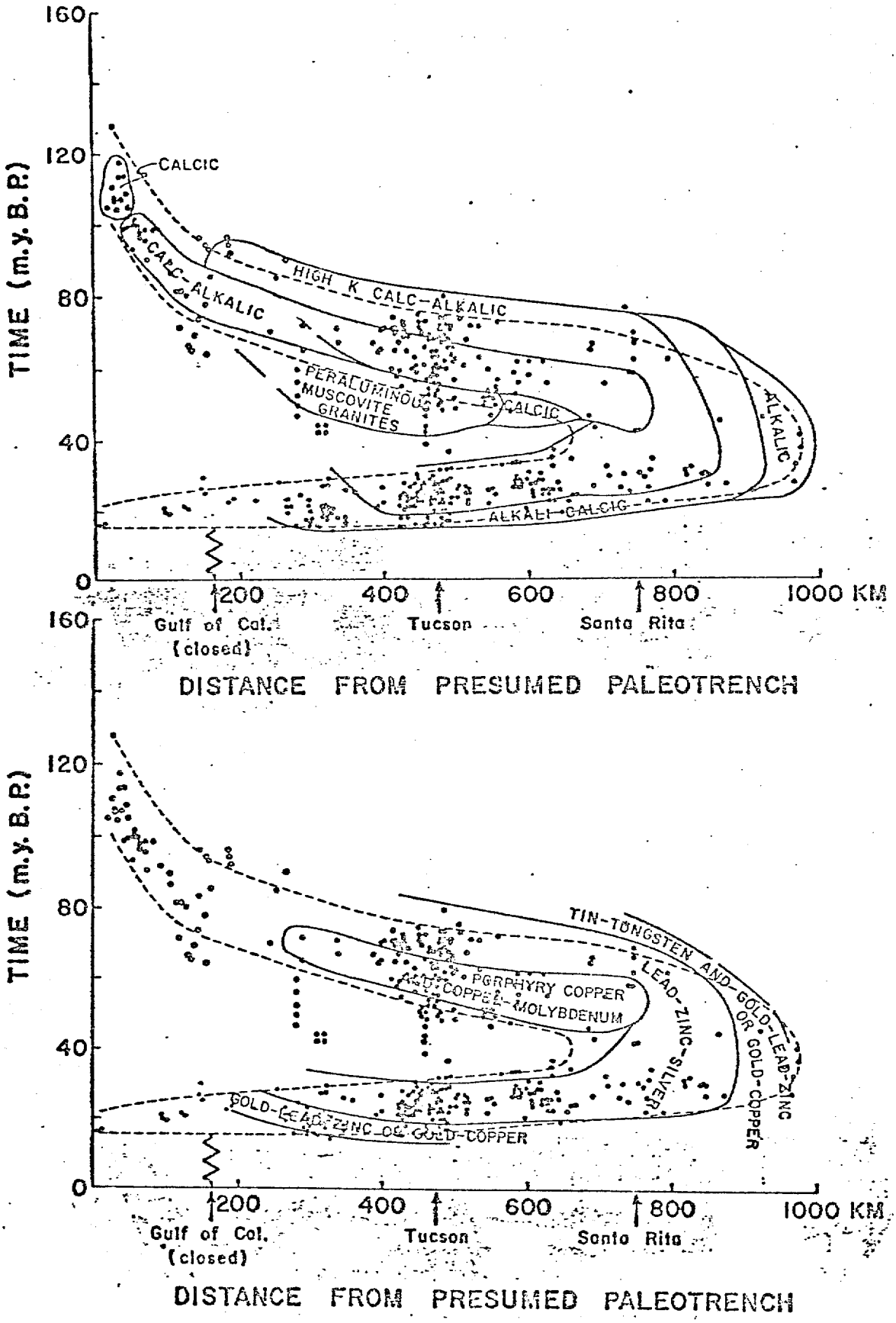
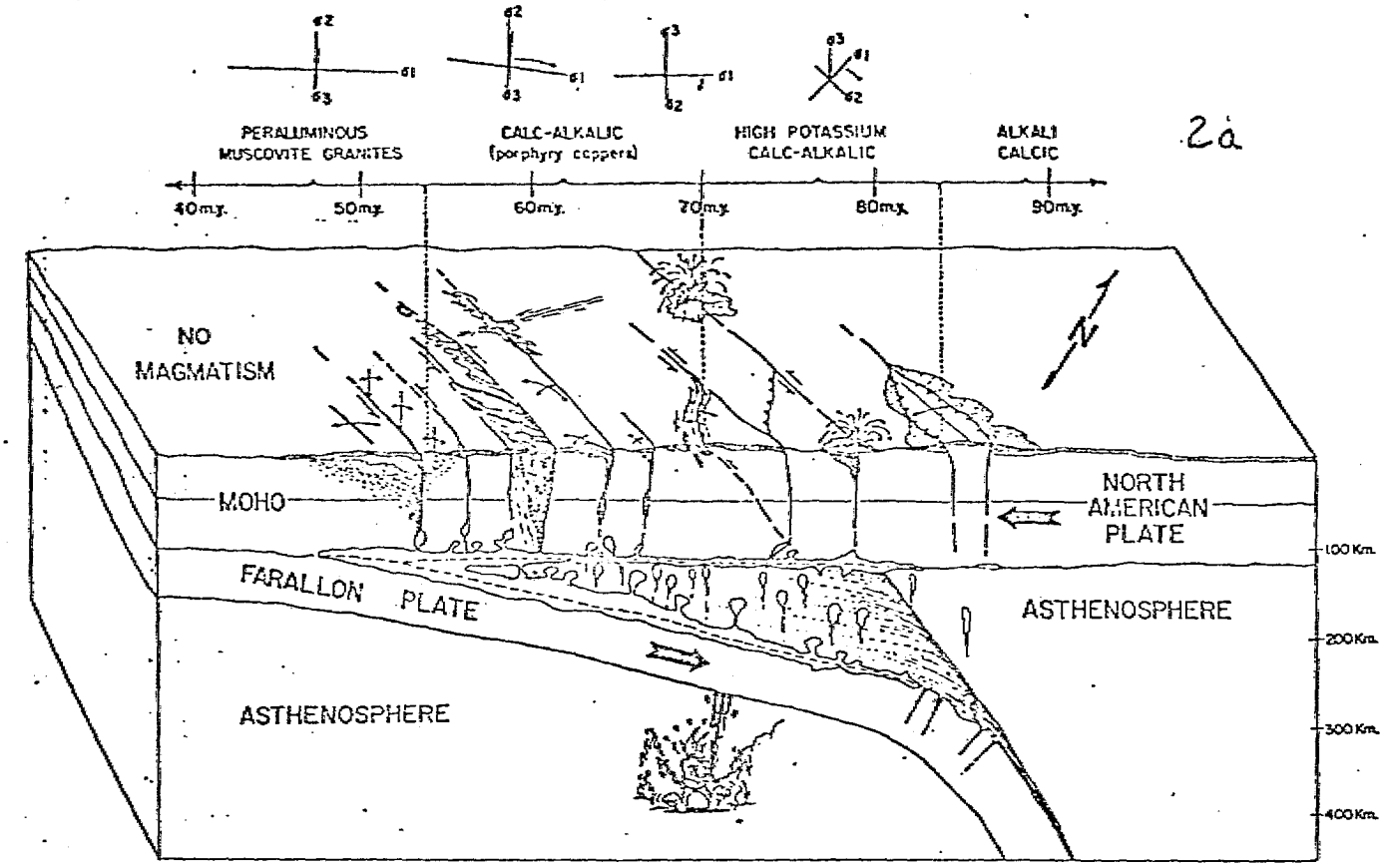


Figure 1
Time-distance plots of radiometrically dated magmatic rocks in southwestern U.S. Each point represents a radiometrically dated pluton or volcanic unit. Figure 1a shows generalized chemistry of magmatic rocks. Figure 2b shows generalized metal chemistry of associated sulfide systems.



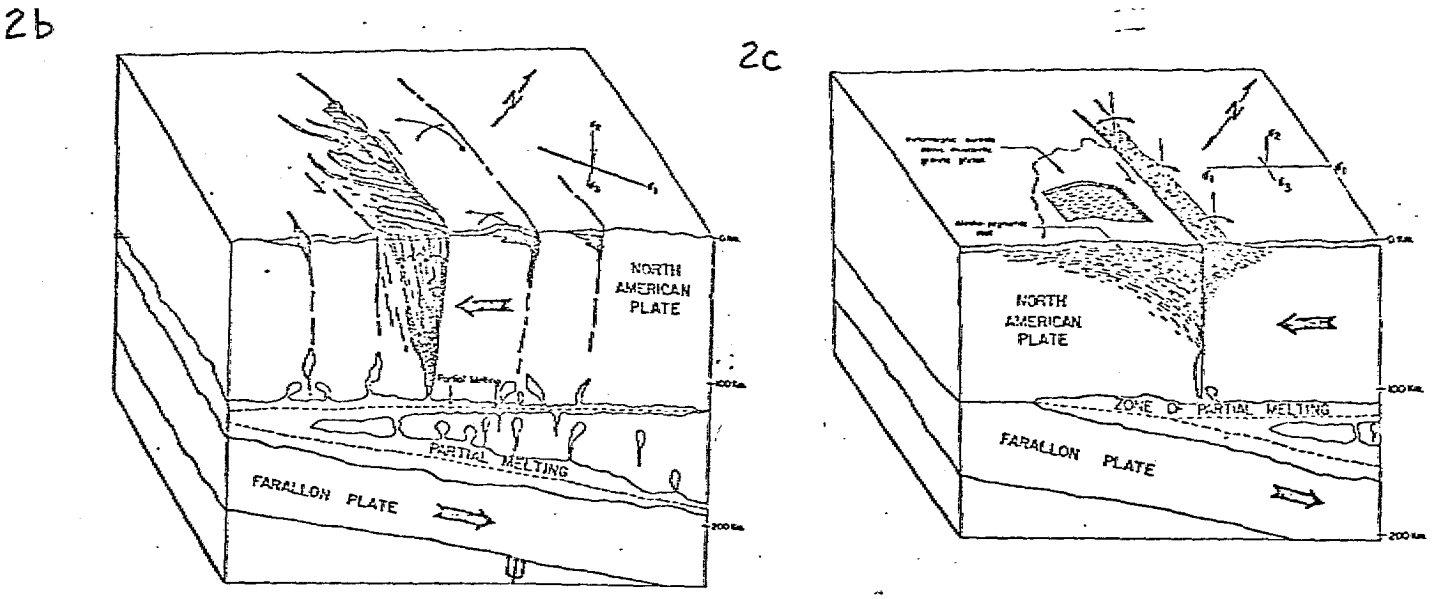


Figure 2: Figure 2a is an idealized block diagram illustrating structural developments in southeast Arizona from 90 to 40 m.y. ago. Deformational and intrusive events moved from west to east as the Benioff zone flattened. In any given area, various elements of the above tectonic sequence may be present. Events at the left of the diagram will generally be the youngest event while events at the right will be the oldest. From left to right events are a peraluminous muscovite granite pluton intruded into crust under high regional compressive stress. b) Calc-alkalic plutonism, ENE striking dike and vein swarms, and porphyry copper mineralization along a WNW basement flaw which is moving in left shear. c) Laccolithic calc-alkalic magmas intruded along WNW striking flaws. d) NW trending basement cored uplifts. e) High-potassium calc-alkalic plutonism and pyroclastic volcanism. f) WNW to E-W trending basement cored uplift with late Cretaceous age clastic wedges at margins (Fort Crittenden equivalent). Figures 2b and 2c are exploded views of porphyry copper mineralization and muscovite granite pluton intrusion.

Silver Bell Introduction

The Silver Bell deposit lends itself well to one day tours. Its size and layout are 'manageable', and by staying aware of one's location with respect to other points one can observe and examine many aspects of porphyry base metal deposit geology. The stops are listed as 'points' because the order in which they are visited is not vital. For the SEG trip, two buses will spend the morning at Points 1, 2, and 3 in Oxide Pit and Point 9 in the El Tiro East Extension, and the other two will visit Points 4-8 in El Tiro. At lunch time we will all meet at Point 11, a viewpoint overlook of the North Silver Bell area preparatory to Friday's visit. The buses will then switch areas for the afternoon. Late in the afternoon we will again converge, this time at Point 10 to examine capping.

Following this page is a road log from Tucson to Silver Bell, the Point Location Map, Kenyon Richard's and Harold Courtright's paper on Silver Bell from the 1966 Titley-Hicks volume, Jim Galey's paper 'General Geology and Hydrothermal Alteration of the Silver Bell Porphyry Copper Deposit' written for this Conference and including a geologic and protore distribution map, seven pairs of geologic maps and empty ground line 1" = 10' maps for your mapping use, one for each of Points 1-7, and some information on Points 8-10.

GEOLOGIC ROAD LOG — TUCSON - SILVERBELL

(Have your Pima-Santa Cruz Geologic Map, and AGS Guidebook III, at hand) Vehicles enter Interstate 10 northbound, Tucson Mountains on left (W), Santa Catalina Mountains at 1:00 o'clock (NE). The Freeway continues N over an intermo ntane valley with as much as 3 Km of post-Paleocene gravels below.

Drive N successively past Grant, Orange Grove, and Ina Exits past Wasson Peak on your left. At Cortaro Road overpass (about 10 minutes), Safford Peak (3576') is at 10:00, the Old Yuma Mine south of Contzen Pass at about 8:00. Most of this northern end of the Tucson Mountains is composed of mid-Tertiary (26 my) andesites and dacites in a long narrow ridge (purple on the PCGM) which obstructs our westward journey. Safford Peak is Safford Dacite, a young unit. The Santa Catalinas at 4:00 are a gneiss dome composed of Precambrian age metasediments 'reset' at their upheaval date of 26 my. It will be best perceived in the afternoon light when we return. The San Manuel-Kalamazoo PCD at the town of San Manuel is at 3:00 behind the gneiss-Apache Group ridge. At 1:00-2:00 are the Tortolita Mountains, mainly Precambrian but shown by G.H. Davis and coworkers to be a complex metamorphic core complex. (As the N end of the Tucsons is approached, their foothills are spiked with saguaro cactus, palo verde is in the median strip, and mesquite is on the right shoulder.)

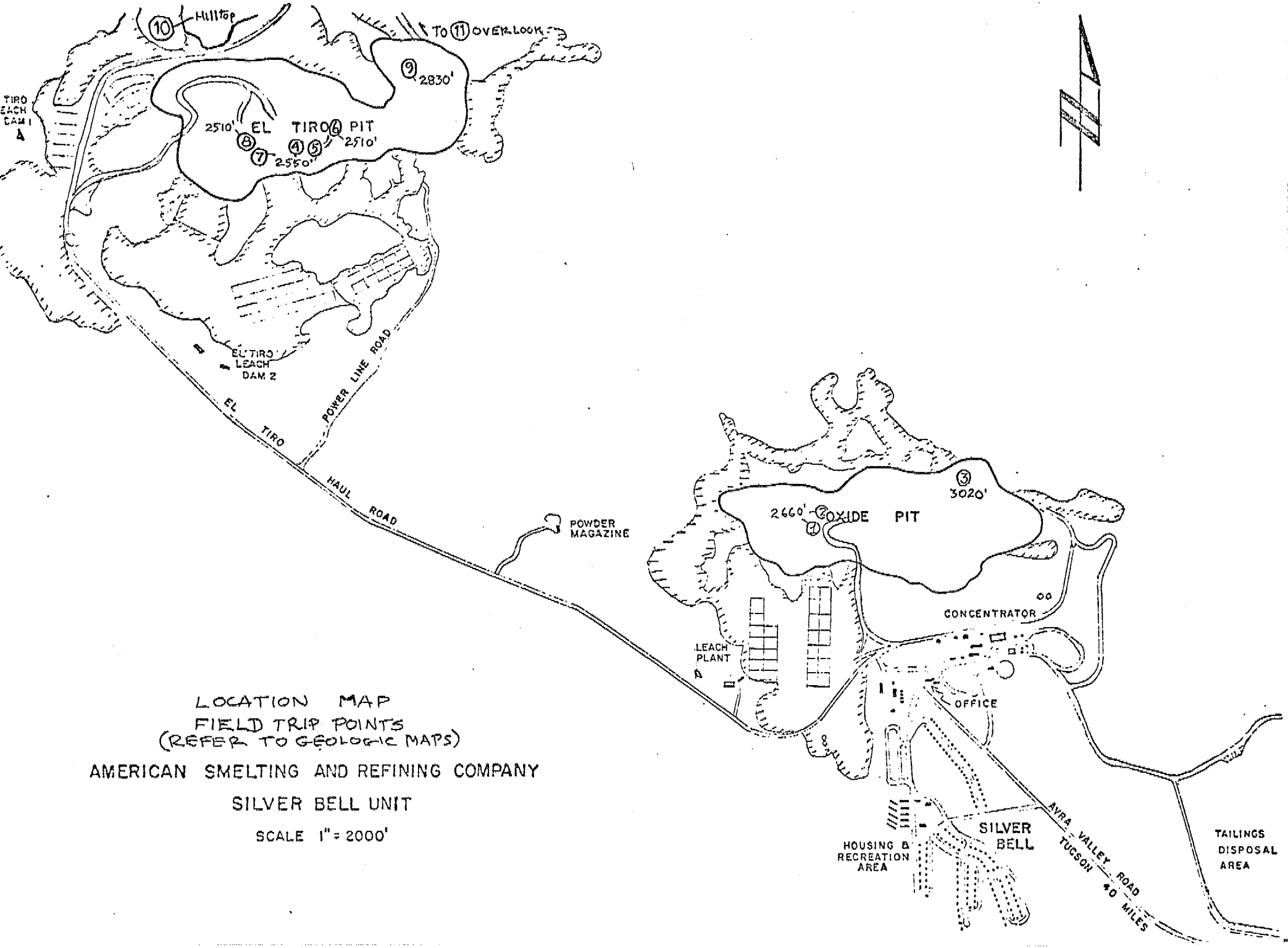
Exit I-10 at Rillito following Silverbell signs, duck under freeway, cross Santa Cruz River, and (1 mile) pass Arizona Portland Cement plant. Cement rock is quarried 5 miles away at Twin Peaks, carried by conveyor belt to the coal, gas, or diesel-powered kilns. Plant serves all of southern Arizona, is in fact a gold mine.

2.5 miles later (on higher ground), you can see the Tucsons (9:00), the cement quarry hills (Twin Peaks, fraternal, not identical-the quarry is in shaley Devonian Martin and Mississippian Escabrosa ls, the other Cambrian Bolsa quartzite) at 10:00, the Coyotes and Quinlans at 10:30 in the distance with Kitt Peak (the NASA-AURA observatory) and Baboquivari Peak (both LGr) prominent, the Roskruge Mountain Laramide and Tertiary volcanics low to the pass south of the El Paso Natural Gas pump plant, the Cretaceous and Paleozoic Watermans at 11:00, and the Silver Bells, dominated by Silver Bell Peak and Mt. Lord, at 12:00. Ragged Top, a Miocene ignimbrite plug to be part of the North Silver Bell skyline, is at 12:30, out of the Silver Bell cluster. Picacho Peak, another young volcanic neck, is at 2:00, and the Precambrian Picacho Mountains are to their east.

We traverse square miles of fields of vegetables and cotton (famous PIMA long staple cotton - your shirt may be made of it!). Portland Ridge and the Silver Bell tailings loom ahead.

At Anway Road (12 miles and 15 minutes from I-10), we begin to climb the long gradual pediment surface to Silver Bell. The thick gravels of the down-faulted basin (see Avra Valley basin, profile B-B[1] on the 1"= 50 mile foldout map, ABGMT) are behind; from here to Silver Bell, veneers of gravel conceal porphyry copper deposits (?!). At 10:00 to 12:00, the Watermans, the Roskruges to left in middle distance. Volcanics are S of pump station, Paleozoic and Cretaceous sediments N of conspicuous saddle. The gray-brown cliffs are Escabrosa limestone. Tailings are on the right.

After the bend, waste dumps on the left, the mill and Portland Ridge at right center, and Silver Bell Peak beyond. Stop at ASARCO offices having passed townsite on left.



LOCATION MAP
FIELD TRIP POINTS
(REFER TO GEOLOGIC MAPS)

AMERICAN SMELTING AND REFINING COMPANY

SILVER BELL UNIT

SCALE 1" = 2000'

GENERAL GEOLOGY AND HYDROTHERMAL ALTERATION OF THE SILVER BELL PORPHYRY COPPER DEPOSIT

Presented to the

Society of Economic Geologists

Silver Bell Field Conference

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J. L. Galey

Fluor Mining & Metals, Inc.

GENERAL GEOLOGY AND HYDROTHERMAL ALTERATION OF THE SILVER BELL PORPHYRY COPPER DEPOSIT

INTRODUCTION

The Silver Bell Unit of ASARCO Incorporated is located 32 airline miles northwest of Tucson, Arizona. The porphyry copper deposit is situated on the western flank of the Silver Bell Mountains which protrude out of the surrounding alluvial plains.

Initially, the deposit was mined in 1865 as a silver prospect. More intense mining using underground methods started at the turn of the century and concentrated in skarn mineralization.

Initial stripping by present open-pit methods began in December 1951. The ore is from two open pits: Oxide and El Tiro. As of December 1978, 75,655,000 tons of ore had been mined which contained 0.80 percent copper, 0.07 oz/ton silver, and 0.013 percent molybdenum.

The ore cutoff grade is 0.40 percent copper, and the mill is rated at 11,400 tons per day. In both mined and reserve tonnages, 85 percent of the economic copper is from the chalcocite blanket and 15 percent is from skarn mineralization. Average protore values of the intrusives within the limits of the pits is approximately 0.25 percent copper and is not of economic interest. Thus, most of the ore at Silver Bell is from the supergene blanket.

STRATIGRAPHY

The stratigraphic section in the Silver Bell district is composed of Precambrian through Tertiary age strata.

Precambrian. Exposures of Precambrian rocks are not found in the immediate vicinity of the Silver Bell deposit. However, limited exposures of Precambrian Oracle Granite and Pinal Schist are noted peripheral to the district (Watson, 1968).

Paleozoic. Approximately 2,000 feet of Paleozoic sediments are located in the Silver Bell district. The section consists of Cambrian Bolsa through the Permian Sherrer Formation. The Permian Concha and Rainvalley formations are located to the south and west of Silver Bell. The Paleozoic section consists principally of carbonates and arenaceous carbonates with the exception of two quartzite formations: the Cambrian Bolsa and the Permian Sherrer.

Mesozoic. The lower Mesozoic is composed of arkoses and sandstones equivalent to the Amole Arkose, and it is overlain by a redbed unit called the Village Redbeds (Watson, 1968). Overlying the lower Mesozoic units in an apparent angular unconformity is the Claflin Ranch Formation. It is composed of volcanic flows and tuffs, volcanoclastics, sandstones and conglomerates. This formation is of importance as it marks the beginning of the Laramide volcanic events. Above the Claflin Ranch is the Silver Bell Formation. It consists of dark gray to purple andesite through rhyodacite flows and breccias, nonwelded and welded ash-flow tuffs, and conglomerate. The Silver Bell Formation grades vertically, and, to a less extent, laterally into the Claflin Ranch Formation.

Overlying the Silver Bell Formation is the Mount Lord Volcanics and they represent the last phase of the Laramide extrusives. They are generally quartz latitic in composition and consist of five or more cooling units of welded ash-flow tuffs. These cooling units are interbedded with nonwelded tuffs, water-lain tuffs, flows and clastic sediments. The Laramide intrusives are possibly coeval to post-Mount Lord in age.

Tertiary. The Tertiary units are present as gravels with intermittent basaltic flows. Ages of 19.5 through 22.2 million years were determined for units which represent the bulk of the basaltic flows (Banks and Dockter, 1976). An intrusive quartz latite that is found throughout the district was dated at 25 million years (Mauger and others, 1965).

LARAMIDE INTRUSIVE SEQUENCE

The first Laramide intrusive is the alaskite and its emplacement was apparently controlled by the northwest trending Silver Bell Fault Zone (Figure 1). The fault zone traverses diagonally through the district. Compositionally, the alaskite is a coarsely crystalline monzonite. The biotite has been replaced by sericite and clays in the zone of more intense hydrothermal activity. Thus, the rock was originally named "alaskite" because of the lack of mafics in the zone of alteration. This name has been retained to avoid confusion in the literature.

The second Laramide intrusive is the dacite. Compositionally it is a sub-volcanic quartz latite porphyry. The dacite intruded up along the Silver Bell Fault Zone, and upon encountering the Claflin Ranch Formation pushed toward the northeast. It has been suggested that the dacite is a sill which is floored by Paleozoic sediments and roofed by the Claflin Ranch Formation (Watson, 1964).

The third intrusive phase is that of the monzonite porphyries. They represent a composite intrusive phase which vary texturally and compositionally. One phase of the monzonites was dated at 65.5 million years (Mauger and others, 1965). The earliest intrusion was by an extensive pyroxene-bearing phase called syenodiorite. The later bulk of the intrusions were quartz monzonitic to granodioritic in composition. The intrusion of the monzonites were less controlled by the Silver Bell Fault Zone than the alaskite and dacite. The monzonites occur as stocks inside the more intense zone of alteration and intrude along ENE trending tensional faults which are located to the east of the district. Drilling suggests that the monzonites possibly become more voluminous at depth. This indicates that the stocks at the present erosional level represent fingers from a more massive body at depth.

STRUCTURE

Regional Structures. Regional structural features in the Silver Bell district are exemplified by major WNW trending faults. The Silver Bell Fault Zone, which represents one of these faults, has played a key role in the localization of the Laramide intrusives and possible channeling of the hydrothermal fluids. The fault zone is probably a Precambrian structure with intermittent movement throughout geologic time. No definite major post mineral movement has been identified. One exception is in the El Tiro pit where a linear breccia feature is located. However, the lack of evidence for offset and the anamalous tungsten values may suggest a late or post mineral explosive hydrothermal event.

It has been suggested that the Silver Bell structure continues into the Bisbee mining district (Titley, 1976). The structure has been referred to as the Silver Bell-Bisbee discontinuity.

Thus, the faults appear to be regional features and have their origins in Precambrian time.

ENE Tensional Fractures. The dikes that are prominent to the east of the deposits are oriented in an ENE direction (Figure 1). These dikes represent intrusions into tensional fractures which probably resulted from weak continental compressional forces oriented in an ENE - WSW direction and tensile stress fields localized over crests of NNW-oriented arches (Rehrig and Heidrick, 1976).

Mineralized Veins. Orientation of the mineralized veins, particularly the phyllic veins, have a northeast to ENE direction and a minor NNW set is present. However, in the Oxide Pit the NNW set often becomes more prominent than the NE set.

Tertiary Tectonics. Analysis of the regional stratigraphy, dips of sedimentary units and foliations in the volcanics shows that the entire area has been tilted toward the northeast. From this data it must be concluded that the entire alteration system is tilted approximately 30° to the northeast resulting in a plunge of 60° toward the southwest. The age of tilting is younger than 19 million years and is undoubtedly associated with Basin and Range tectonics.

HYDROTHERMAL ALTERATION AND MINERALIZATION

General Description. The general pattern of hydrothermal alteration and mineralization is a wide propylitic zone with the more intense potassic and phyllic alteration occurring in the Oxide and El Tiro pit areas. The alteration zone is linear and its position is generally centered along the Silver Bell Fault Zone. If the monzonites are the causitive

intrusive for the porphyry system, it is suggested that the alteration zonation reflects the position of the more voluminous monzonites at depth. Thus, the position of the alteration phases along the Silver Bell Fault Zone may reflect the position of the monzonite more than an actual channeling of hydrothermal fluids by the fault zone. However, it is recognized that the fault zone could possibly have some influence on the channeling of the hydrothermal fluids.

The alteration assemblages defined at Silver Bell are potassic, propylitic and phyllic. As discussed later in the paper the potassic and propylitic assemblages are coeval and the phyllic phase is paragenetically later than the potassic-propylitic phase.

Each alteration assemblage will be described as a cumulative of all rock types. It is noted that at Silver Bell and other deposits, each rock type will vary in alteration effects within each alteration type. Thus, the chemistry of each rock type is a control on the alteration mineralogy.

Potassic Alteration. Potassic alteration at Silver Bell is defined as the introduction of secondary k-feldspar quartz, biotite, chalcopyrite, pyrite and molybdenite. Secondary k-feldspar occurs as flooding of the groundmass, replacement of plagioclase and in vein assemblages. The secondary biotite is present as a recrystallization of primary biotite, as a dusting throughout the groundmass, as a replacement of hornblende and in vein assemblages. The occurrence of secondary biotite is minor and is more notable with microscopic examination as compared to megascopic identification.

Propylitic Alteration. The propylitic assemblage is defined by the presence of secondary chlorite, epidote and calcite. All three minerals occur as replacement of the groundmass

and in vein assemblages. Microscopic examination of the vein chlorites, particularly on the southwest side of the deposit, shows that the chlorite sometimes replaces vein biotite. It is suggested that biotite was deposited originally, and as the hydrothermal system progressed in time and chemistry, chlorite and epidote became the dominant alteration assemblage.

Phyllic Alteration. Phyllic alteration is defined as the vein occurrence of quartz-sericite-pyrite. The quartz and sericite occur as vein selvages around a pyrite core. An abundance of disseminated sericite occurs in the groundmass. However, this occurrence is not included in the phyllic alteration as its origin is questionable. Much of the disseminated sericite is associated with supergene enrichment. It has been suggested that some of the disseminated sericite could be of supergene origin.

Metallic Mineralization. The principal metallic minerals associated with the hydrothermal mineralization are pyrite, chalcopyrite, molybdenite and less amounts of sphalerite, bornite, galena and magnetite. The metallic mineralization is viewed as an integral part of the alteration assemblages.

The assay contour map shows the relative occurrence of chalcopyrite and molybdenite in the protore zone of the intrusives. The general pattern in the El Tiro Pit is a depleted chalcopyrite center that is flanked by higher chalcopyrite to the east and west. The east and west limbs of the high chalcopyrite zone coalesce immediately north of the El Tiro Pit, but opens again in the North Silver Bell area.

The assay contours in the Oxide Pit show an enriched center of chalcopyrite in the east and central portion of the pit. However, at the west end of the pit a greater amount of

chalcopyrite occurs on the north and south sides, and the interior of the alteration shows a decrease in chalcopyrite relative to the sides. It is suggested that the east end of Oxide is higher in the porphyry system than the west end. Further evidence for this hypothesis is the knowledge that the deposit is tilted to the northeast. Thus, the erosional level of the system on the west end would be deeper than that on the east.

Two large quartz veins on the north and south sides of the Oxide Pit have apparently channeled the hydrothermal fluids. An elevated copper content paralleling each quartz vein indicates a damming and channeling of the fluids (Figure 3). The silicate alteration assemblage also suggests channeling has occurred. Phyllic alteration is abruptly terminated at the veins. Also, a marked change of potassic alteration on the inside of the veins and propylitic alteration on the outside is noted. This evidence indicates the quartz veins are pre or early mineralization in age.

Molybdenite is erratic in occurrence. The 0.010 percent molybdenite contour is delineated on the assay contour map and greater amounts of molybdenum occur inside the contour. Contour patterns inside the 0.010 percent molybdenum contour could not be established with the available data.

Paragenesis. The paragenesis of the different alteration assemblages was evaluated by cross cutting vein relationships. This was supplemented by microscopic examination. The results of the study revealed that the potassic and propylitic assemblages are coeval and the bulk of the phyllic assemblage is later than the potassic-propylitic phase (Figure 3).

Examination of the potassic paragenesis showed that most of the biotite and chalcopyrite are paragenetically earlier than the molybdenite.

The evidence suggests that the hydrothermal system was continually changing with time. These changes in the chemistry of the hydrothermal fluids appear to be slow. For example, the chalcopyrite deposition overlaps in time with the molybdenite, demonstrating that the chemical change was not abrupt. However, the bulk of the molybdenite alteration phase is later than the bulk of the earlier chalcopyrite phase as evidenced by cross-cutting vein relationships. This same overlap of time of depositional environments is noted with the later phyllic alteration and its partial overlap with the earlier potassic-propylitic phase.

Thus, the data at Silver Bell demonstrates that the depositional environments for the different minerals evolve with time. A distinct boundary between each mineral or alteration phase is nonexistent. The hydrothermal system does not stop and another influx of fluids creates a different alteration phase. The system continually evolves with time.

CONTROLS OF MINERALIZATION

Localization of mineralization at Silver Bell has been partially controlled by regional structure. Also, rock chemistry has apparently controlled the deposition of chalcopyrite.

Structural Controls. The more intense alteration and metallic mineralization occur in the Oxide and El Tiro areas. Analysis of the geologic map shows that to the east and northeast of each pit, the density of the ENE trending dikes increases.

It is suggested that the structural intersection of the ENE fault system and the Silver Bell Fault Zone provided an avenue for intrusion of the monzonites and possible channeling of the hydrothermal fluids.

Controls of Chalcopyrite Deposition. The chalcopyrite mineralization was influenced by the rock chemistry. The chalcopyrite appears to have been controlled by the mafic content of the intrusives. Generally, the higher the mafic content of the intrusives, the higher the chalcopyrite content. This close association of mafic minerals and chalcopyrite may suggest that the chalcopyrite is acquiring some of its iron from the mafics. It is interesting to note that the available data does not show a major increase in iron content in the mineralized rock as compared to the less altered rock.

FLUID INCLUSION DATA

A fluid inclusion study was conducted on vein quartz from the alteration assemblages of the El Tiro Pit. Table 1 depicts the maximum and mean filling temperatures of each alteration assemblage. The results of the data suggest the highest temperatures occurred during early potassic alteration and chalcopyrite deposition. The mean filling temperature for this stage was 360°C. The temperature declined in the later potassic phase and molybdenite deposition as marked by a mean filling temperature of 325°C. The coeval propylitic alteration formed at a lower temperature than the interior potassic assemblage. The temperature of the paragenetically later phyllic assemblage denotes a cooling of the porphyry system with time. Its mean filling temperature was 305°C.

The fluid inclusion study also revealed a late and lower temperature event with a mean temperature of 220°C. It is unknown if this population of inclusions represents the final hydrothermal event or a later heating event not associated with copper mineralization. A vein assemblage of sericite selvages with alunite cores has been identified as cross-cutting phyllic veins. This might represent the last and low temperature stage of the hydrothermal system. Also, a post copper mineralizing assemblage of sphalerite, galena, fluorite, barite and calcite has been identified. Filling temperatures of fluid inclusions for this system are in the low 200°C range.

The temperatures represent filling temperatures which have not been corrected for pressure. Thus, the actual temperatures of formation of each alteration assemblage is slightly higher than those temperatures that are reported.

SUMMARY

In summary, an environment consisting of Precambrian, Paleozoic and Mesozoic rocks was intruded by three Laramide intrusive phases: alaskite, dacite and monzonites. The emplacement of the intrusives was structurally controlled by the Silver Bell Fault Zone. The hydrothermal alteration followed the intrusion of monzonite porphyrites which has been dated at 65.5 million years. The more intense alteration occurred in two areas as exemplified by the location of potassic and phyllic alteration. These two intense centers are surrounded by a broad linear zone of propylitic alteration. The phyllic alteration is paragenetically later than the coeval potassic-propylitic assemblage.

Regional tilting associated with Basin and Range tectonics tilted the deposit 30° toward the northeast. Exposure of the deposit to surficial weathering conditions resulted in the formation of the chalcocite blanket.

TABLE 1

SUMMARY OF FILLING TEMPERATURES

Alteration Phase	Maximum Filling Temp. (°C)	Mean Filling Temp. (°C)
Early Potassic (K-spar, biotite, chalcopyrite)	394	360
Late Potassic (quartz, molybdenite, ± K-spar)	344	325
Propylitic	286	286 (?)
Phyllic	344	305
Late Hydrothermal		220

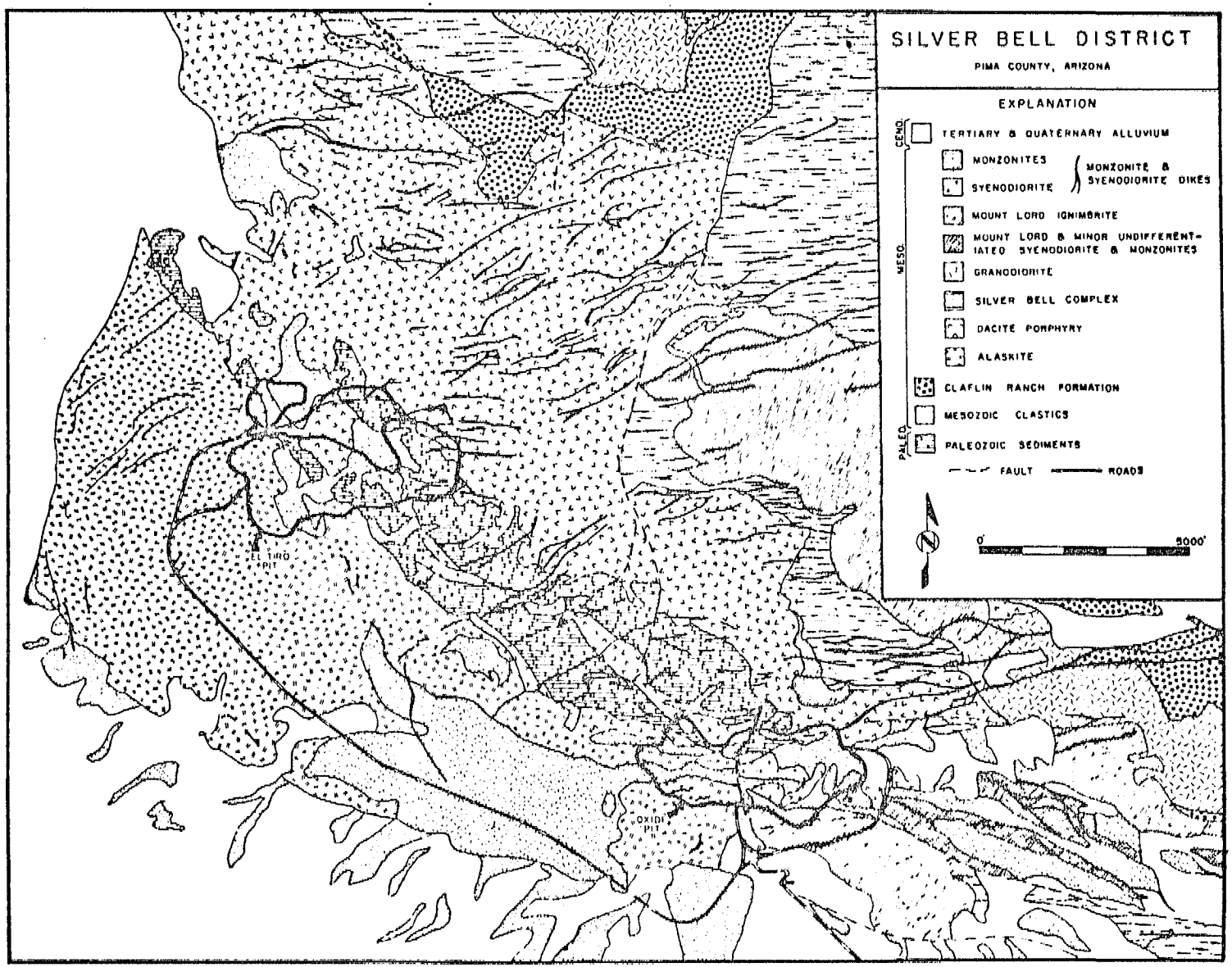
SILVER BELL DISTRICT
PIMA COUNTY, ARIZONA
EXPLANATION
CENO.
TERTIARY & QUATERNARY ALLUVIUM
MESO.
MONZONITES
SYENODIORITE
MONZONITE & SYENODIORITE DIKES
MOUNT LORD IGNIMBRITE
MOUNT LORD & MINOR UNDIFFERENTIATED SYENODIORITE & MONZONITES
GRANODIORITE
SILVER BELL COMPLEX
DACITE PORPHYRY
ALASKITE
CLAFLIN RANCH FORMATION
MESOZOIC CLASTICS
PALEO.
PALEOZOIC SEDIMENTS
FAULT
ROADS
N
0'
5000'
EL TIRO PIT
OXIDE PIT

FIGURE 1

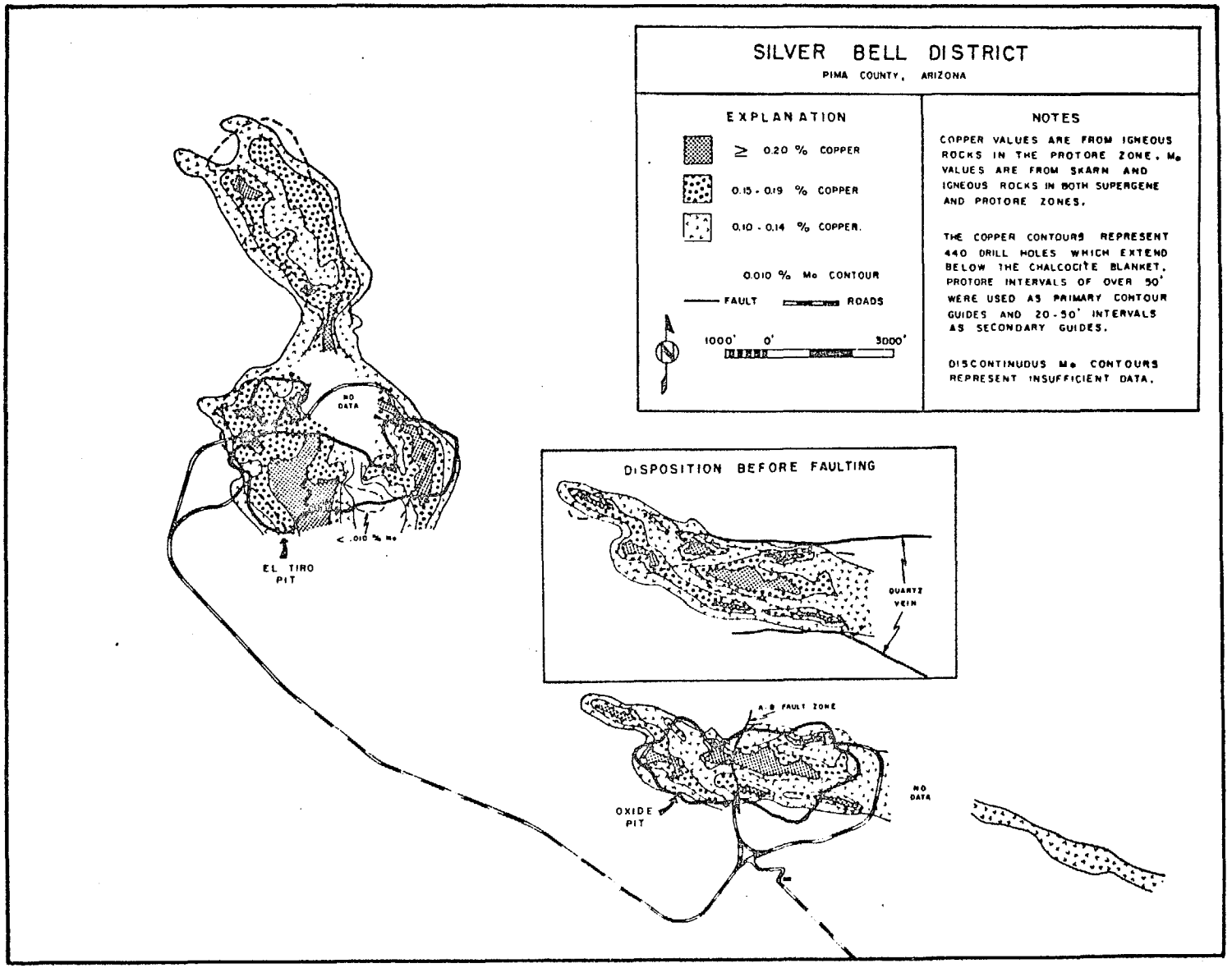
SILVER BELL DISTRICT
PIMA COUNTY, ARIZONA
EXPLANATION
≥ 0.20 % COPPER
0.15 - 0.19 % COPPER
0.10 - 0.14 % COPPER.
0.010 % Mo CONTOUR
FAULT
ROADS
1000' 0' 3000'
NOTES
COPPER VALUES ARE FROM IGNEOUS ROCKS IN THE PROTORE ZONE. Mo VALUES ARE FROM SKARN AND IGNEOUS ROCKS IN BOTH SUPERGENE AND PROTORE ZONES.
THE COPPER CONTOURS REPRESENT 440 DRILL HOLES WHICH EXTEND BELOW THE CHALCOCITE BLANKET. PROTORE INTERVALS OF OVER 50' WERE USED AS PRIMARY CONTOUR GUIDES AND 20-50' INTERVALS AS SECONDARY GUIDES.
DISCONTINUOUS Mo CONTOURS REPRESENT INSUFFICIENT DATA.
DISPOSITION BEFORE FAULTING
QUARTZ VEIN
NO DATA
< .010 % Mo
EL TIRO PIT
A-B FAULT ZONE
OXIDE PIT
NO DATA

FIGURE 2

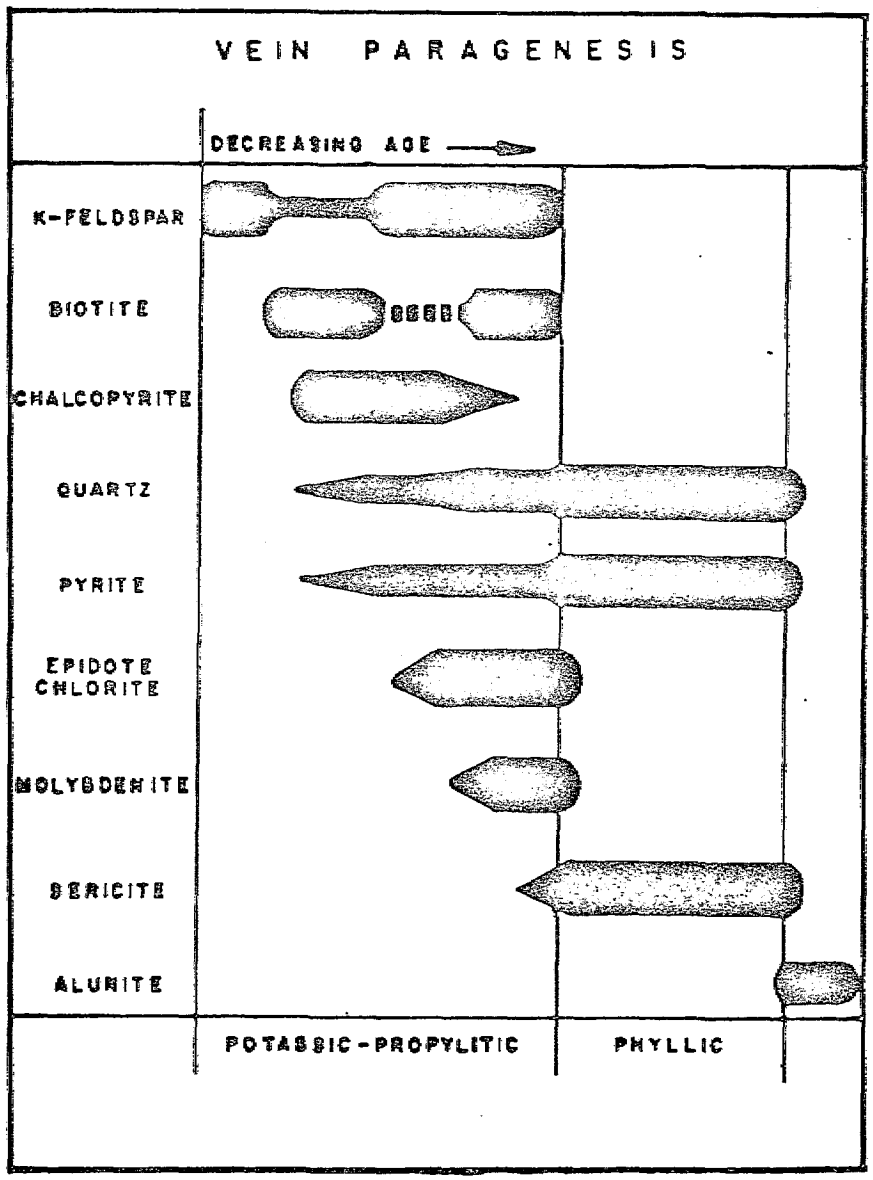
VEIN PARAGENESIS
DECREASING AGE
K-FELDSPAR
BIOTITE
CHALCOPYRITE
QUARTZ
PYRITE
EPIDOTE
CHLORITE
MOLYBDENITE
SERICITE
ALUNITE
POTASSIC-PROPYLITIC
PHYLLIC

FIGURE 3

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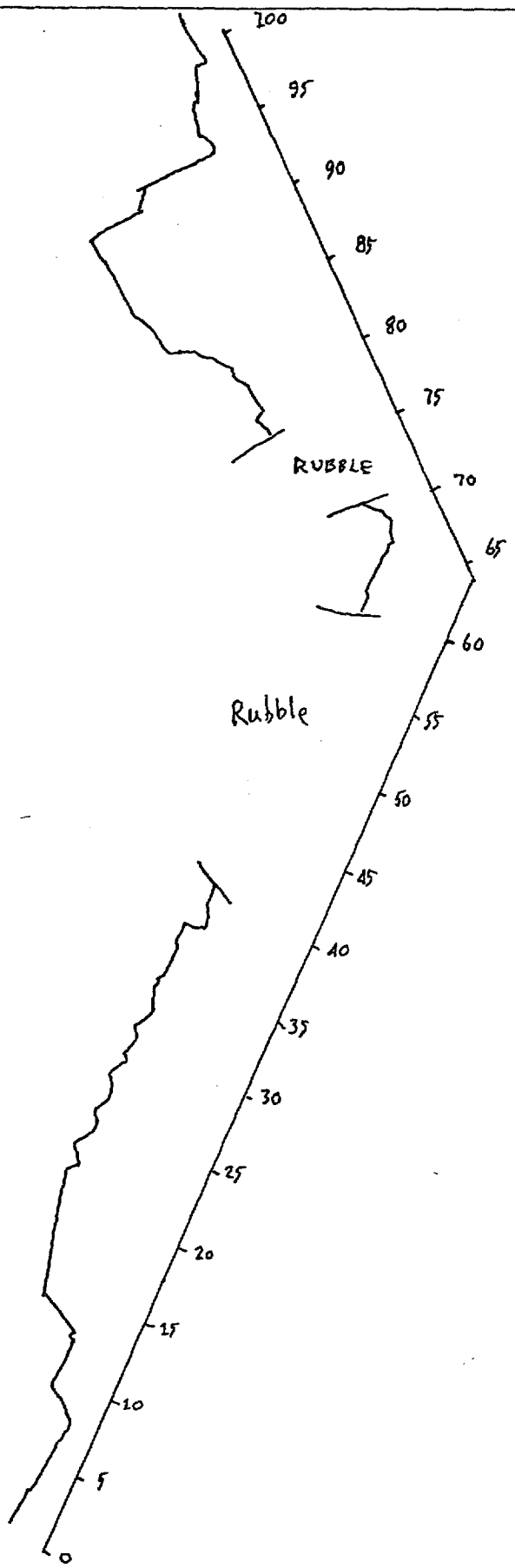
◇ ◇ ◇ STRUCTURE AND MINERALIZATION AT SILVER BELL, ARIZONA

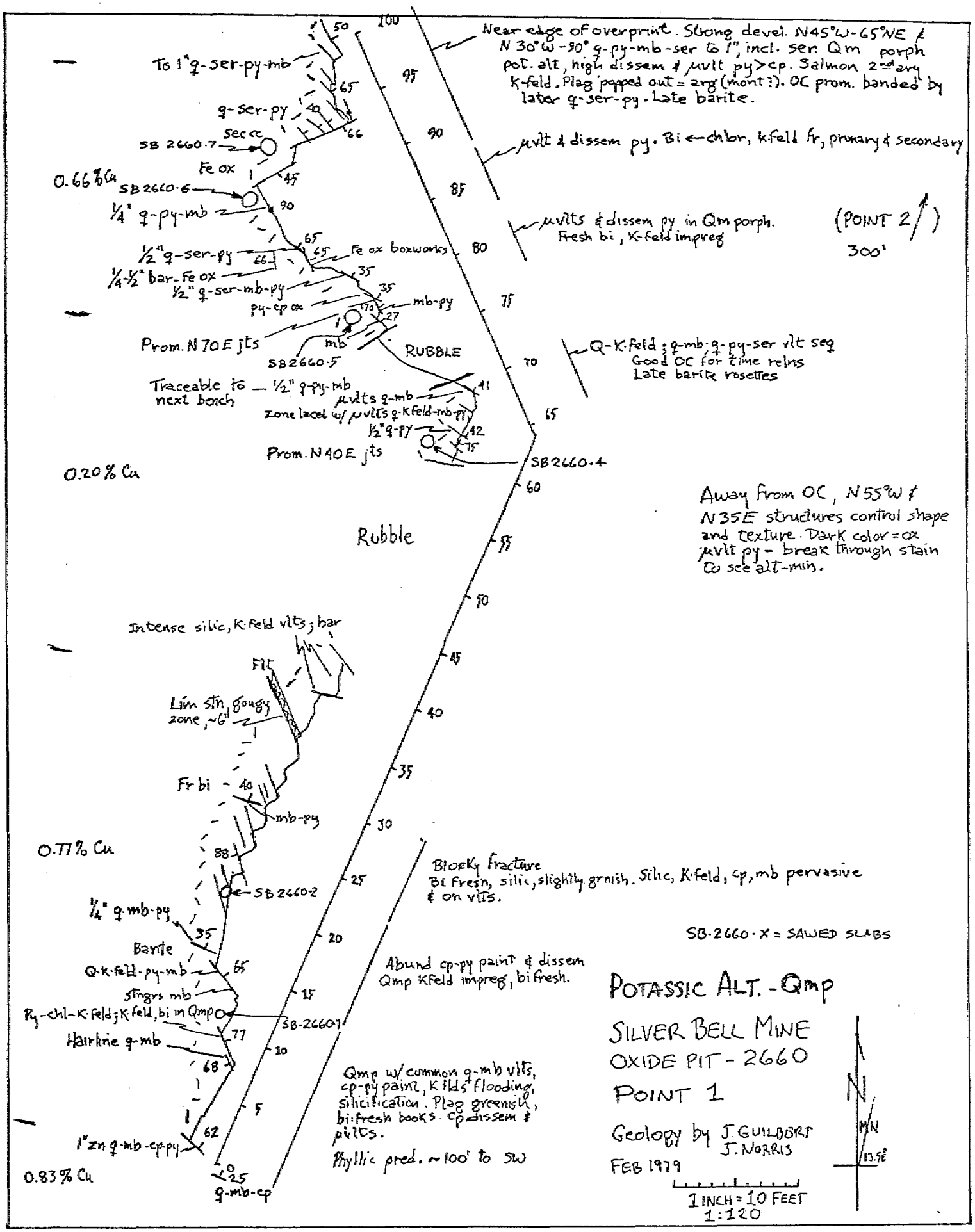
BY KENYON RICHARD AND JAMES H. COURTRIGHT

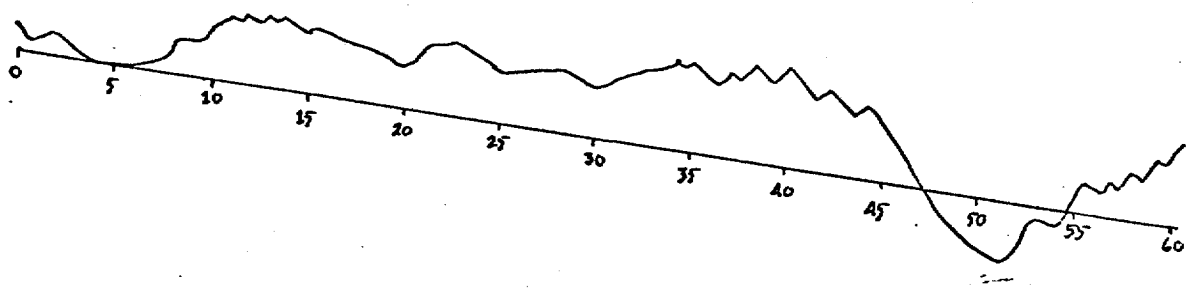


POTASSIC ALT. - Qmp

SILVER BELL MINE
OXIDE PIT - 2660
POINT 1

1 INCH = 10 FEET
1:120


Near edge of overprint. Strong devel. N45°W-65°NE & N 30°W-90° q-py-mb-ser to 1", incl. ser. Qm porph pot. alt, high dissem & µvlt py>cp. Salmon 2ndary K-feld. Plag popped out = arg (mont?). OC prom. banded by later q-ser-py. Late barite.
µvlt & dissem py. Bi ← chlor, K-feld fr, primary & secondary
µvlts & dissem py in Qm porph. Fresh bi, K-feld impreg
(POINT 2)
300'
To 1" q-ser-py-mb
q-ser-py
sec cc
SB 2660-7
Fe ox
0.66% Cu
SB 2660-6
1/4" q-py-mb
1/2" q-ser-py
Fe ox boxworks
1/4-1/2" bar-Fe ox
1/2" q-ser-mb-py
py-cp ox
mb-py
Prom. N70E jts
mb
SB2660-5
RUBBLE
Q-K-feld; q-mb; q-py-ser vlt seq
Good OC for time relns
Late barite rosettes
Traceable to next bench
1/2" q-py-mb
µvlts q-mb
zone laced w/ µvlts q-K feld-mb-py
1/2" q-py
Prom. N40E jts
SB2660-4
0.20% Cu
Away from OC, N55°W & N35E structures control shape and texture. Dark color = ox µvlt py - break through stain to see alt-min.
Rubble
Intense silic, K-feld vlts; bar
Flt
Lim stn, gougy zone, ~6'
Fr bi
mb-py
0.77% Cu
SB 2660-2
Blocky fracture
Bi fresh, silic, slightly grnish. Silic, K-feld, cp, mb pervasive & on vlts.
1/4" q-mb-py
Barite
Q-K-feld-py-mb
stngrs mb
Abund cp-py paint & dissem Qmp K feld impreg, bi fresh.
Py-chl-K-feld; K feld, bi in Qmp
SB-2660-1
Hairline q-mb
Qmp w/ common q-mb vlts, cp-py paint, K flds flooding, silicification. Plag greenish, bi fresh books. cp dissem & vlts.
Phyllic pred. ~100' to SW
1" zn q-mb-cp-py
0.83% Cu
q-mb-cp
SB-2660-X = SAWED SLABS
POTASSIC ALT. - Qmp
SILVER BELL MINE
OXIDE PIT - 2660
POINT 1
Geology by J. GUILBERT
J. NORRIS
FEB 1979
1 INCH = 10 FEET
1:120
N
MN
13.5°E

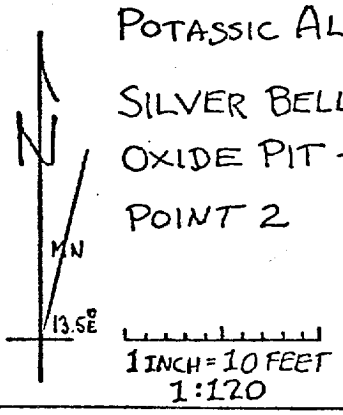


POTASSIC ALT - ALASKITE

SILVER BELL MINE

OXIDE PIT - 2660 BENCH

POINT 2

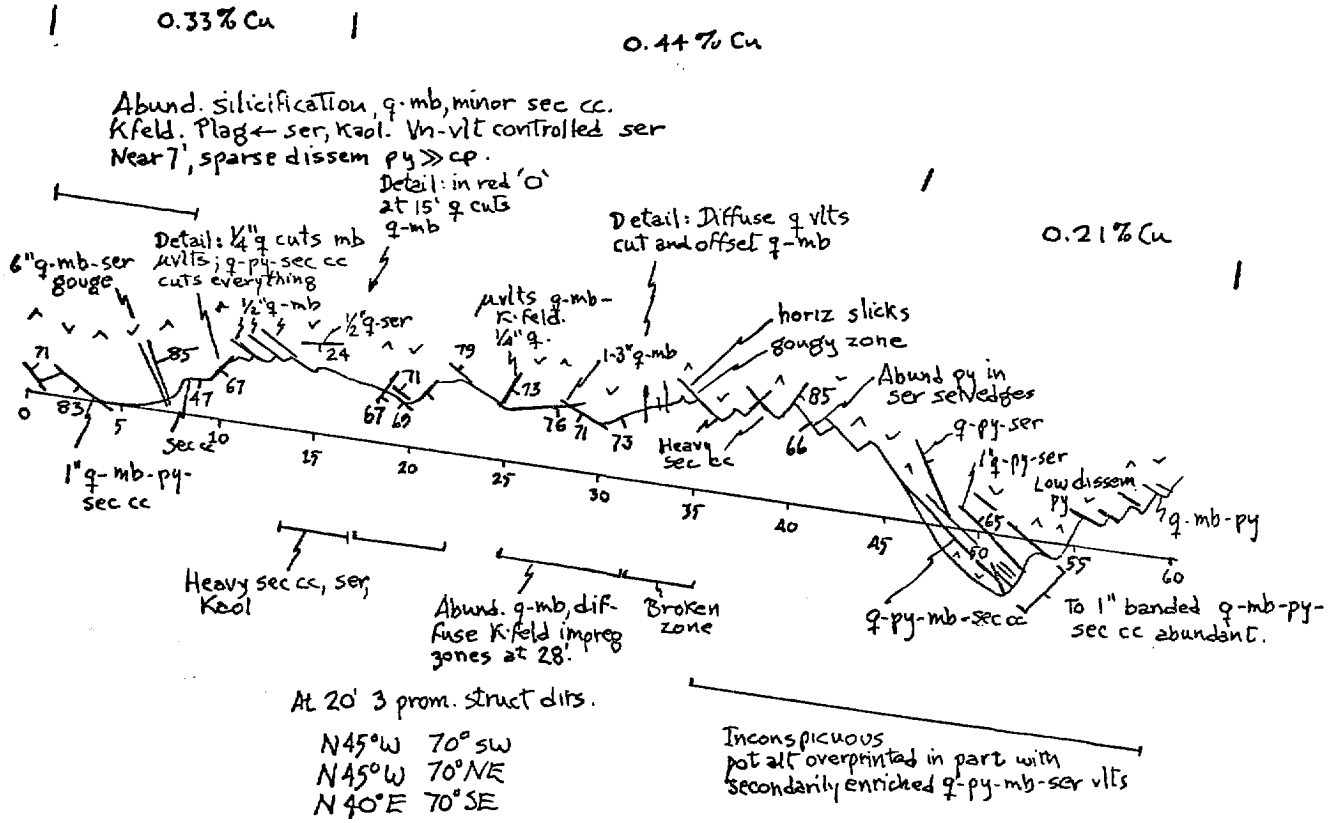


Points 1 and 2

These stops provide an excellent opportunity to examine some of the qualitative and quantitative differences in structural, alteration, and mineralization response of different rock types. Point 1 is in Qmp, and Point 2 is in Alaskite. Both areas show strong development of N40-60°W and N30-50°E fracturing, with variable N10-20°W and random orientations. The alaskite breaks more massively, the Qmp more blockily, and fracture density varies accordingly.

Careful study is required to see differences in alteration response. Note first that Point 1 constitutes a nose in a linear zone of potassic alteration relatively deep and central to Oxide Pit, the color contrast (dark potassic, much lighter phyllic) being apparent. Phyllic overprint encroaches only a few tens of feet SW of Point 1, and predominates about 100 feet SW of the tape end point. Similarly, q-ser takes over north of the 100 foot tape intercept. You may want to walk these gradational contacts out a bit. Be sure also to compare and contrast within the rock types. The alteration assemblage is relatively rich in K-feldspar and quartz. Biotite, sericite, and the characterizing accessories such as anhydrite have been seen in thin section, but they are inconspicuous. Note both diffuse, impregnation salmon-colored K-feldspar zones which appear earliest (see also Points 4 and 5), & more discrete quartz-filled veinlets with K-feldspar sporadically in the veinlets and abundantly replacing wall-rock feldspars, with sparse biotite ranging from fresh to chloritized. Sulfides include cp, py-mb. No epidote, albite, or zeolite has been found here (see Point 6). These veinlets are cut at least by q-py and q-py-mb with ser, especially toward the phyllic-predominant borders. Potassic alteration is quantitatively best developed in Qmp, and alaskite (originally only quartz and K-feldspar) is a poor recorder. Disseminated sulfides vary accordingly. Try to see the quantitative and qualitative differences. Use the sawed slabs and map notes to zero in, and consider Points 1 and 2 one stop.

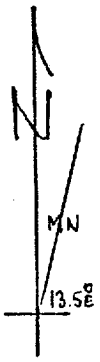
Veins of barite ± galena are noted occasionally across the face. The orientation of the veins is generally NNE and they cross-cut copper mineralization. In El Tiro pit, the veins become dominated by a mineralogical assemblage of fluorite, galena, calcite, and sphalerite. This post-copper mineralizing stage is found throughout the district.



Alaskite throughout. Poor recorder of K-alt. Minor dissem py-cp. Abund vlts-µvlts q, q-mb, q-mb-py-sec cc, q-ser-py. Low plag cont ← ser & Kaol, K-feld ess. fresh. Evidence of prev. Kalt = q-mb w/ K-feld selvedges, K-feld impreg. Cut by q-ser-py w/ general overprint of sericite and kaolinite, not recess py-stable. Whole face lightly ox-lim.

SB-2660-X = SAWED SLABS

(POINT 1 ↙)
300'



POTASSIC ALT - ALASKITE

SILVER BELL MINE

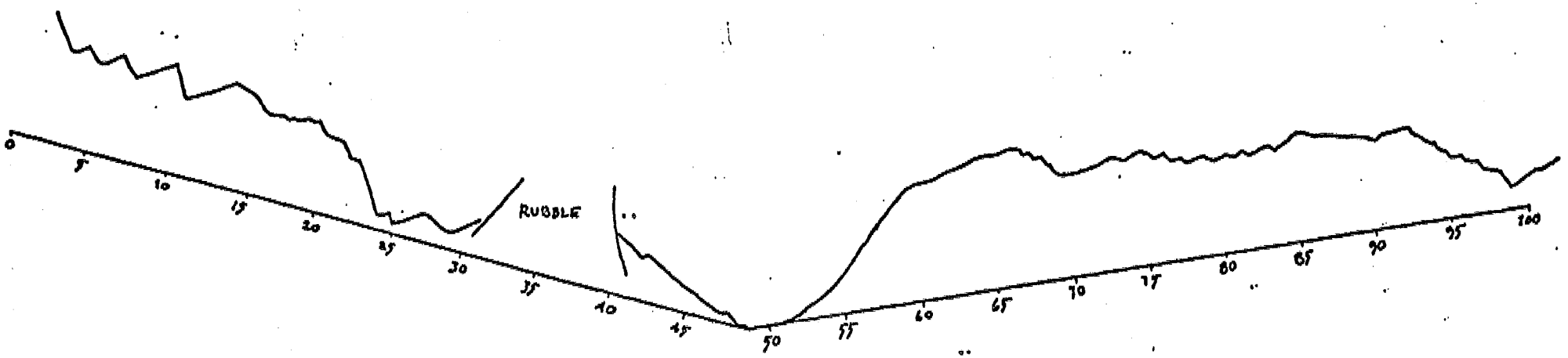
OXIDE PIT - 2660 BENCH

POINT 2

Geology by J. Guilbert
Feb 1979 J. Norris

1 INCH = 10 FEET
1:120

= Alaskite

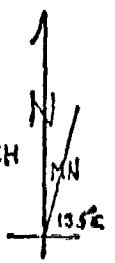


PROPYLITIC ALT.

SILVER BELL MINE

OXIDE PIT -3020 BENCH

POINT 3



1 INCH = 10 FEET
1:120

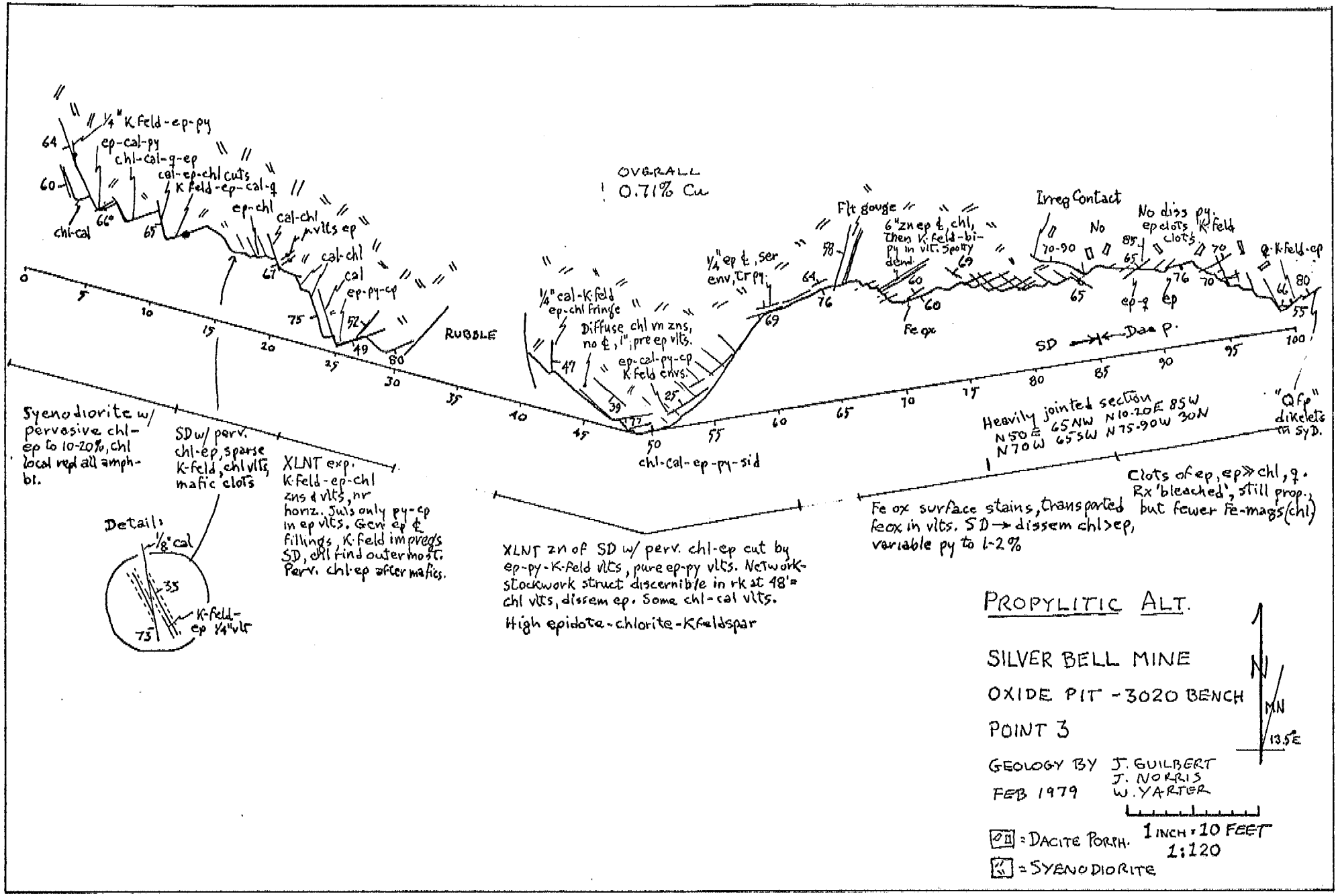
Point 3

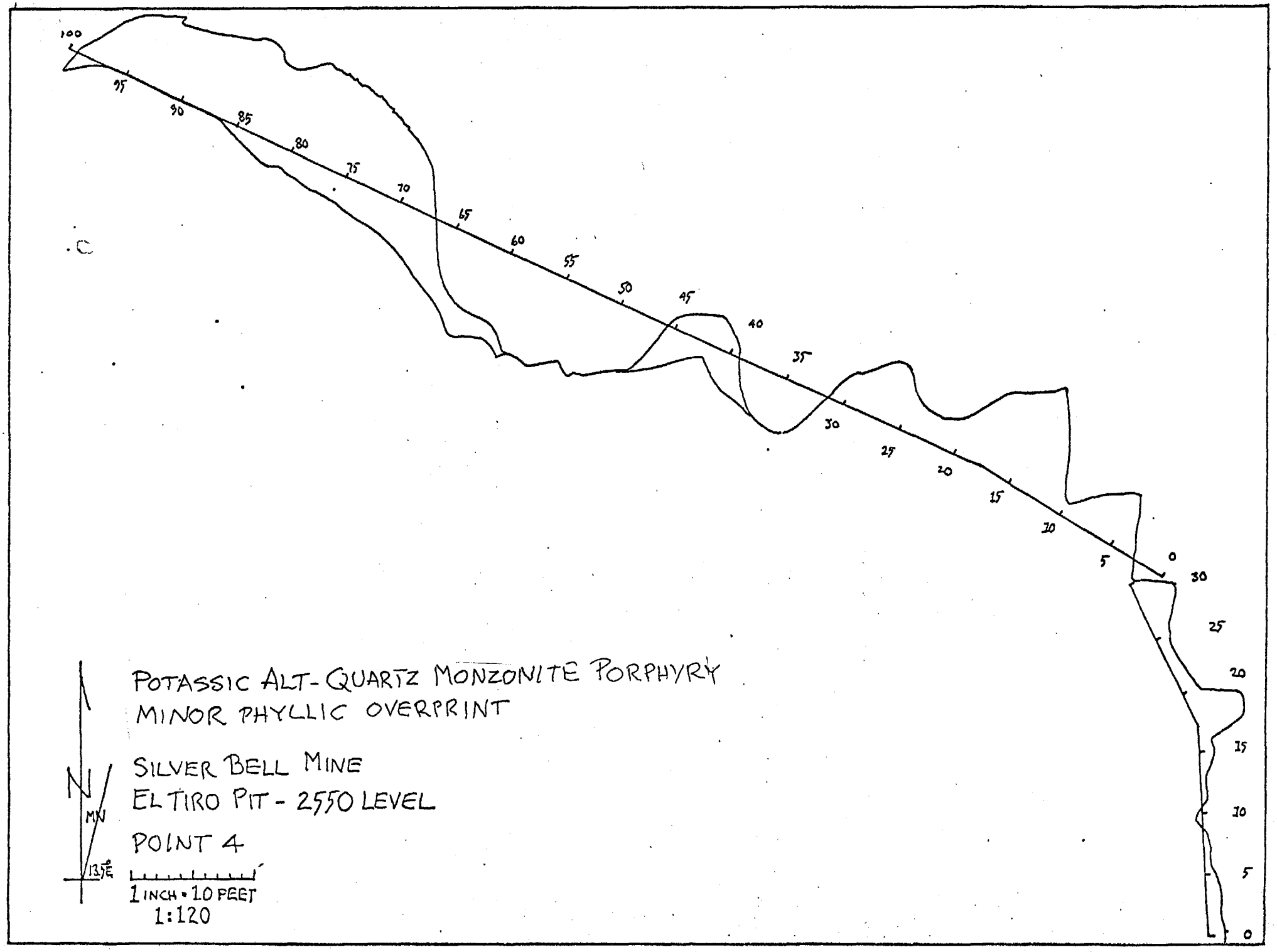
This stop provides an excellent example of propylitic alteration. Note that this 'reagent' rock is more mafic than the quartz monzonite porphyry, alaskite, and dacite porphyry, so it is not surprising that it is an excellent register of propylitization. The syenodiorite contains K-feldspar, hornblende, biotite, and plagioclase, when fresh. The hornblende and plagioclase are especially susceptible to epidotization and calcitization, and hornblende and biotite to chlorite. K-feldspar appears stablized by high K activities and K^+/H^+ ratios consistent with the abundance of primary K-feldspar and alteration calcite. Biotite even appears stable with respect to chlorite (K-vs non-K-minerals) in a veinlet at 70 feet. Albite has not been reported.

The normal propylite assemblage - epidote, chlorite, carbonate (normally calcite), and K-feldspar - is abundantly displayed here, with modest plus amounts of pyrite and chalcopyrite. Mixed 'spotty' and normal dendrites suggest a few hundred ppmCu. The assemblage occurs pervasively, as the chlorite-epidote generalized replacement of primary amphibole from 0-15, and as early,diffuse,chlorite vein-zones which are vaguely structure-controlled but which lack centerlines, and may be analogous to the diffuse K-feldspar zones at Point 4 in the presence of lower K and higher Fe-Mg. K-feldspar, epidote, chlorite, and calcite, $\pm$ quartz and sulfides appear in coeval veinlets in varying proportions. Generally, epidote-sulfide veinlets cut the chlorite zones (as at 45-50 feet), and calcite-rich veinlets appear younger. Either chlorite selvedges or K-feldspar impregnations flank quartz or epidote-chlorite-filled veinlets. Note too that propylitized dacite porphyry, slightly more felsic, is lighter in color with some sericite? and few ferromagnesian alteration phases (chlorite), although epidote remains at higher levels.

This outcrop is too restricted to show real zoning within propylitization such as will be described and visited at North Silver Bell.

Plan to study and map temporal relationships, and consider how potassic alteration of this rock might be manifested. This outcrop is reasonably typical of propylitization in other districts. The width of the 'propylitic halo' is measured in hundreds of feet here, but is narrower than at North Silver Bell.


OVERALL
0.71% Cu
1/4" K.feld-ep-py
ep-cal-py
chl-cal-g-ep
cal-ep-chl cuts
K feld-ep-cal-q
ep-chl
cal-chl
vlts ep
cal-chl
cal
ep-py-cp
chl-cal
RUBBLE
1/4" cal-K.feld
ep-chl fringe
Diffuse chl in zns, no ℄, 1"; pre ep vlts.
ep-cal-py-cp
K feld envs.
chl-cal-ep-py-sid
1/4" ep ℄, ser env, tr py.
Flt gouge
6" zn ep ℄, chl, then K.feld-bi-py in vlt. Spotty dend.
Fe ox
Irreg Contact
No
No diss py, ep clots
K feld clots
ep-q
ep
Q-K.feld-cp
SD → ← Dac P.
Syenodiorite w/ pervasive chl-ep to 10-20%, chl local repl all amph-bl.
SD w/ perv. chl-ep, sparse K-feld, chl vlts, mafic clots
XLNT exp. K.feld-ep-chl zns & vlts, nr horiz. Jts only py-cp in ep vlts. Gen ep ℄ fillings, K.feld impreds SD, chl rind outermost. Perv. chl-ep after mafics.
Details:
1/8" cal
35
K-feld-ep 1/4" vlt
73
XLNT zn of SD w/ perv. chl-ep cut by ep-py-K-feld vlts, pure ep-py vlts. Network-stockwork struct discernible in rk at 48'= chl vlts, dissem ep. Some chl-cal vlts.
High epidote-chlorite-K feldspar
Fe ox surface stains, transported feox in vlts. SD → dissem chl>ep, variable py to 1-2%
Heavily jointed section
N50E 65NW N10-20E 85W
N70W 65SW N75-90W 30N
Clots of ep, ep≫chl, q. Rx 'bleached', still prop., but fewer Fe-mags (chl)
"Qfp" dikelets in SYD.
PROPYLITIC ALT.
SILVER BELL MINE
OXIDE PIT - 3020 BENCH
POINT 3
GEOLOGY BY J. GUILBERT
J. NORRIS
FEB 1979 W. YARTER
N
MN
13.5°E
1 INCH = 10 FEET
1:120
= DACITE PORPH.
= SYENODIORITE

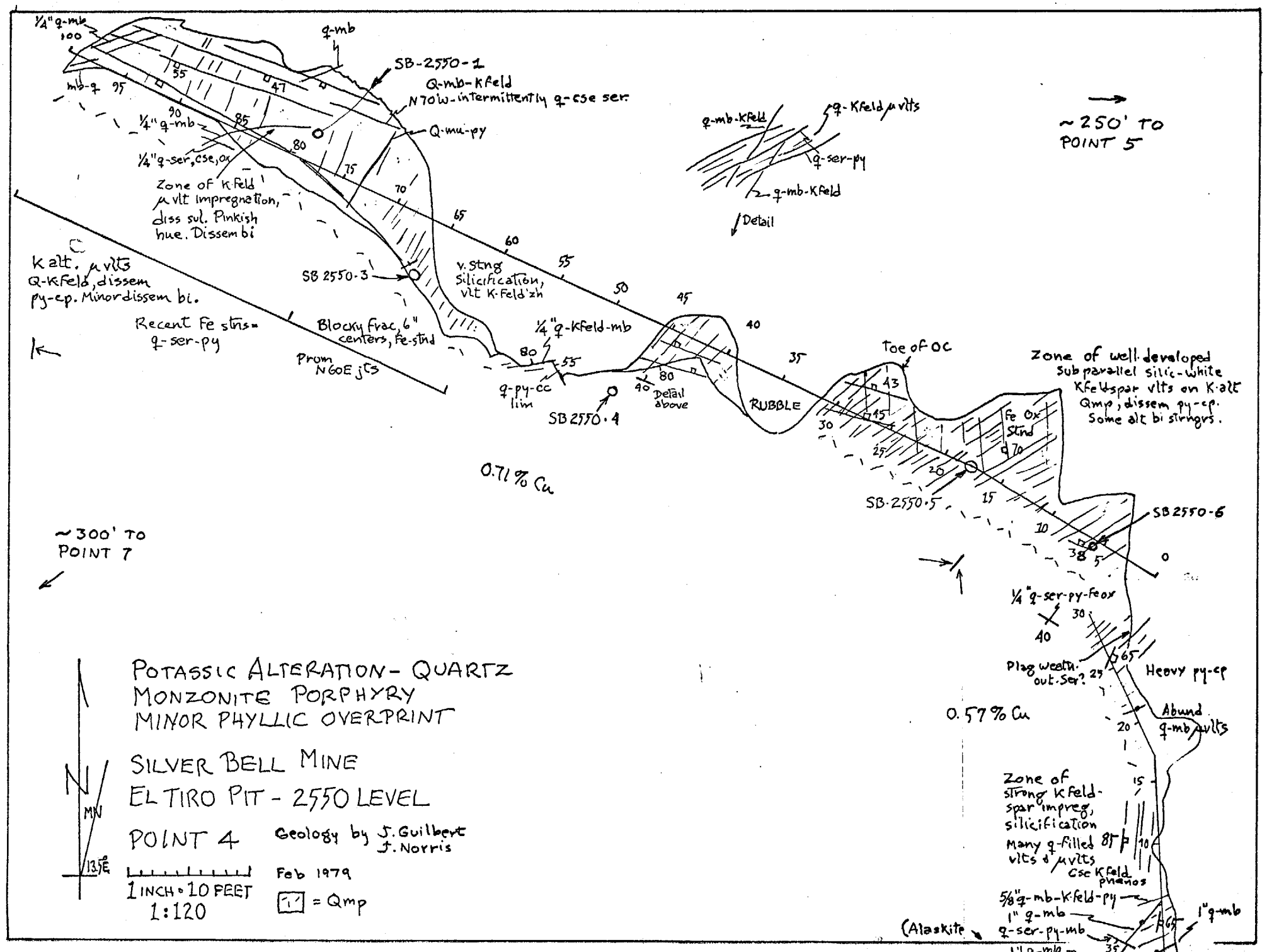

POTASSIC ALT-QUARTZ MONZONITE PORPHYRY
MINOR PHYLLIC OVERPRINT
SILVER BELL MINE
EL TIRO PIT - 2550 LEVEL
POINT 4
N
MN
13.5°E
1 INCH = 10 FEET
1:120

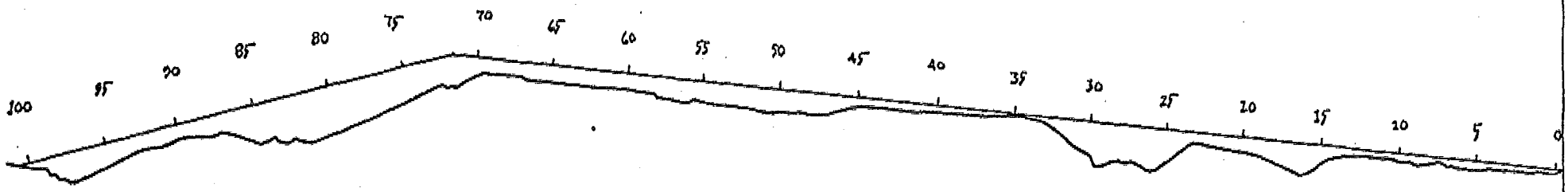
Points 4 and 5

These two localities are 300 feet apart deep in the El Tiro Pit. They were selected to demonstrate potassic alteration in quartz monzonite porphyry, and to suggest (as at Points 1 and 2) that such alteration is not a single static 'thing', a single 'event', but rather a process, a continuum, with chemical, structural, and temporal evolution. These two observation points both show potassic alteration to excellent advantage, but some effort (as usual) is required. Both points also show later, superimposed quartz-sericite-pyrite, clearly structurally controlled and generally in the N70E, nearly vertical attitude, the 'phyllic overprint' shown to excellent advantage at Point 7 to the northwest around the ramp. Study the veinlets in the outcrops, and have a look at the slabs for clarification.

Quartz monzonite porphyry is probably the best recorder of potassic alteration. It seems to have fractured well, to have lent itself well to healing and refracture, and to have been chemically receptive. The earliest manifestations are structurally diffuse, like the diffuse but planar impregnations of K-feldspar, suggesting diffusion contact in barely competent, perhaps not totally crystallized rock. These earliest zones may or may not have thin quartz centerlines, and the K-feldspar may be pink or white. Next to form here were fine quartz-biotite-cp-py micro-veinlets (1-3 mm wide), either diffuse or sharp-walled, and commonly now chloritized. These veinlets are cut by veinlets of q-K-feld-py-cp in widely varying proportions and styles, from nearly pure quartz to thin (to less than 1 mm) high-sulfide hairline veinlets. The high quartz ('bull' quartz) generally show little K-impregnation and may be early within the group. Molybdenite relationships are not clear. Veinlets with molybdenite may contain K-feldspar, although simple q-mb veinlets are common. They are typically straight and continuous, may cut and offset each other, and appear late within the group.

Quartz-sericite-pyrite in well-defined veinlets and veins to several cm wide with prominent, gray silicified-sericitized envelopes are young. Some appear to be cut by a second generation (?) q-K-feldspar assemblage, but as a group they clearly post-date potassic alteration. Close study of the slabs is informative.


1/4" q-mb
q-mb
SB-2550-1
Q-mb-Kfeld
N70W-intermittently q-cse ser.
Q-mu-py
1/4" q-mb
1/4" q-ser, cse, ox
Zone of K-feld μ vlt impregnation, diss sul. Pinkish hue. Dissem bi
mb-q
q-mb-Kfeld
q-Kfeld μ vlts
q-ser-py
q-mb-Kfeld
Detail
~250' TO POINT 5
K alt. μ vlts Q-Kfeld, dissem py-cp. Minor dissem bi.
SB 2550-3
v. stng Silicification, vlt K-feld'zn
Recent Fe stns = q-ser-py
Blocky frac, 6" centers, Fe-stnd
Prom N60E jcs
1/4" q-Kfeld-mb
q-py-cc lim
SB 2550-4
Detail above
RUBBLE
Toe of OC
Zone of well developed sub parallel silic-white Kfeldspar vlts on K-alt Qmp, dissem py-cp. Some alt bi stringrs.
Fe Ox Stnd
0.71 % Cu
SB-2550-5
SB 2550-6
~300' TO POINT 7
1/4" q-ser-py-feox
Plag weath. out. Ser?
Heavy py-cp
Abund q-mb μ vlts
0.57 % Cu
Zone of strong Kfeld-spar impreg, silicification
Many q-filled vlts & μ vlts
Csc Kfeld phenos
5/8" q-mb-Kfeld-py
1" q-mb
(Alaskite
q-ser-py-mb
1" q-mb
1" q-mb
POTASSIC ALTERATION - QUARTZ MONZONITE PORPHYRY
MINOR PHYLLIC OVERPRINT
SILVER BELL MINE
EL TIRO PIT - 2550 LEVEL
POINT 4
Geology by J. Guilbert J. Norris
Feb 1979
1 INCH = 10 FEET
1:120
= Qmp
N
MN
13.5°E

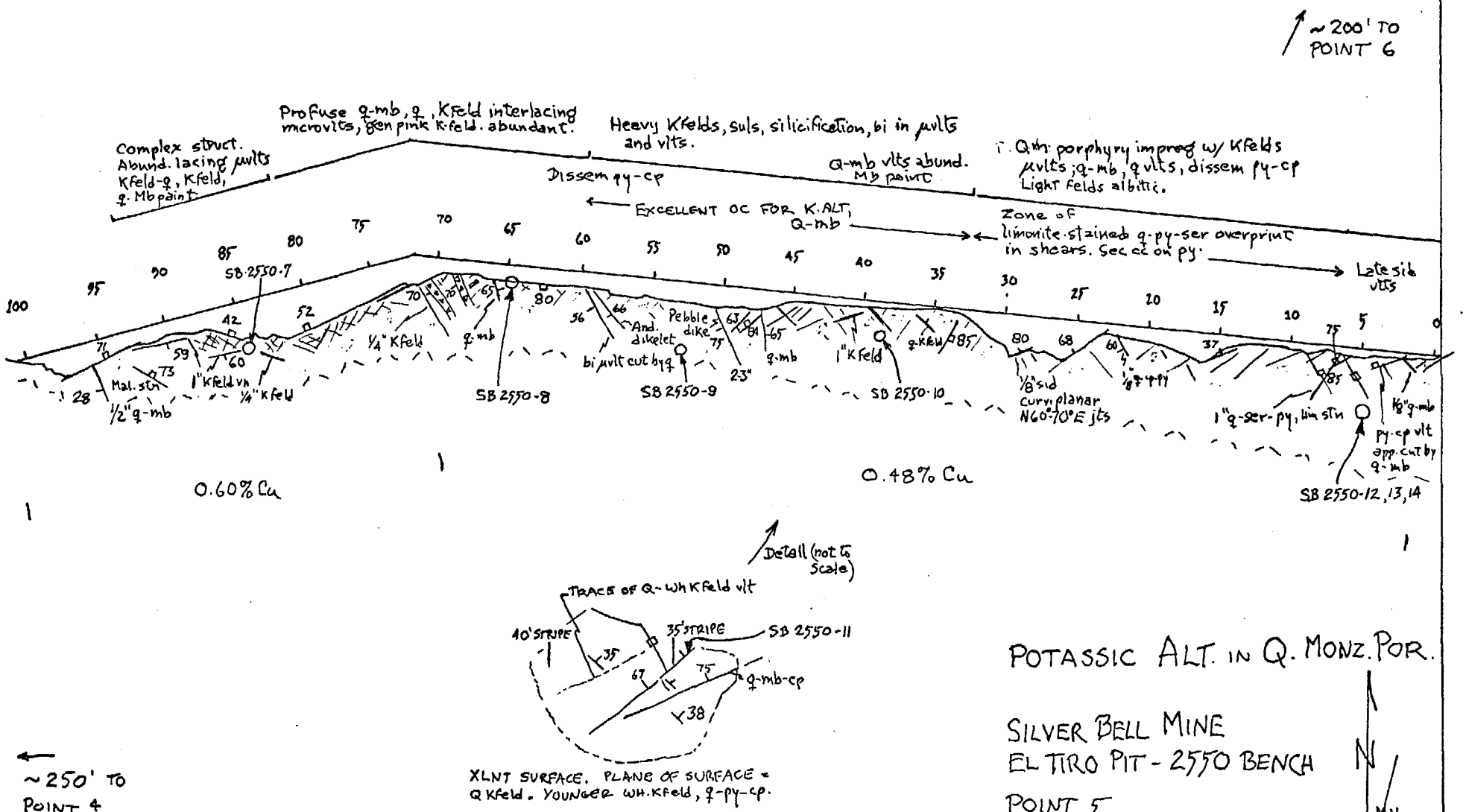


POTASSIC ALT.

SILVER BELL MINE
EL TIRO PIT - 2550 BENCH
POINT 5

N
MN
13.5°

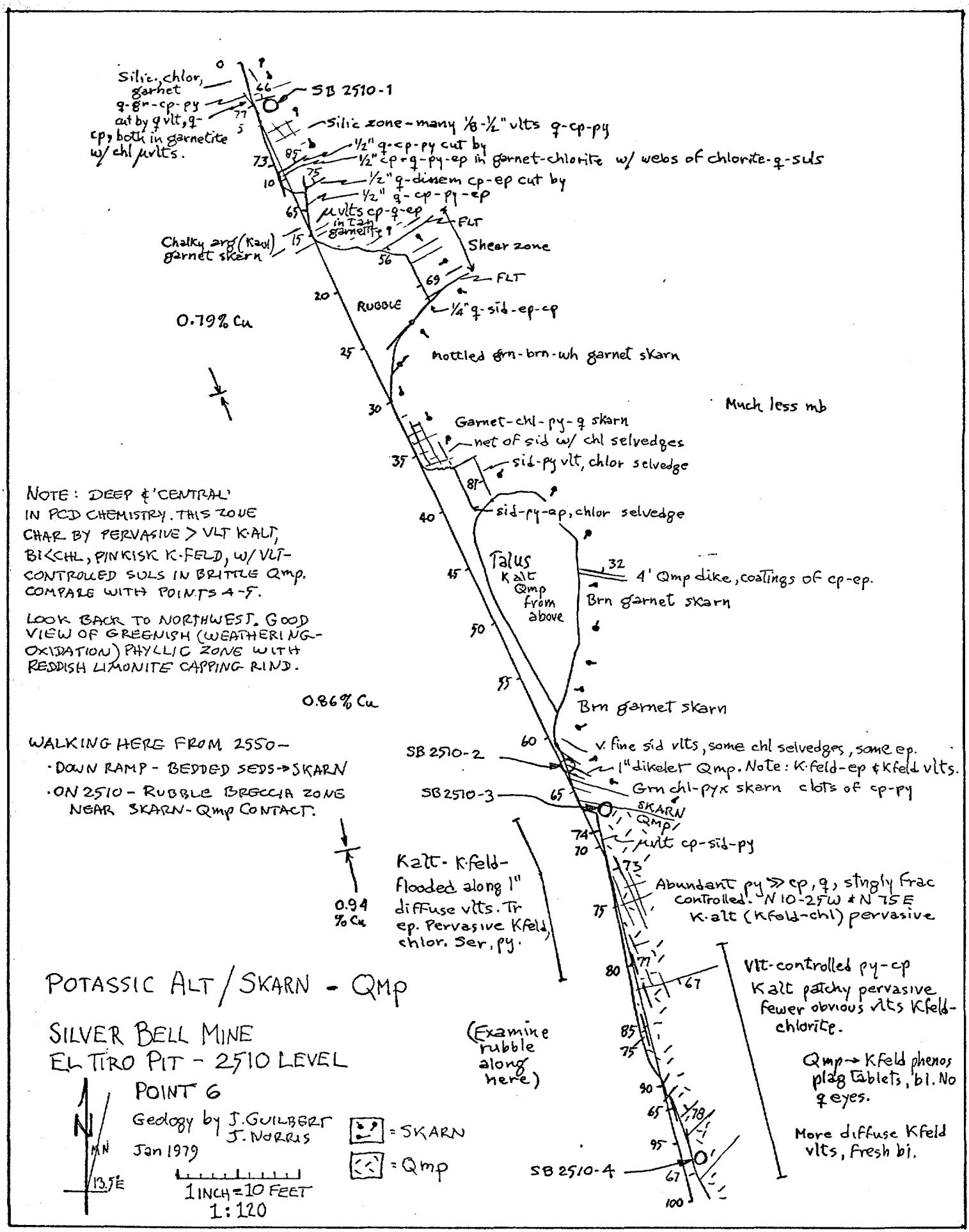
1 INCH = 10 FEET
1:120


~200' TO POINT 6
Complex struct. Abund. lacing µvlts Kfeld-q, Kfeld, q. Mb paint
Profuse q-mb, q, Kfeld interlacing microvlts, gen pink K-feld. abundant.
Heavy Kfelds, suls, silicification, bi in µvlts and vlts.
Q-mb vlts abund. Mb paint
T. Qtz porphyry impreg w/ Kfelds µvlts; q-mb, q vlts, dissem py-cp Light felds albitic.
Dissem py-cp
EXCELLENT OC FOR K. ALT, Q-mb
Zone of limonite-stained q-py-ser overprint in shears. See cc on py.
Late sil vlts
SB 2550-7
SB 2550-8
SB 2550-9
SB 2550-10
SB 2550-12, 13, 14
Mal. stn
1/2" q-mb
1" Kfeld vn
1/4" Kfeld
1/4" Kfeld
q-mb
bi µvlt cut by q
And. dikelet
Pebble dike
23"
q-mb
1" Kfeld
q-Kfeld
1/8" sil curviplanar N60°-70°E jts
1/8" q-py
1" q-ser-py, lim stn
1/8" q-mb
py-cp vlt app. cut by q-mb
0.60% Cu
0.48% Cu
Detail (not to Scale)
TRACE OF Q-WH KFeld vlt
40' STRIPE
35' STRIPE
SB 2550-11
q-mb-cp
XLNT SURFACE. PLANE OF SURFACE = Q KFeld. YOUNGER WH. KFeld, q-py-cp.
~250' TO POINT 4
POTASSIC ALT. IN Q. MONZ. POR.
SILVER BELL MINE
EL TIRO PIT - 2550 BENCH
POINT 5
Geology by J. Guilbert, J Norris
Jan 1979
= Qmp
1 INCH = 10 FEET
1:120
N
MN
13.5°E

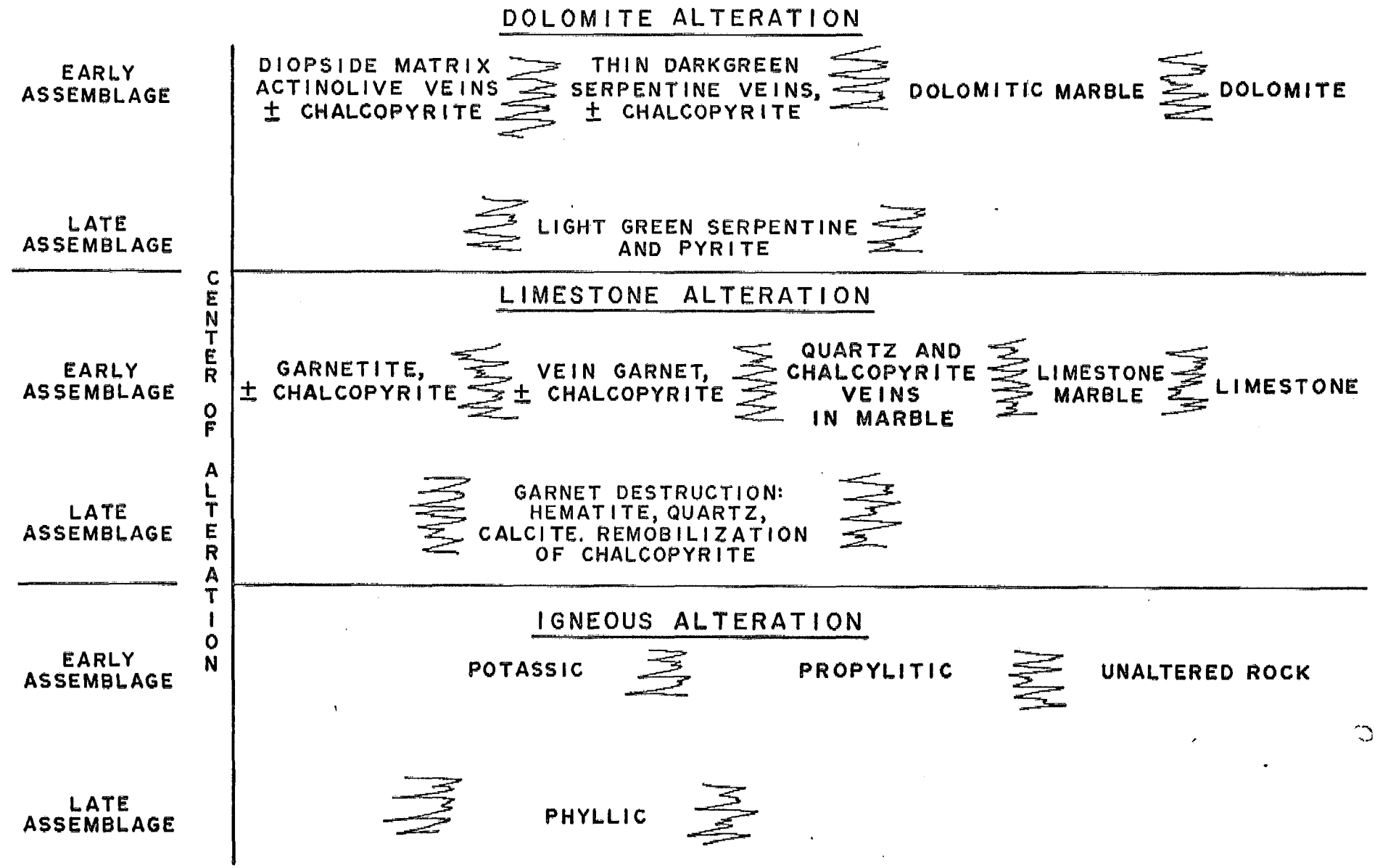
Point 6

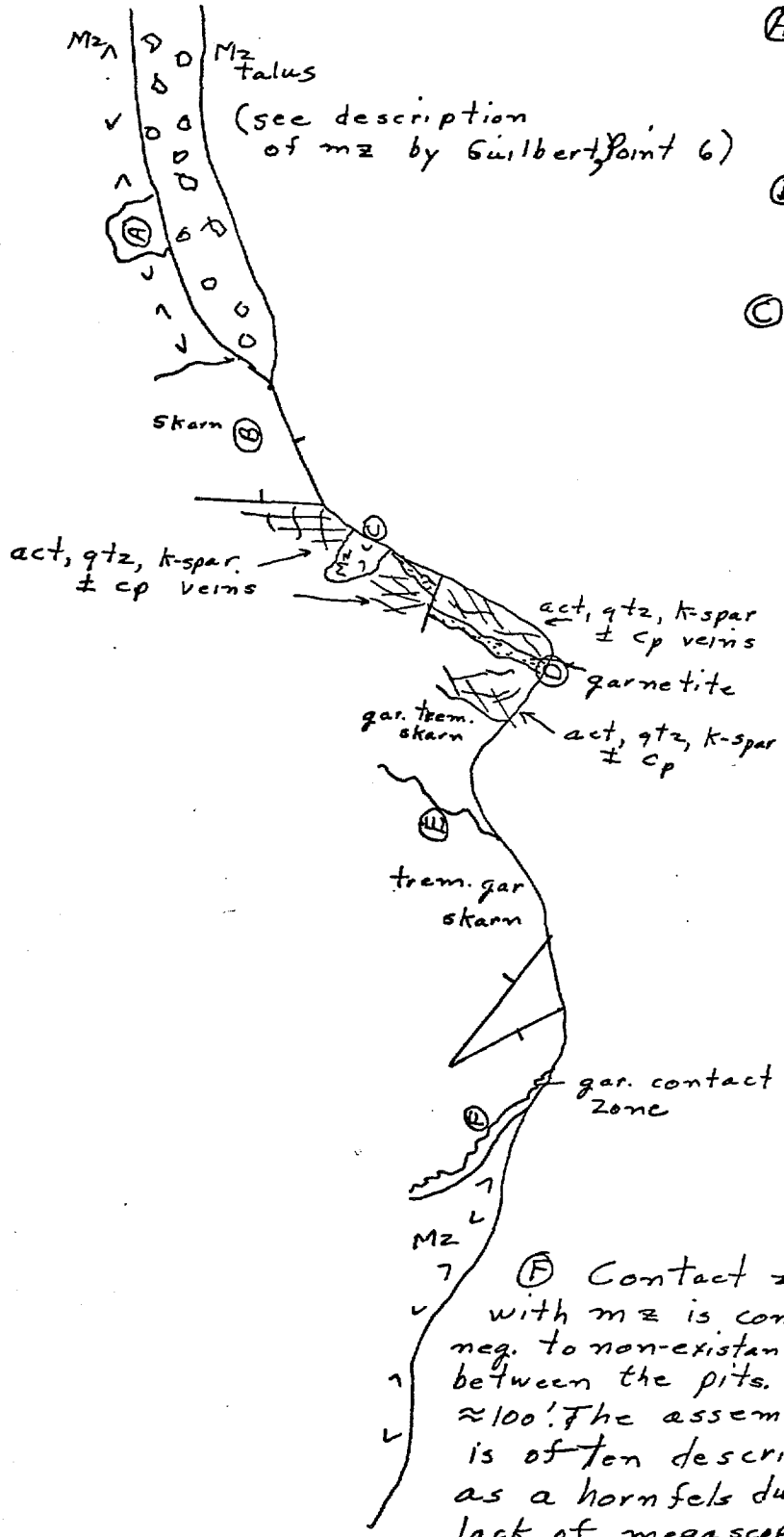
This stop has been chosen to show wall rock effects on alteration. We have walked past skarns, breccias and pebble breccias (presumably the upper reaches of Qmp intrusive activity), and several reentrants of the Qmp-skarn contact. Many of the pebble breccias are associated with hydrothermal activity. Mineralized veins are abruptly terminated at the pebble boundary. We are here as deep and central in the El Tiro Pit and the PCD system at Silver Bell as we can conveniently get. There is no evidence of 'phyllic overprint' having reached this volume except for traces of sericite-pyrite near 75 feet on the tape.

It is worthwhile here to compare the potassic alteration mineralogy here with that at Points 1 and 2 and Points 4 and 5. The small dike of Qmp in skarn at 63 feet, and at several locales close to the contact, contain a K-feldspar-epidote assemblage not apparently unlike that at Sierrita, but here the result of high Ca activity resultant from ex-limestone-skarn proximity rather than more mafic-silicate intrusive rocks. Chlorite is more prevalent than biotite in Qmp near the skarn contact, suggesting relatively lower K^+ activity in the presence of significant Fe-Mg; biotite reappears with K-feldspar near 100 feet on the tape 30 or so feet from the contact. Note also that green chlorite-pyroxene skarn appears at the contact with Qmp. The mode of occurrence of sulfides in the skarn is as clots, veinlets, and disseminations in the metamorphic silicates, appearing truly epigenetic.


Silic., chlor, garnet
q-grn-cp-py
cut by q vlt, q-cp, both in garnetite w/ chl µvlts.
SB 2510-1
Silic zone - many 1/8-1/2" vlts q-cp-py
1/2" q-cp-py cut by
1/2" cp-q-py-ep in garnet-chlorite w/ webs of chlorite-q-suls
1/2" q-dissem cp-ep cut by
1/2" q-cp-py-ep
µvlts cp-q-ep in tan garnetite
FLT
Chalky arg (Kaol) garnet skarn
Shear zone
FLT
RUBBLE
1/4" q-sid-ep-cp
0.79% Cu
mottled grn-brn-wh garnet skarn
Much less mb
Garnet-chl-py-q skarn
net of sid w/ chl selvedges
sid-py vlt, chlor selvedge
sid-py-ep, chlor selvedge
Talus
Kalt Qmp from above
4' Qmp dike, coatings of cp-ep.
Brn garnet skarn
Brn garnet skarn
0.86% Cu
v. fine sid vlts, some chl selvedges, some ep.
SB 2510-2
1" dikelet Qmp. Note: K-feld-ep & Kfeld vlts.
Grn chl-pyx skarn clots of cp-py
SB 2510-3
SKARN
QMP
µvlt cp-sid-py
Kalt-K-feld-flooded along 1" diffuse vlts. Tr ep. Pervasive Kfeld, chlor. Ser, py.
0.94 % Cu
Abundant py >> cp, q, stingly frac controlled. N 10-25W & N 75E
K-alt (Kfeld-chl) pervasive
Vlt-controlled py-cp
Kalt patchy pervasive
fewer obvious vlts Kfeld-chlorite.
(Examine rubble along here)
Qmp → Kfeld phenos plag tablets, bi. No q eyes.
More diffuse Kfeld vlts, fresh bi.
SB 2510-4
NOTE: DEEP & 'CENTRAL' IN PCD CHEMISTRY. THIS ZONE CHAR BY PERVASIVE > VLT K-ALT, BI<CHL, PINKISH K-FELD, W/ VLT-CONTROLLED SULS IN BRITTLE Qmp. COMPARE WITH POINTS 4-5.
LOOK BACK TO NORTHWEST. GOOD VIEW OF GREENISH (WEATHERING-OXIDATION) PHYLLIC ZONE WITH REDDISH LIMONITE CAPPING RIND.
WALKING HERE FROM 2550-
· DOWN RAMP - BEDDED SEDS → SKARN
· ON 2510 - RUBBLE BRECCIA ZONE NEAR SKARN-Qmp CONTACT.
POTASSIC ALT / SKARN - QMP
SILVER BELL MINE
EL TIRO PIT - 2510 LEVEL
POINT 6
Geology by J. GUILBERT
J. NORRIS
Jan 1979
= SKARN
= Qmp
MN
13.5°E
1 INCH = 10 FEET
1:120

SCHEMATIC OF SKARN ALTERATION





(A) Mz - Pot alteration with Gar. trem. skarn block in mz.

(B) Fault face masks gar, pyx, act, skarn

(C) act, qtz, k-spar, cp veins can be traced into mz. Mz shows assemblage of qtz, k-spar, cp veins.

D. Garnetite bed. Probably represents original bedding of ls. sandwiched by dolo. The alteration produced the garnetite and the act, qtz, cp, k-spar veins with a diopside & calcite matrix. Veins can be traced across each alteration phase.

(E) Change from low to high tremolite. This suggests a change in the original chemistry of the sed rx.

(F) Contact zone with mz is commonly neg. to non-existant, especially between the pits. Max. is ≈100'. The assemblage is often described as a hornfels due to lack of megascopic identification. However, this 2-3' contact shows a zone of garnet.

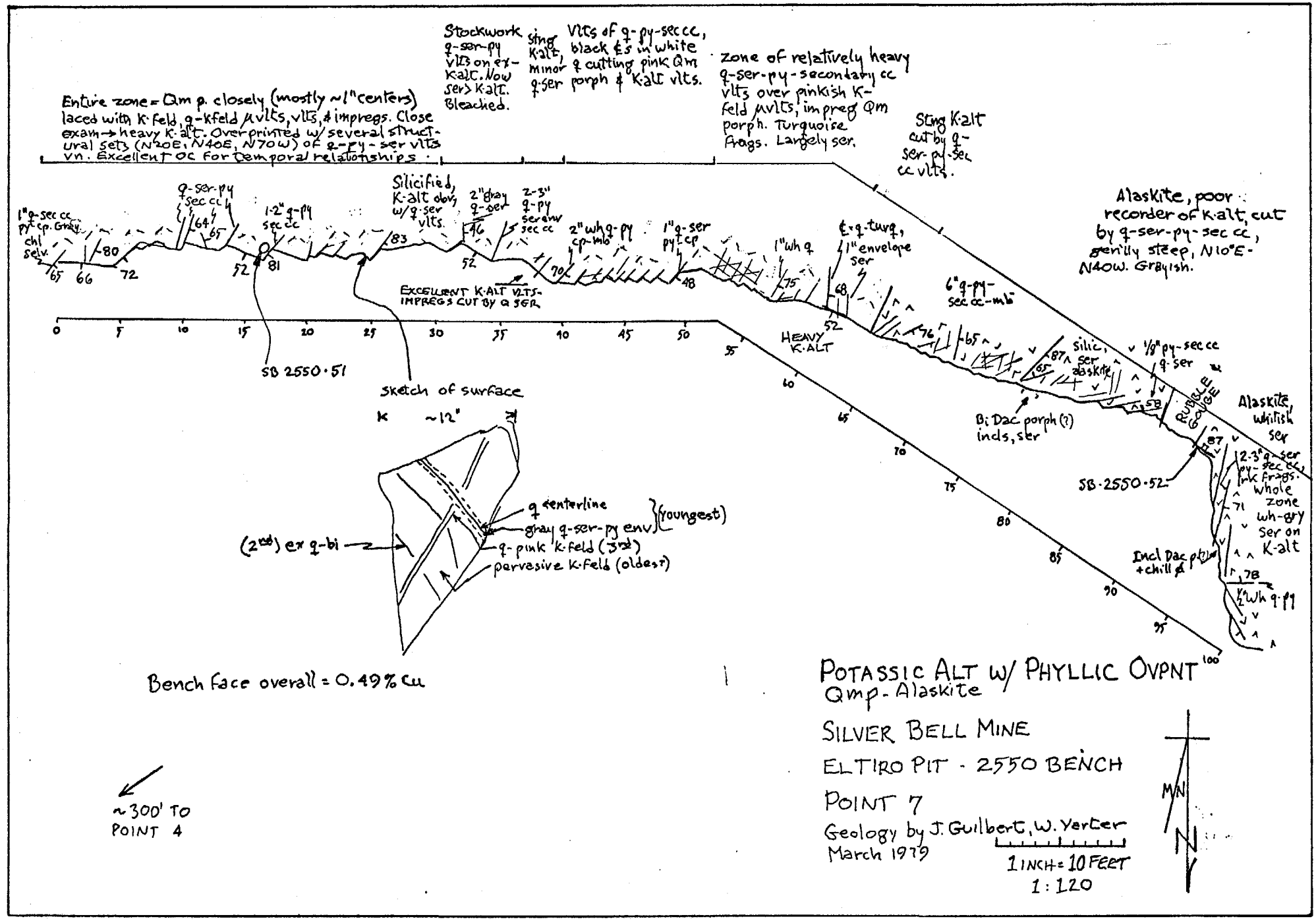
Point 6 - Supplement

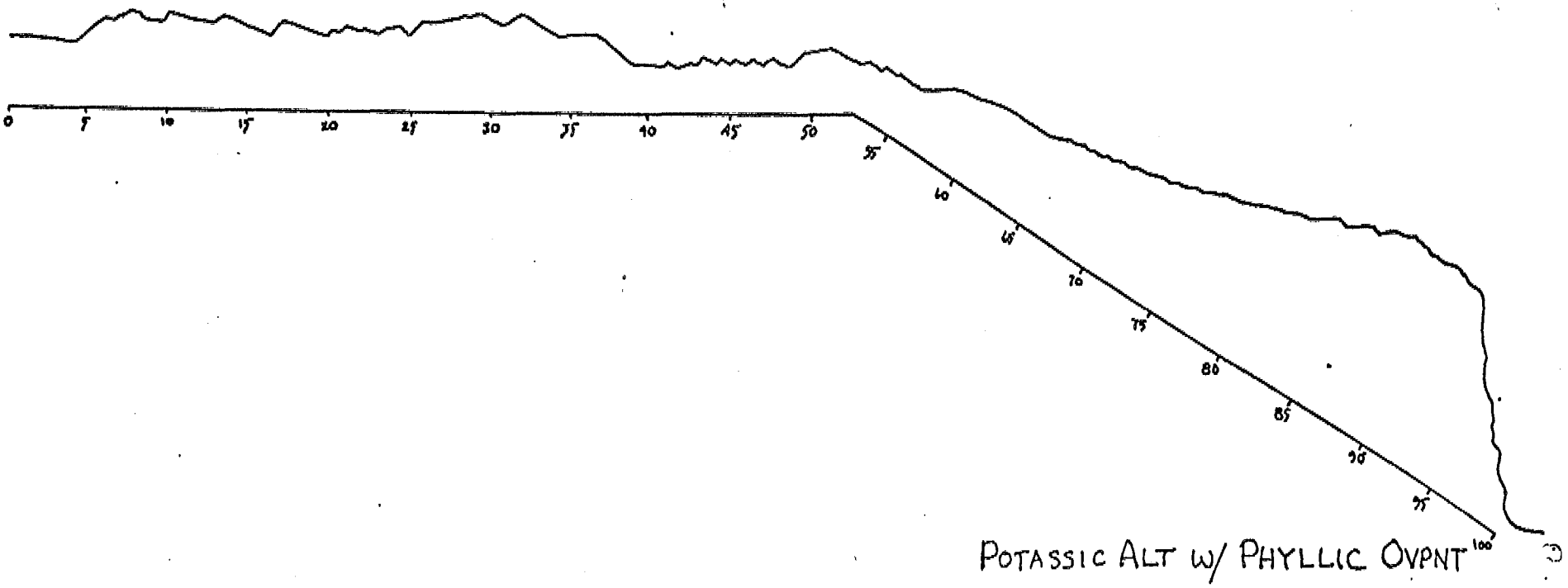
El Tiro Pit

Point 7

This bench face shows temporal relations between potassic alteration (in quartz monzonite porphyry and alaskite) and phyllic alteration of the sort that is currently being examined in the context of 'phyllic overprint'. Clearly, the quartz-sericite-pyrite assemblage here is younger than the various subtypes of potassic alteration which it cuts -- but again, the phyllic alteration is more of a process that it is a thing. There are probably at least two generations of sericite here, one which is more pervasive, associated with pyrite and strong silification, and almost certainly hypogene in the traditional sense. In some deposits-- Butte, San Manuel, Morenci -- this sericite ranges from white through shades of tan, green, even lavender. But especially since Carson and Jambor (1974) and Gustafson's and Hunt's elucidation of El Salvador (1976), 'overprint' has come to mean more surface-related, thermally retrograde effects related to invasion of lower temperature, generally less saline and more meteoric, and hence in a real sense supergene, waters. Such waters would have to have been sulfide-stable, hence of relatively low Eh, and sericite-generative. Supergene, in the older sense, was thought associated with supergene enrichment, presumably of low pH and low K^+/H^+ (and therefore more likely to strip K^+ from earlier micas producing kaolin-halloysite-allophane minerals) and of high Eh, presumably pyrite-unstable. Whether supergene sericite—supergene in the old sense — really exists has not satisfactorily been demonstrated, but you should keep this physico-chemical genetic continuum in mind as you examine these outcrops.

If production schedules and time permit, you will be able to compare these outcrops with totally sericitized ones behind you to the northeast. The 'totalness' can be either a higher component of pervasive sericitization, or greater development of 'overprint' sericite by back-to-back coalescence of veinlet-controlled q-ser-py. In many districts -- like Morenci, Cananea, and of course Butte -- sericitization of large volumes of rock is <u>total</u>; at others, like Sierrita and El Arco, sericitization is almost absent.

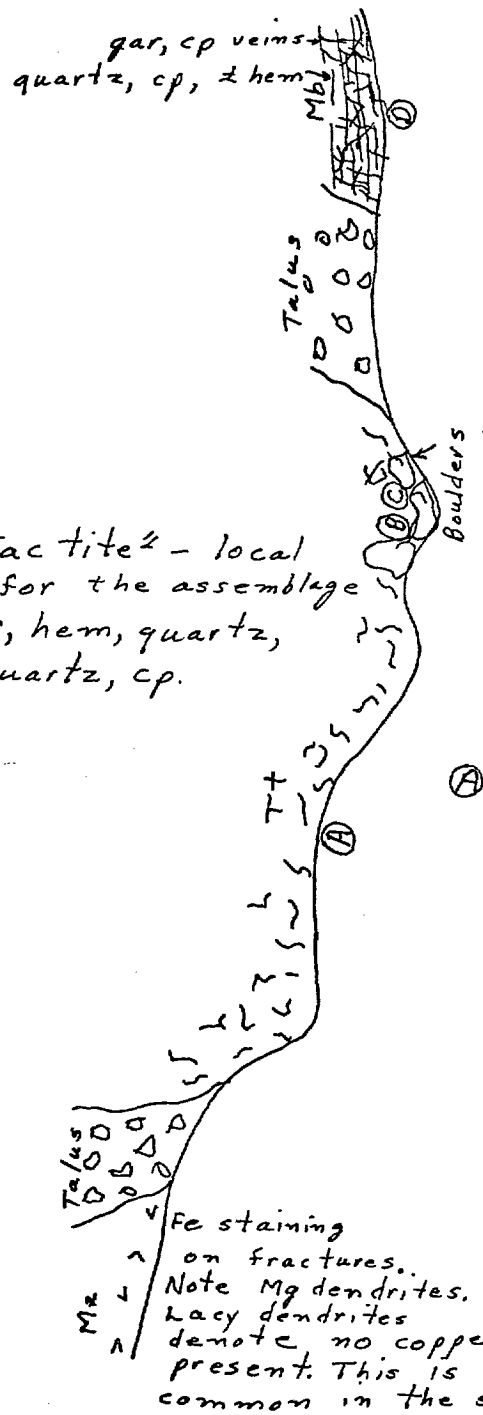

Entire zone = Qm p. closely (mostly ~1" centers) laced with K-feld, q-kfeld µvlts, vlts, & impregs. Close exam → heavy K-alt. Overprinted w/ several structural sets (N20E, N40E, N70W) of q-py-ser vlts vn. Excellent OC for temporal relationships.
Stockwork q-ser-py vlts on ex-K-alt. Now ser > K-alt. Bleached.
sting K-alt, minor q-ser porph & K-alt vlts.
vlts of q-py-sec cc, black ts in white & cutting pink Qm
zone of relatively heavy q-ser-py-secondary cc vlts over pinkish K-feld µvlts, impreg Qm porph. Turquoise frags. Largely ser.
Sting K-alt cut by q-ser-py-sec cc vlts.
Alaskite, poor recorder of K-alt, cut by q-ser-py-sec cc, gen'lly steep, N10°E-N40W. Grayish.
1" q-sec cc py cp. Gray chl selv.
q-ser-py sec cc
1-2" q-py sec cc
Silicified, K-alt obv, w/ q-ser vlts.
2" gray q-ser
2-3" q-py ser env sec cc
2" wh q-py cp-mb
1" q-ser py cp
1" wh q
t-q-turq, 1" envelope ser
6" q-py-sec cc-mb
EXCELLENT K-ALT VLTS-IMPREGS CUT BY Q SER.
HEAVY K-ALT
silic, ser alaskite
1/8" py-sec cc q-ser
Bi Dac porph (?) inds, ser
RUBBLE
Alaskite, whitish ser
2-3" q-ser py-sec cc, pink frags. Whole zone wh-gry ser on K-alt
SB 2550·51
SB·2550·52
Incl Dac porph + chill
½" wh q-py
Sketch of surface
~12"
q centerline
gray q-ser-py env
(youngest)
q-pink K-feld (3rd)
pervasive K-feld (oldest)
(2nd) ex q-bi
Bench face overall = 0.49% Cu
~300' TO POINT 4
POTASSIC ALT W/ PHYLLIC OVPNT
Qmp-Alaskite
SILVER BELL MINE
ELTIRO PIT - 2550 BENCH
POINT 7
Geology by J. Guilbert, W. Yerter
March 1979
1 INCH = 10 FEET
1:120
MN



POTASSIC ALT W/ PHYLLIC OVPNT

SILVER BELL MINE
ELTIRO PIT - 2550 BENCH
POINT 7

1 INCH = 10 FEET
1 : 120



Tt = Tactite" - local name for the assemblage of gar, hem, quartz, cal, quartz, cp.

(D) Coarsely X'line mb. on margin of garnetite. Occ. veins of garnet noted. Most have been replaced by hem, qtz. & cal which is typical of the later hydrothermal event. Cp is abundant and suggested to represent remobilization & continued deposition. Note pseudomorphs of garnet. Cal. often is dark in color when assoc with qtz-cp veins.

(B) (C) Boulders of serpentine skarn. Light green serp. veins cut dark green serp-cp veins. This assemblage reverts to the actinolite-diopside phase on the interior of the deposit (Point 6)

(A) Tt- Assemblage represents early garnetite (Potassic equivalent) which has overprint of later destructive phase. Garnets are broken down & replaced by hem, cal, & qtz assemblage. Cp has been remobilized. The Tt is always ore.

Point 9: Notes

Skarn
El Tiro Pit-2790
April, 1979

Scale: approx 1" = 20'

Point 9

The mapping of this point is brief as it is an active face and this fact precluded advanced mapping.

The rocks are illustrative of the paragenesis of the limestone skarn. The point is located on the outside of the garnetite zone and inner portion of the garnet vein zone. It also is situated in the zone of garnet destruction (phyllic equivalent). The garnetite (potassic equivalent) at area A has been replaced by hematite, calcite and quartz. The chalcopyrite was remobilized during the later destructive phase. This rock type is called tactite at Silver Bell.

The boulders at areas B and C illustrate the dolomite with the magnesium forming serpentine. Two ages of veins can be noted. An early assemblage (potassic age veins) is composed principally of serpentine and chalcopyrite. The veins are approximate one millimeter in width and the serpentine is dark green in color. The later veins (phyllic age) is composed of light green serpentine, calcite and pyrite. These veins cross cut the earlier dark green veins. Chrysotite is more common in the later vein assemblage than the earlier veins. Both antigorite and lizardite have been identified but antigorite is the more common serpentine occurrence.

Area D illustrates the marble which contained veins of garnet. (most of the garnet is now replaced by hematite, quartz and calcite.) The vein intersections normally form replacement fronts. As the vein frequency increases, the marble will be completely replaced by garnet to form the garnetite noted in Area A. Occasional remanents of marble can be observed in the garnetite or tactite.

SOME GEOLOGIC ASPECTS OF THE SIERRITA-ESPERANZA COPPER-MOLYBDENUM DEPOSIT, PIMA COUNTY, ARIZONA

by

Daniel M. Aiken[1] and Richard J. West[2]

Abstract

The Esperanza property, which had been worked sporadically since 1895, was purchased by Duval Corporation in 1955. Following completion of an exploration drilling program under the direction of Harrison Schmitt, pre-mine stripping started in 1957 and subsequent production started in 1959. With the beginning of stripping in early 1968 and the start of mill operations in March 1970, the Sierrita mine became one of the largest copper-molybdenum ventures in Arizona. The combined Sierrita-Esperanza complex will eventually be a pit 12,500 feet long, 6,500 feet wide, and 2,250 feet deep.

The Sierrita and Esperanza properties constitute a porphyry-type copper-molybdenum deposit which occurs within intensely fractured and moderately altered rhyolite and andesite, quartz diorite, dacite porphyry, quartz monzonite, and quartz monzonite porphyry with an attendant intrusive breccia. Essential to the emplacement of the orebody is the Laramide Ruby Star granodiorite from which ore solutions were derived. The deposit lies at the south end of this pluton, which makes up much of the Sierrita Mountains.

Alteration in the ore zone is predominantly potassic, with phyllic and minor argillic assemblages. Propylitic minerals commonly occur outside the pit areas. All rock types are mineralized and altered.

Major primary minerals are limited to pyrite, chalcopyrite, and molybdenite. Silver, although recovered in minor amounts, is not recognized in mineral form. Minor minerals include galena, sphalerite, tennantite-tetrahedrite, magnetite, marcasite, fluorite, and rare bornite. Significant amounts of secondary enrichment were limited to Esperanza and West Esperanza. Initial interest in these two areas was due to the presence of a well-developed chalcocite blanket, most of which has been mined. Other secondary minerals commonly found include cuprite, tenorite, malachite, azurite, chrysocolla, native copper, and minor turquoise.

Mineralization at Sierrita-Esperanza is structurally and lithologically controlled. Linear mineralized zones parallel or girdle fault trends, major joint sets, and intrusive contacts. In addition, hypogene mineralization is associated with specific rock types and is generally fracture controlled within these units. Minor disseminations commonly occur in the breccia and quartz monzonite porphyry.

Introduction

The Duval Sierrita-Esperanza complex is located 25 miles south-southwest of Tucson, Arizona, on the southeast flank of the Sierrita Mountain range. Five miles to the east lies the Twin Buttes deposit and about 12 miles to the northeast, the Pima-Mission orebodies.

The Sierrita and Esperanza deposits were brought into production as separate open pits within parts of a single large mineralized system and are now being integrated into one of the world's largest copper-molybdenum operations.

Mining in the Esperanza area began late in the 19th century as sporadic underground working of relatively high grade base and precious metal veins. The New Years Eve mine (known then as the Red Carbonate mine), located in what is now the Esperanza pit, was partly developed by the Calumet and Arizona Mining Company in 1907-08 and abandoned due to low copper prices. During the 1930s and 1940s several companies examined the New Years Eve

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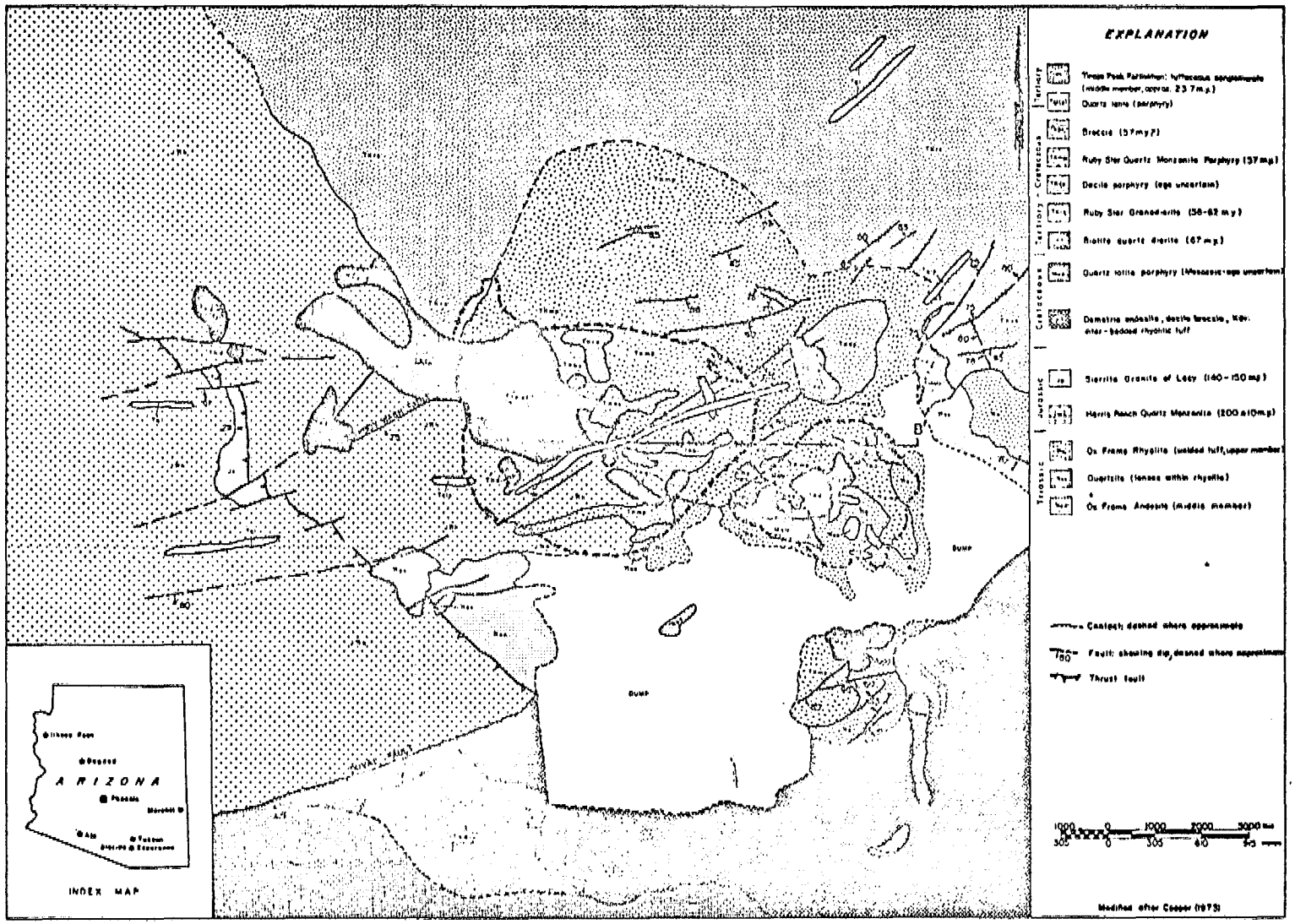

Fig. 1. Geologic map of Sierrita-Esperanza deposit—modified from Cooper (1973)

mine as a potential source for molybdenum. The U.S. Bureau of Mines, seeking new sources of molybdenite against the possible shortage of that mineral for war uses, examined the New Years Eve mine area in 1943 and 1944.

In the early 1950s the Duval Sulphur and Potash Company (later Duval Corporation) began searching for major copper deposits. Harrison A. Schmitt, consulting geologist, was retained to locate possible targets. Following an examination of the Esperanza deposit by Schmitt, Duval acquired the claims in February 1955 from the Sierrita Mining and Ranching Company. A drilling program was initiated and by 1957 had revealed sufficient tonnage to warrant development of an open-pit mine.

Duval was initially attracted to Esperanza by the presence of a well-developed chalcocite blanket, most of which has now been mined out. Pre-mine stripping began in 1957 with production commencing in 1959. The ore grade at Esperanza has averaged 0.5% Cu and 0.028% Mo since the start of operations. Ore reserves for Esperanza are now about 36 million tons with grades of 0.38% Cu and 0.027% Mo (Pennzoil Company, 1974). Current daily production is 18,000 tons ore and 18,000 tons waste.

In 1963 Duval acquired additional properties which comprised approximately 60 percent of the then undeveloped Sierrita orebody. Exploration and development drilling has established total ore reserves of 554 million tons with a grade of 0.32% Cu and 0.033% molybdenum (Pennzoil Company, 1974). Pre-mine stripping began in 1968 with initial production in 1970. Ore mined during the early years at Sierrita has averaged 0.29% Cu and 0.028% Mo. Present daily production is about 90,000 tons ore and 135,000 tons waste.

General Mine Geology

The Sierrita-Esperanza deposit occurs within intensely fractured and moderately altered rhyolitic and andesitic volcanic rocks, quartz diorite, quartz latite porphyry, dacite porphyry, quartz monzonite, and quartz monzonite porphyry, with an attendant intrusive breccia. Except for quartz monzonite, which is restricted to southwest Sierrita, all rock types crop out in both pits.

Rock Types

Table 1 gives a summary of the age and description and occurrence data for rock types in the Sierrita-Esperanza mine area.

Extrusive Rocks

The Ox Frame Volcanics of Triassic age are mainly flows which cover much of the terrain west of Sierrita and comprise the upper levels of the Esperanza pit. The lower member of the Ox Frame does not crop out in the mine area. Subdivisions of the formation present in the mine area consist of:

1. Andesite—the middle member of the extrusive sequence. Typical andesite is dark gray to black and microporphyritic, consisting of 20 to 30 percent plagioclase phenocrysts set in an aphanitic groundmass of albite, actinolite, and magnetite microlites with a cryptocrystalline texture.

2. Rhyolite welded tuff—the upper member of the Ox Frame Volcanics. This dark-gray rock was subdivided by Lynch (1967) into vitric tuff, fragmented tuff, and siliceous-aphanitic tuff based on suble differences in texture, welded characteristics, and microstructure.

3. Quartzite—occurs as isolated pods and irregular masses interbedded with the rhyolite in Esperanza.

Only andesite was an important host for hypogene mineralization. Significant secondary copper enrichment has been restricted to highly fractured zones in all units of the Ox Frame Volcanics.

Intrusive Rocks

Harris Ranch Quartz Monzonite. An extension of the southeast end of the Harris Ranch quartz monzonite stock crops out in southwestern Sierrita (Fig. 1). Diagnostic of this light-gray, medium-grained rock is the biotite, which normally occurs as subhedral flakes in aggregates. Tourmaline is common in the Harris Ranch quartz monzonite above the 3900 level and may be a primary mineral. It diminishes toward the contact with the Laramide intrusions reflecting a chemical change possibly caused by hydrothermal solutions associated with the younger Laramide rocks (Guilbert, 1977, personal communication).

The Harris Ranch quartz monzonite was not originally recognized as an important host for mineralization. The results of deep drilling indicate an extensive hypogene ore zone which begins several hundred feet below the original surface and continues downward into younger Laramide rocks (Fig. 2). The Harris Ranch quartz monzonite, with an age date of 200 ± 10 m.y., is the oldest intrusive rock in the mine area (Figs. 2 and 3).

Table 1. Extrusive and intrusive rocks in the Sierrita-Esperanza mine area

Name	Age	Description and Occurrence
Quartz latite porphyry	Eocene (?)	Pods and high-angle dikes (weakly mineralized)
Ruby Star quartz monzonite porphyry	Eocene 53.5 m.y. (Damon and associates, 1966) 56 m.y. (Creasey and Kistler, 1962) 56.9 m.y. (Cooper, 1973)	Stocks and plugs (probable source for metal-bearing hydrothermal solutions and an important host for mineralization)
Breccia	Eocene 57 m.y.?	Irregular pipelike bodies; large discontinuous masses; dikes
Dacite porphyry	Eocene-Paleocene	Dikes and irregularly shaped bodies; may be genetically related to quartz monzonite porphyry
Ruby Star granodiorite	Eocene 58.7 m.y. (Damon and associates, 1966) 59 m.y. (Damon and associates, 1965) 61.6 m.y. (Cooper, 1973)	North-northwest-trending batholith considered to be source magma for quartz monzonite porphyry
Biotite quartz diorite	*Paleocene(?) 67.0 m.y. (Cooper, 1973)	Northwest-trending, rectangular stock and smaller bodies (excellent host for mineralization)
Quartz latite porphyry	age uncertain	Irregular plugs and pods within and north of Esperanza mine
Demetrie Volcanics	Late Cretaceous	Sequence of andesitic and dacitic breccias and flows located southeast of Esperanza mine
Sierrita granite	Jurassic 140 m.y. (Damon and associates, 1966) 150 m.y. (Cooper, 1973)	Located west and north of Sierrita-Esperanza
Harris Ranch quartz monzonite	Jurassic-Triassic 190 m.y. 210 m.y. (Cooper, 1973)	Northwest-trending stock (excellent host for mineralization)
Ox Frame Volcanics	Triassic	Rhyolite flows, tuffs, and tuff breccias with intercalated lenticular beds of sandstone; andesite and dacite flows, with a few flow breccias; andesite is a good host for mineralization at Esperanza

*Additional radiometric dates of 47.0, 56.0, and 60.0 m.y. have been obtained from minerals in quartz veinlets in diorite (Cooper, 1973); vein emplacement may be related to Ruby Star granodiorite intrusion.

Quartz Latite Porphyry. The Mesozoic quartz latite porphyry, a light-colored, fine-grained porphyritic rock, intrudes the Ox Frame Volcanics on the southwest side and central part of the Esperanza deposit. North of Esperanza, a similar unit is recognized. The quartz latite porphyry was a favorable host for primary copper and molybdenum and secondary enrichment in the mine. However, because of its limited areal extent, it does not provide an important source of ore. Field relationships indicate that this rock type is younger than the Triassic volcanic rocks but older than the Ruby Star quartz monzonite porphyry.

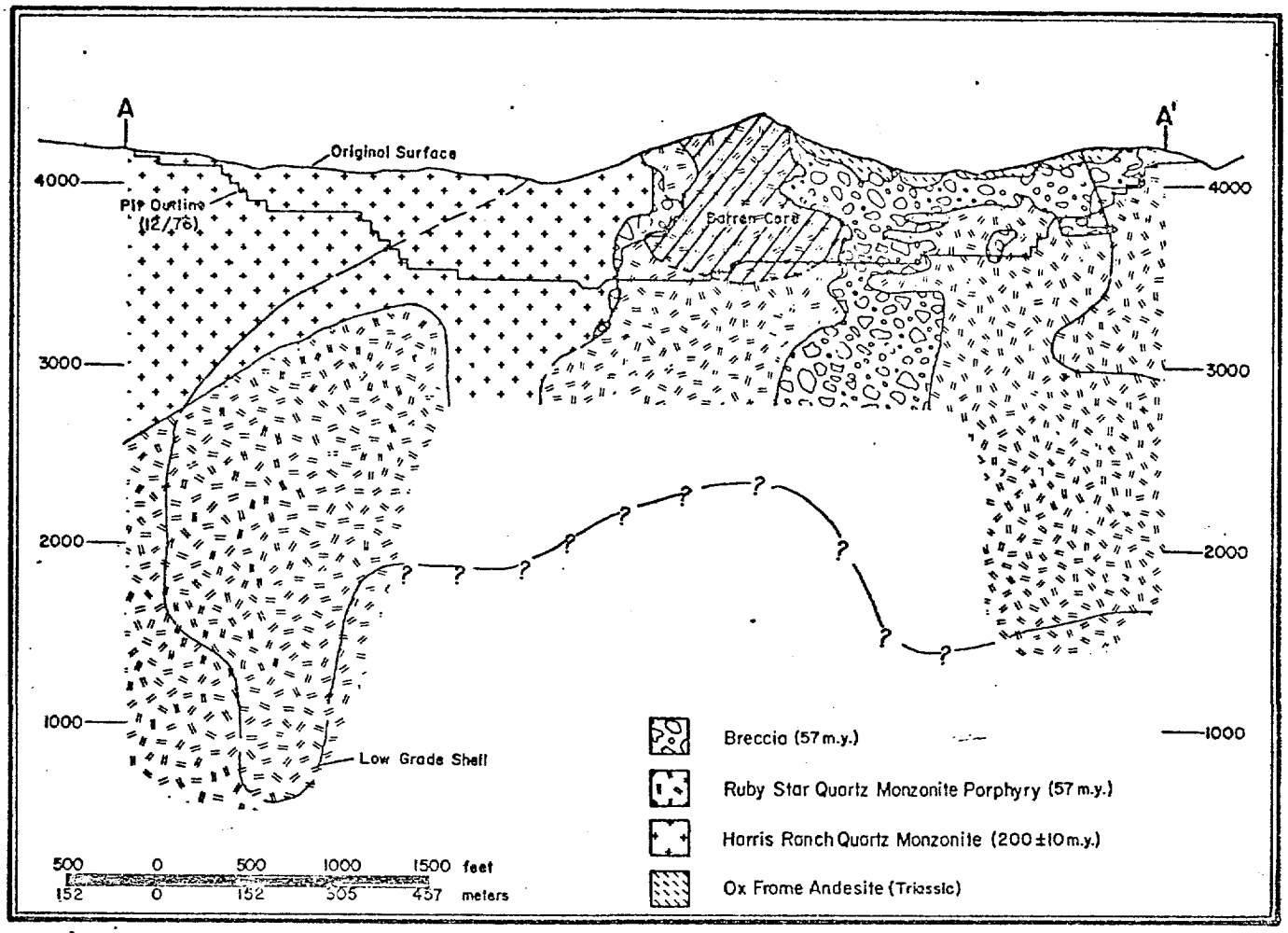

Fig. 2. Section A-A', showing Sierrita geology

Biotite Quartz Diorite. Biotite quartz diorite is found north of Sierrita as irregular plutons and extends into the north end of the mine as a northwest-trending tabular body. The unit is also present in the west and southeast part of Esperanza. In an east-west cross-sectional view of the Sierrita pit (Fig. 4a), the wedge-shaped diorite is intruded by the Ruby Star quartz monzonite porphyry. This dark-green to black, fine- to medium-grained rock commonly exhibits a salt-and-pepper appearance in both weathered and fresh exposures. The diorite is an excellent host for hypogene copper-molybdenum mineralization. Moderate shattering prepared the chemically receptive rock for the invasion of hydrothermal solutions that accompanied the younger Laramide intrusions.

The biotite quartz diorite is Late Cretaceous (Laramide) having an age of approximately 67 m.y.

Ruby Star Granodiorite and Quartz Monzonite Porphyry. Occurring north of the biotite quartz diorite is the Ruby Star granodiorite, a north-northwest-trending batholith with two textural variations and a quartz monzonite porphyry differentiate. The granodiorite in the mine area is a light-gray, medium-grained rock distinguished from other rock types by an abundance of "fresh" equidimensional books of biotite and occasional small, honey-colored crystals of sphene. Mineralization in the granodiorite is sparse, usually occurring as rare chalcopyrite blebs replacing biotite and as copper oxides and carbonates. The several potassium-argon age dates determined for this Laramide intrusive rock average approximately 60 m.y.

The Ruby Star quartz monzonite porphyry, a light-gray, porphyritic facies of the Ruby Star granodiorite, is characterized by anhedral quartz "eyes" which are preserved even in intensely weathered rock. The intrusion is inti-

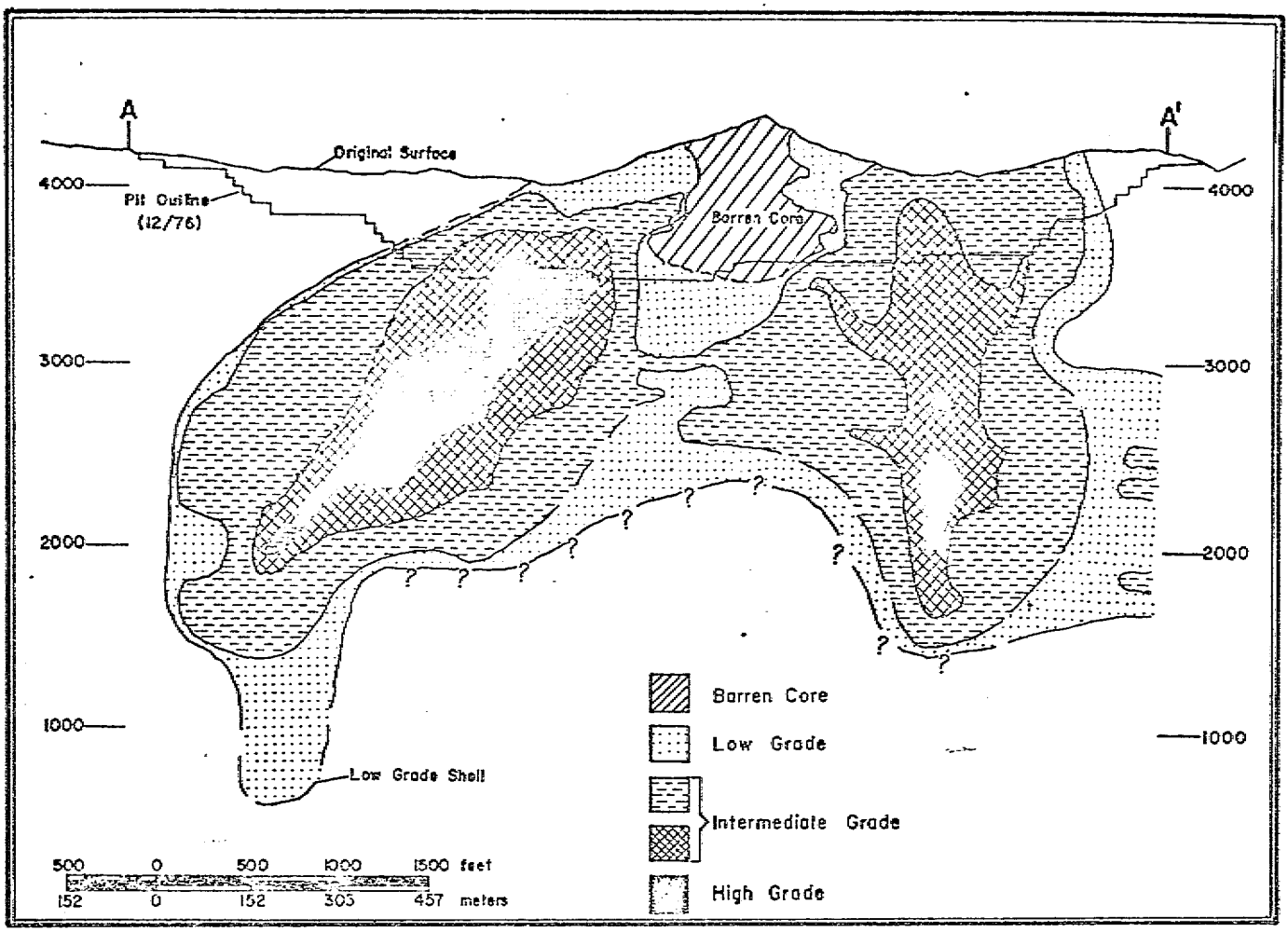

Fig. 3. Section A-A', showing distribution of economic mineralization at Sierrita

mately associated with mineralization and alteration and is considered to be the source for the metal-bearing hydrothermal solutions. Several variable textures in the Ruby Star quartz monzonite porphyry may suggest successive periods of intrusive activity, or they may be contemporaneous and represent different zones in the cooling magma.

The Ruby Star quartz monzonite porphyry occurs as a central stock with several smaller quartz monzonite porphyry bodies marginal to it. These bodies are irregularly shaped and trend northwestward, reflecting a major regional structural trend. Both the lateral and vertical extent of the porphyry are much greater than might be inferred from surface exposures. The stock has generally not penetrated through the older volcanic and intrusive rocks in the southern part of the mine area. The contact on the north, between the quartz monzonite porphyry and its parent, the Ruby Star granodiorite, is commonly gradational.

Mineralization in the Ruby Star quartz monzonite porphyry occurs predominantly as chalcopyrite, pyrite, and molybdenite fracture fillings, but chalcopyrite and pyrite are also present as disseminations and blebs.

Sierrita Intrusive Breccia. Several irregular breccia masses occupy an area in the eastern portion of the Sierrita pit. These are remnants of a much larger, roughly east-west-trending body. In the upper levels of Sierrita, clasts derived from the Ox Frame volcanic rocks, Harris Ranch quartz monzonite, Ruby Star quartz monzonite porphyry, and biotite quartz diorite are common in the breccia body. The lower part of the breccia as exposed on the 3600 level is composed of subangular fragments, typically Ruby Star quartz monzonite porphyry. The clasts become more angular toward the edges of the breccia zone. Fragments are set in a matrix of fine-grained biotite, rock flour, silica, and some magnetite. The shape and distribution of breccia masses and pods

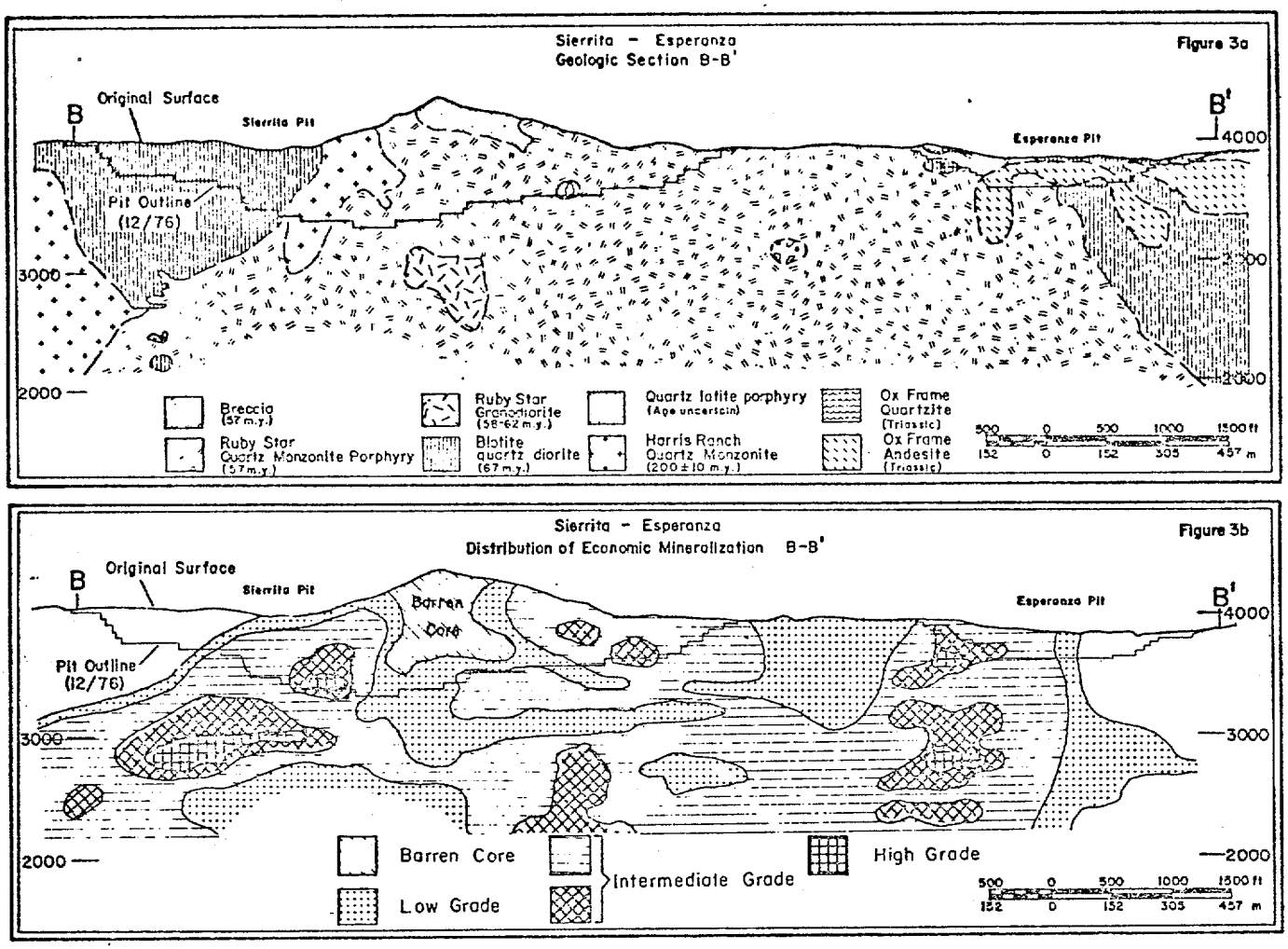

Fig. 4. Section B-B': (a) Geology of the Sierrita-Esperanza deposit; (b) distribution of economic mineralization

(Fig. 2) suggest that the unit is related to Ruby Star quartz monzonite porphyry and was developed by the channeling of magmatic fluids up irregular conduits and fissures. These structural controls were probably associated with stockwork fracturing caused by the emplacement of the quartz monzonite porphyry pluton in the mine area.

The zone of brecciation expands laterally along rock contacts near the 3900 elevation (Fig. 2) and fingers out in Ox Frame andesite, biotite quartz diorite, and other units that crop out on the pre-mine surface. This may explain the relative abundance of mafic fragments in upper breccia occurrences as noted earlier. The configuration of breccia as described above may be as much as 2500 feet long and 600 to 1000 feet wide in the upper body but narrows below the 3750 bench typically into discontinuous bodies of variable size.

The breccia is generally characterized by moderate alteration of fragments, biotite flow features around clast edges, relatively large fragments with little microbrecciation, and a dark, dense matrix composed mainly of fine-grained biotite with rare open channels or vugs.

Copper and molybdenum mineralization in the breccia, good in upper levels of Sierrita, diminishes with depth. Apparently, the increased grade in the upper part of the breccia is related to the abundance of (receptive) fragments of Ox Frame andesite, biotite quartz diorite, and Harris Ranch quartz monzonite.

Mudd Hill Breccia. A distinctive intrusive(?) breccia exists south of Esperanza (Fig. 1), now partially covered by waste dumps. The hydrothermal alteration of the breccia is unusually intense compared to other breccia occurrences in the deposit. Strong quartz-sericite alteration has almost completely de-

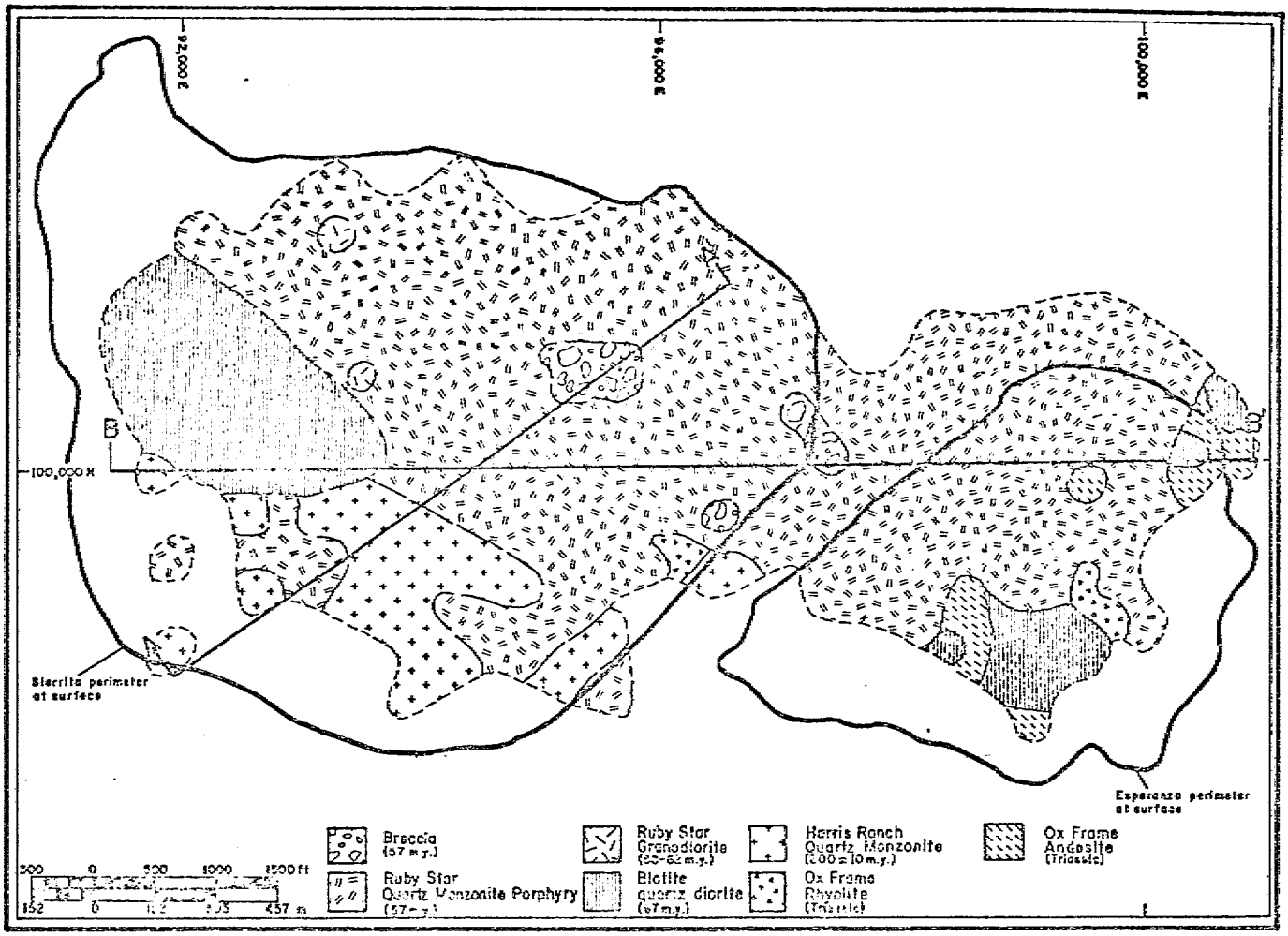

Fig. 5. 3200 bench, showing Sierrita-Esperanza deposit geology

stroyed angular and rounded fragments of andesite and quartz latite porphyry set in a pyrite-silica matrix. This breccia has sparse economic mineralization.

Contact Breccia. Brecciation at Sierrita is also common along the contacts of the Harris Ranch quartz monzonite, biotite quartz diorite, and Ruby Star quartz monzonite porphyry. Reworking of inclusions detached from the country rock during multiple episodes of intrusive activity has resulted in localized breccia masses of intermixed angular fragments, and chilled and hybrid contact zones.

Quartz Latite (Porphyry). At Sierrita, Tertiary porphyritic quartz latite dikes cut all rock types, including the Laramide Ruby Star intrusions, indicating two periods of igneous activity involving similar rock types in the Sierrita-Esperanza system. The dikes are mineralized with pyrite and chalcopyrite fracture coatings.

Structures and Characteristics of Orebodies

Hypogene sulfide mineralization in the Sierrita-Esperanza deposit consists of pyrite, chalcopyrite, and molybdenite with comparatively minor amounts of galena, sphalerite, magnetite, tennantite-tetrahedrite, and rare marcasite, cubanite, and bornite(?). Within the ore zone, the pyrite-chalcopyrite ratio is roughly 1 to 2; total sulfide content is normally 1 to 2 percent or less, seldom exceeding 3 percent by volume. This ratio increases to greater than 20 to 1 in the propylitic zone, with total sulfide content estimated at 1 to 3 percent.

Mineralization at Sierrita-Esperanza is structurally and lithologically controlled. Linear mineralized zones, for example, parallel or girdle fault trends and intrusive contacts (Fig. 4). In addition, hypogene mineralization is associated with specific rock types and is generally fracture controlled within

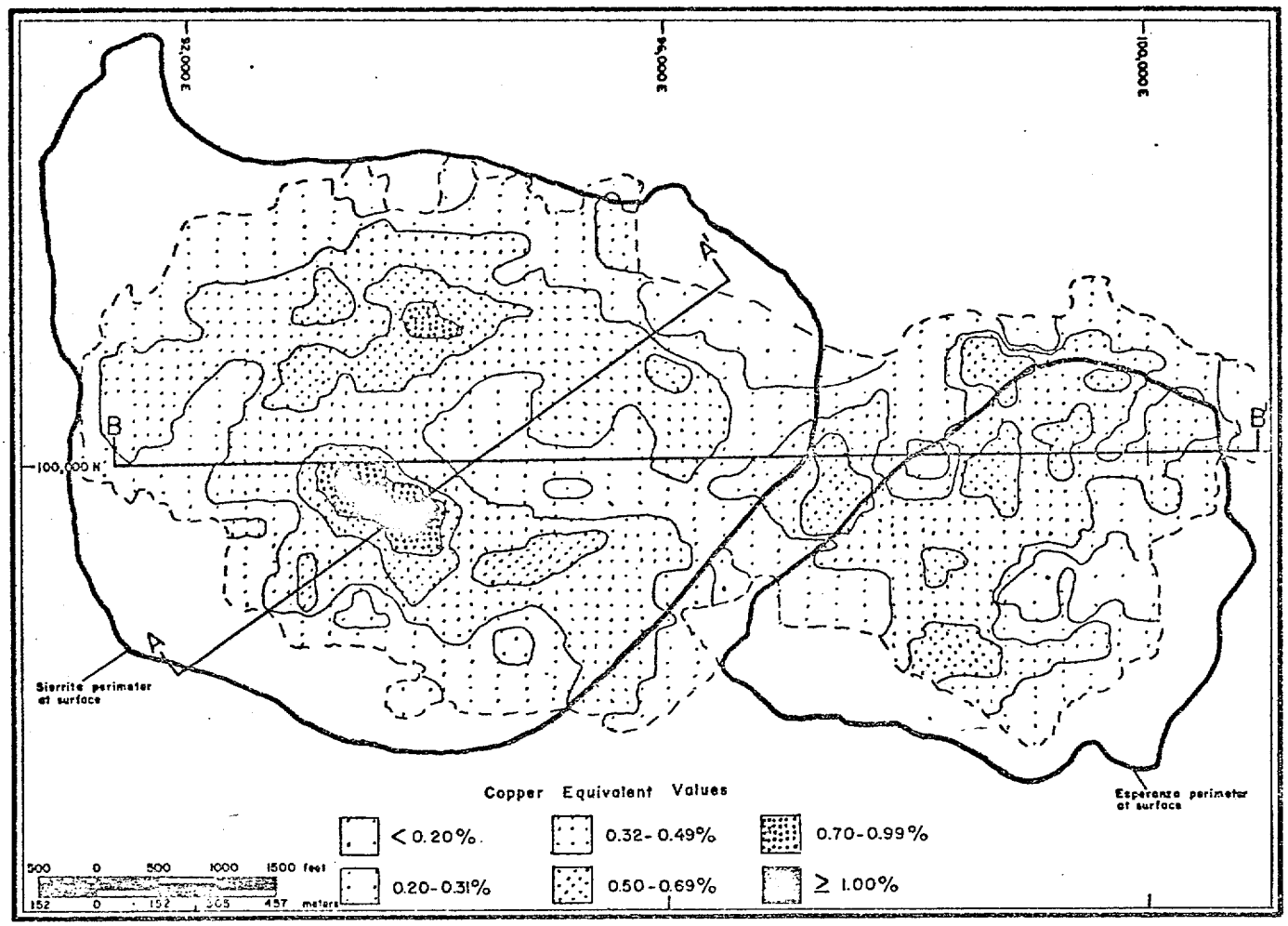

Fig. 6. 3200 bench, showing distribution of mineralization at Sierrita-Esperanza

these units. A dominant system of N. 50°-85° E. and N. 5°-25° W.-trending, steeply dipping, mineralized fractures occurs at Sierrita. The east-northeast fracture set is most strongly mineralized and parallels a major structural trend in the mine area. Also, the east-northeast mineralized set appears to be superimposed on the northwest-trending ore zones, coincident with contacts between the Laramide Ruby Star quartz monzonite porphyry, biotite quartz diorite, and Harris Ranch quartz monzonite. Mineralization and alteration are controlled by this composite structural framework.

Mineralization at Esperanza, occurring mainly in Ruby Star quartz monzonite porphyry, trends N. 40° E., approximately parallel to the contact between the Ruby Star quartz monzonite porphyry and Triassic Cx Frame rhyolite. Economic concentrations also occur in Ox Frame andesite and biotite quartz diorite, which are good hosts (Figs. 5 and 6). Another Esperanza ore zone extends northwestward into Sierrita (Fig. 4b).

The hypogene Sierrita orebody is composed of two major parallel mineralized zones. The east zone, which connects with Esperanza to the southeast (as noted above), occurs in the Ruby Star quartz monzonite porphyry and breccia. The west zone occurs primarily in biotite quartz diorite, Harris Ranch quartz monzonite, and Ruby Star quartz monzonite porphyry. This zone may trend into Esperanza (Fig. 6).

Deep drilling indicates that the west Sierrita zone plunges steeply (60°-80°) westward. A similar configuration exists for the east zone (Fig. 3). These two zones expand laterally with depth and are connected by a well-mineralized, northeast-trending crossover zone in northwest Sierrita to form a concentric zone enveloping a central barren core (Fig. 3). The barren core, as shown on Figures 3 and 6, is roughly 900 feet long and 600 feet wide. This "barren" area has a copper equivalent of less than 0.20 percent. Below the 3500 level, min-

eralization increases to economic grade.

As discussed above, mineralization is primarily associated with fracture fillings and veinlets. Disseminated mineralization is less common. The paragenetic sequence of veinlet formation (oldest to youngest) recognized at Sierrita is as follows:

1. Biotite.
2. Quartz-anhydrite-orthoclase.
3. Quartz-orthoclase-chalcopyrite-molybdenite-pyrite.
4. Quartz-sericite-chalcopyrite-molybdenite-pyrite.
5. Sphalerite-galena with quartz-chalcopyrite-pyrite.
6. Quartz-molybdenite.
7. Quartz-pyrite-sericite.
8. Gypsum and zeolites.

Alteration

Hydrothermal alteration at Sierrita and Esperanza is primarily controlled by the composition and reactivity of host rocks and regional and local structures.

Potassic Metasomatism

Potassic metasomatism is the most significant and widespread alteration in the deposit. The potassic zone encompasses much of the central portion of the Sierrita pit and the northern half of Esperanza, with localized occurrences northeast of Sierrita. The potassic mineral assemblage includes secondary orthoclase and biotite, accessory anhydrite, and in some places, quartz, sericite, and epidote (Smith, 1975).

Secondary potassic feldspar is more widespread than secondary biotite in the deposit and occurs most commonly in the felsic to intermediate rocks at Sierrita. It occurs as:

1. Unmineralized K-feldspar veinlets.
2. K-feldspar-chalcopyrite-pyrite-chlorite veinlets.
3. K-feldspar flooding, which often destroys the original rock texture completely.

Secondary biotite is common in the biotite quartz diorite, the Sierrita breccias, and in the Harris Ranch quartz monzonite at Sierrita and the mafic rocks at Esperanza. It is present mainly as:

1. Fine-grained alteration halos around quartz-sulfide veinlets.
2. Coarse-grained fracture fillings.
3. Zones of flooding which replace or displace other minerals (as in certain brecciated zones).
4. Recrystallization of primary groundmass biotite and hornblende in the biotite quartz diorite.

Anhydrite is a common accessory mineral in the potassic zone and is present in all rock types at Sierrita, particularly the biotite quartz diorite. Epidote, which is not normally recognized as part of the potassic zone, appears to have an intimate relationship with some of the early-formed vein systems at both pits. It appears to have been generated as a companion mineral to secondary orthoclase (Smith, 1975; Titley, 1975). At least some of the epidote observed in this environment may be attributed to retrograde effects and related to temperature fluctuations which accompanied the complex Laramide intrusive activity.

Quartz-Sericite Alteration

Quartz-sericite alteration occurs throughout the deposit and is relatively intense in east Esperanza. At Sierrita, quartz veining with sericite alteration envelopes occurs within and peripheral to the potassic zone and diminishes with depth. The distribution of this assemblage is the result of several periods of hydrothermal fluid circulation as indicated by (1) the offsetting and crosscutting relationships of veins; (2) the varied thicknesses of selvages; and (3) varied vein trends and sulfide content in individual specimens.

An early phase of quartz-sericite alteration accompanies chalcopyrite (and molybdenite) mineralization. A later stage of quartz-sericite-pyrite alteration cuts all fractures except for those containing gypsum and zeolites.

Other Alteration Types

Argillic alteration is mainly restricted to faults and fractures and no major pattern has been delineated. Much of the clay alteration in the upper levels of the mines may be attributed to supergene effects.

Propylitic alteration is prominent at Sierrita and Esperanza and forms a gradational halo around the potassic and phyllic zones. Ore limits roughly coincide with the boundary between the propylitic and higher grade alteration assemblages.

Chlorite and epidote are two of the most important minerals in the propylitic zone, mainly from alteration of the mafic minerals and plagioclase. In Harris Ranch quartz monzonite, the biotite becomes progressively more chloritized toward west Sierrita. In biotite quartz diorite, epidote is pervasive. Minor albite veining is

observed in the propylitic zone at Sierrita. Locally intense groundmass albitization is also recognized. Recent work at Esperanza indicates that at least some albite alteration accompanied potassic metasomatism and metallization (Smith, 1975). However, insufficient petrographic work has been completed to determine the extent of albitization at Sierrita.

Stilbite and other zeolites are commonly found with gypsum in veins and fissures within Harris Ranch quartz monzonite, biotite quartz diorite, and Ruby Star quartz monzonite porphyry.

Gypsum as selenite, alabaster, and satin spar is widespread throughout both Sierrita and Esperanza and occurs as pseudomorphs after or replacements of anhydrite or as post-mineral fracture fillings.

Acknowledgments

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Special thanks are given to the previous members of the Sierrita and Esperanza geology staff for their accumulated data and ideas that formed the basis for much of the material presented in this report. In particular, we wish to thank Messrs. Dean W. Lynch, Robert A. Metz, Calvert D. Iles, Chester A. Oakley, A. Harvey James, and Frank Mack.

We express our appreciation to Mr. Harry L. Shively, General Manager, Duval-Sierrita Corporation, and to Duval Corporation for permission to prepare and publish this paper.

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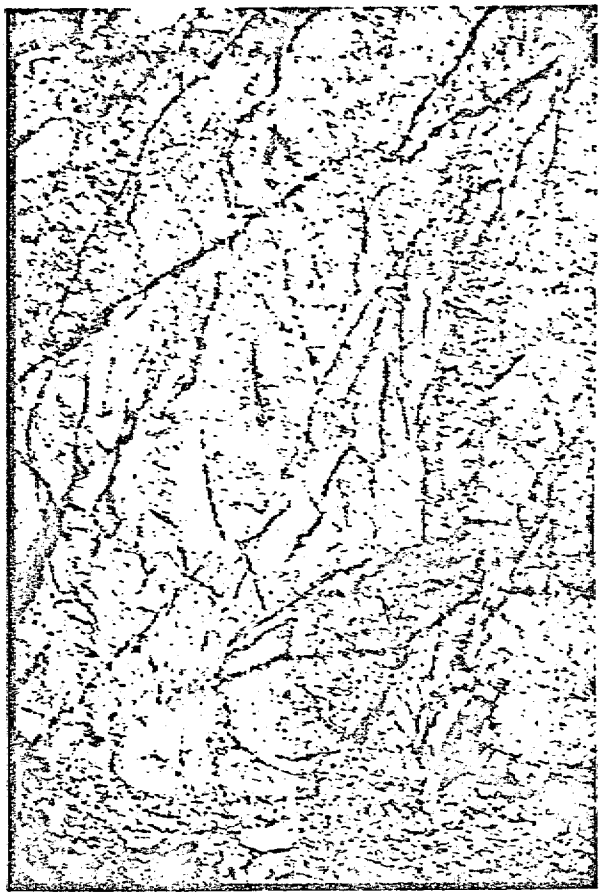
FRACTURE DENSITIES

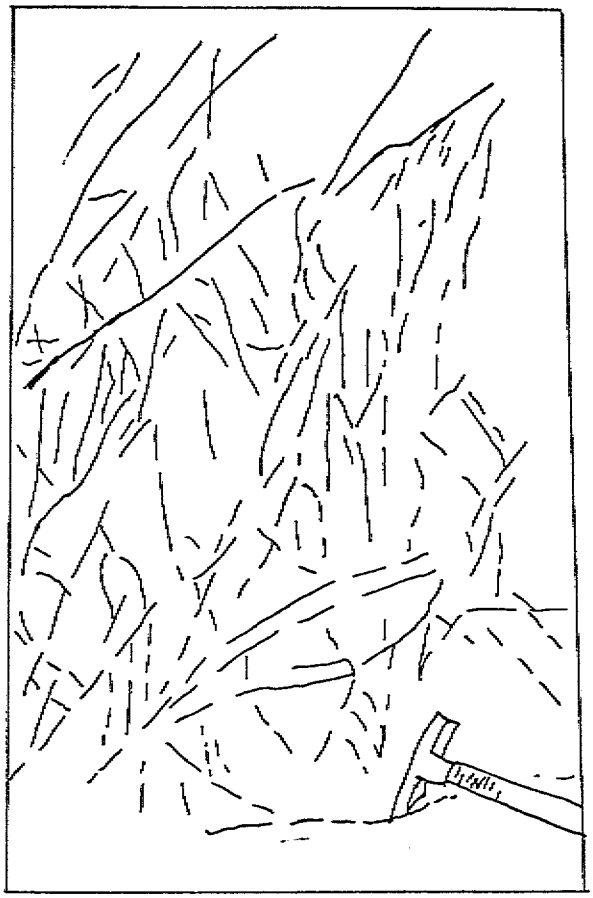
An aid to understanding the progress of alteration and mineralization in fracture-controlled hydrothermal systems is the knowledge of evolution of fracture permeability. Studies completed and in process reveal that the cracking of rocks is a continuing phenomena during the history of pluton cooling, the end result of which is a porphyry copper system characterized by a large volume of densely fractured rock. Results of studies of the fractured rocks from many deposits indicate that fractures with different alteration products on their walls crosscut each other in the same volumes of rock in sequences that are generally repeated from deposit to deposit. The interpretation is thus, that fracturing is a continuing process and occurs repeatedly during the life of the hydrothermal process. Each set of cracks which opens is altered by solutions to produce stable mineral assemblages under the existing physical chemical conditions. It is therefore possible to "track"the evolution of fracture permeability in a system and to simultaneously gauge temperatures and the chemical environment as they relate to time (paragenesis) and space.

Measurement of fracture densities may be carried out in different ways. In drill core, the quantity is commonly expressed as fractures per unit of length. In outcrop or on bench face, the measurements may be made in selected "sample" areas. Fracture density as used here (the quantity is sometimes expressed as fracture frequency) is a number expressing the linear length of mesoscopic fractures divided by the area of the sample. It has the units of length^{-1}, commonly cm^{-1}. The quantity may be used to determine permeability (k) if aperture (d) can be determined.

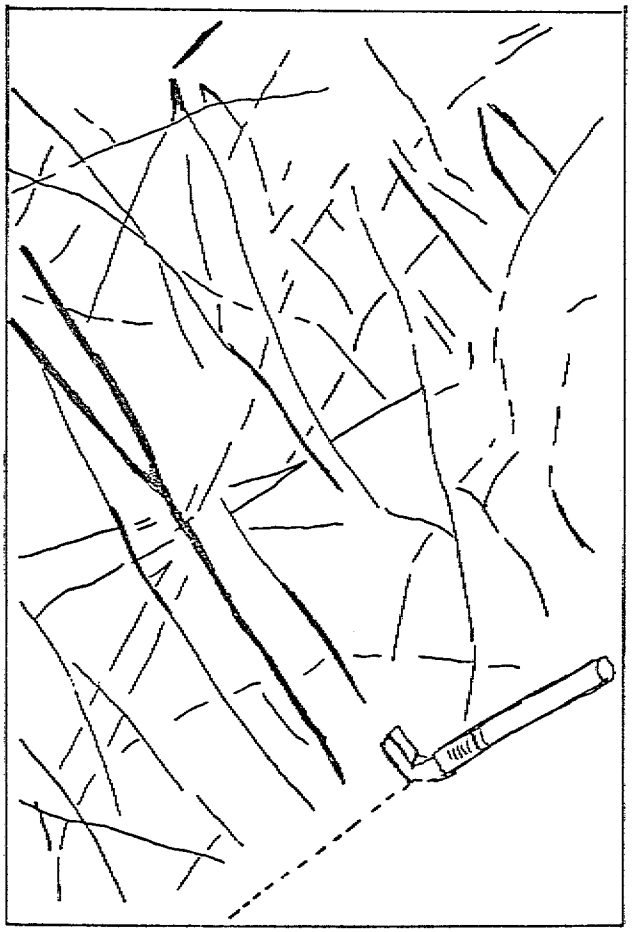
$$k = \frac{nd^3}{12}$$

Examples of exposures with mappable fractures are shown on page (B) Exposure (1) has a fracture density of about 1.2 cm^{-1} and exposure (2) reveals a density of about 1.0 cm^{-1}.





(1)



(2)

Fracture density is a quantitative expression of a geologic phenomenon, but as with all such measurements, it value is dependent upon the objectivity of the measurement. Present studies in porphyry systems are objective attempts to assess the evolution of fracture permeability. However, in systems of the southwestern United States, where very strong preferred orientations of fractures are present, certain precautions must be taken and interpretations of the data carefully weighed. Bias may be introduced from preferred fracture directions when measurements are made on pit walls. Consequently, where possible, the densities are integrated from measurements on faces with different orientations, the most reliable data obtained from faces with about N45E or N45W which cut across both preferred directions. Because it is necessary to measure a large number of samples, and because of the variation from sample to sample, the geometry of the sample area has not been found to be critical - only that it include a representative area of fracturing. In most instances a circle vs. a square on the same area yields only a few percent of difference in the measurements.

The integrated fracture density is the sum of all fractures which opened in a rock volume during the alteration-mineralization process. The integrated density is composed of sets of fractures which opened at different times and it appears that the fracture density, at any particular time is comparatively small, thus the permeability at any particular alteration stage is considerably less than would appear from all of the fractures present on an outcrop or bench face. We have seen, in addition to different mineral stabilities in time, a difference also in orientation of fracture sets, particularly in their dips. There is growing evidence that at some time, permeability may be anisotropic to some degree although the net effect of this has yet to be assessed. It is becoming increasingly clear, however, that it may be possible to assess different alteration assemblages of vein walls as contemporaneous or not contemporaneous in

in different wall rocks, as expressed by their geometry.

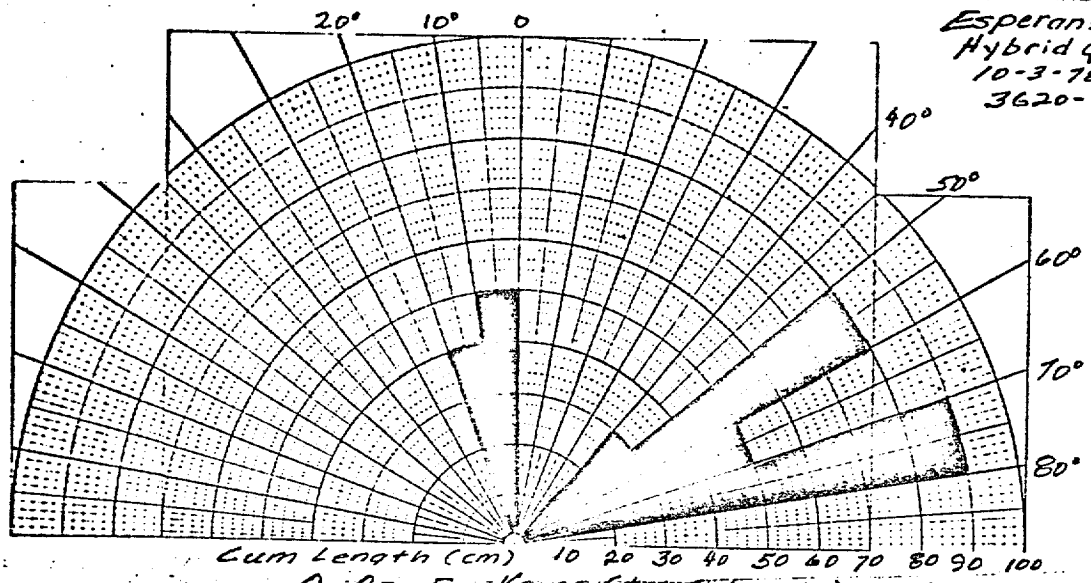
In Sierrita-Esperanza, the following measurements appear to be representative of Fracture Densities of different vein types in different host rocks. The sequence is expressed in paragenetic order.

	Harris Ranch qm	Tert. Qmp (Ruby Star)	Bi-Q Dior ?	
Biotite Veins	0.12 cm^{-1}			
Q-Or-Veins	0.05 cm^{-1}	0.08 cm^{-1}	0.08 cm^{-1}	
Q-Or-Musc-Cpy Veins	0.15 cm^{-1}	0.05 cm^{-1}	0.09 cm^{-1}	
Q-Ser-Py Veins	0.08 cm^{-1}	0.05 cm^{-1}	0.02 cm^{-1}	
Q-Mt-Cpy-Py Veins	0.07 cm^{-1}			
Q-Or-Ep Veins	0.05 cm^{-1}	0.02 cm^{-1}	0.08 cm^{-1}	(cpy)
Ep. Veins	0.08 cm^{-1}	0.02 cm^{-1}	0.05 cm^{-1}	(cpy)
Integrated Fracture Density	0.60 cm^{-1}	0.22 cm^{-1}	0.32 cm^{-1}	

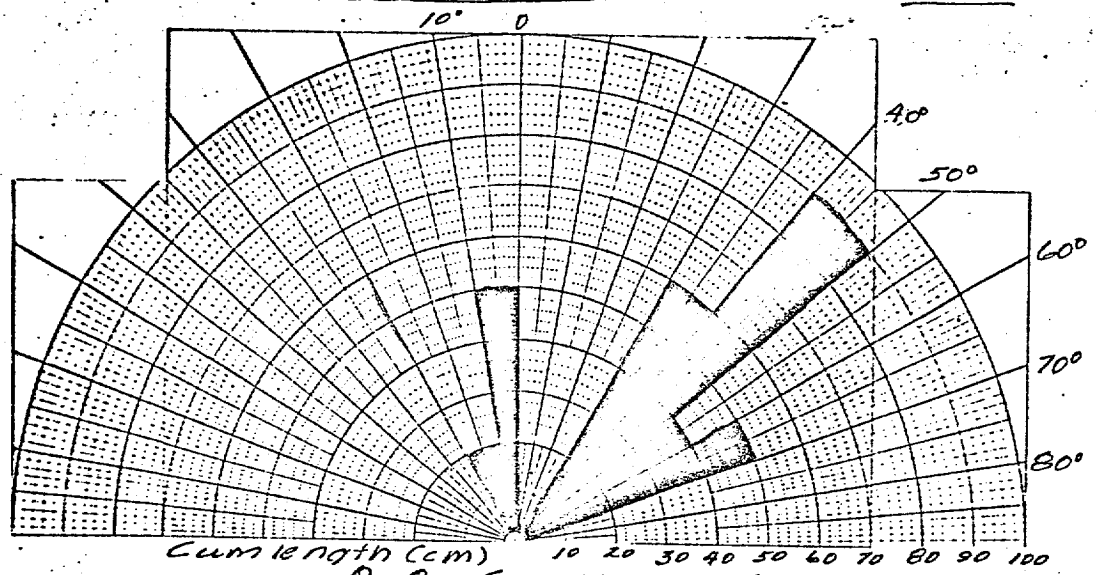
Orientation of different fracture-alteration types, expressed as a function of cumulative lengths for each orientation is shown on the next page. The lengths shown are those measured in a 50 cm x 50 cm sample area in the northeast part of the Esperanza orebody and appear to be typical of relative densities and orientations of fractures in the Ruby Star Granodiorite (qmp) porphyritic phases.

Studies beyond the limits of the Sierrita pit, confined largely to the qmp reveal progressive decrease in the lateral extent of fractures associated with each successive fracturing event. Early quartz-orthoclase-magnetite veins, extending to distances of more than 4 km from the pit edge are crosscut by quartz-sulfide-magnetite veins which extend to about 3.5 km. Integrated densities indicate that the number of veins in rocks is generally uniform for a distance of about 1.5 km away from the pit.

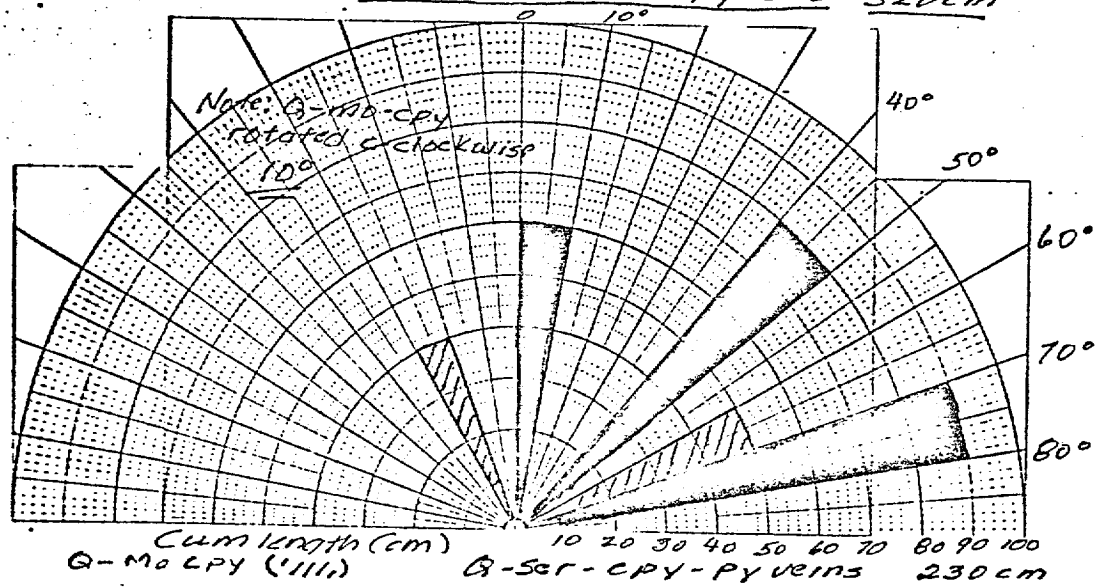
Esperanza
Hybrid qmp
10-3-78
3620-A



Q-Or-Ep Veins (± cpy ± MoS_2) - 330cm



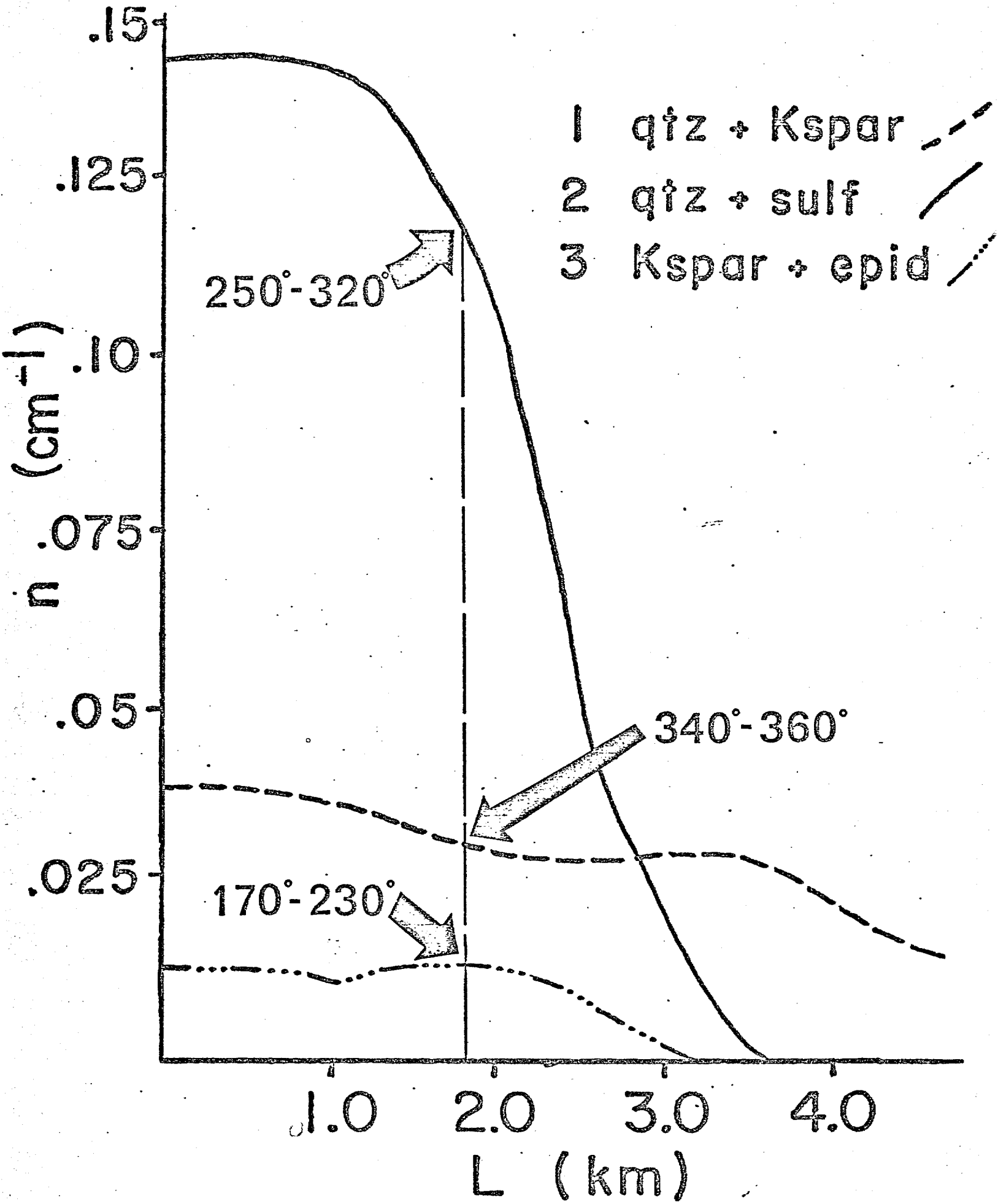
Q-Or-Ser-Chl-cpy Veins 320cm



Q-Mo cpy ('111,) Q-Ser-cpy-Py veins 230cm

At this point they appear to begin to systematically diminish and at a distance of about 4 km from the pit, to the north, mineralization and associated fracturing disappears. Over this distance, beyond the limits of mineralization presently being mined, domains of both, pervasively fractured rock and unfractured rock occur but much of the volume of these peripheral rocks express integrated fracture densities of about 0.1 to 0.2 cm^{-1}

(S.R.T., F.J.H.)


.15
.125
.10
.075
.05
.025
n (cm⁻¹)
1 qtz + Kspar
2 qtz + sulf
3 Kspar + epid
250°-320°
340°-360°
170°-230°
1.0
2.0
3.0
4.0
L (km)

PARAGENESIS AND TEMPERATURES OF FORMATION OF ALTERATION ASSEMBLAGES

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University of Arizona, Tucson, Arizona

Field and laboratory studies of porphyry copper deposits have shown that significant variations in temperature, pressure and fluid chemistry apparently occur during the lifetime of the ore-forming process as evidenced in part by alteration paragenetic relations (cf., Bodnar & Beane, 1977, Nash, 1976; Roedder, 1971). Also, it has long been recognized that the ore-bearing potential of a particular rock unit often depends on its chemical and mineralogical composition (West & Aiken) 1979; Beane, 1979; Guilbert & Lowell, 1974; Phillips et al., 1974). This study is an attempt to monitor the evolution of porphyry copper-type alteration and mineralization in wall rocks of differing chemistries through the use of paragenetic relationships, mineral compositions and fluid inclusions. By correlating associated fluid characteristics and mineral assemblages, the alteration products in different rocks due to the same fluid can be identified.

Samples for petrographic and fluid inclusion studies were collected along the contact between Harris Ranch quartz monzonite and biotite quartz diorite, about 200m from the contact of the two with Ruby Star quartz monzonite porphyry. Representative samples were selected from each rock type showing single and cross-cutting veins for detailed examination. As only a single point in space was represented in this study, the results should not be considered to characterize the entire deposit, although observed mineral associations are generally in accord with those of West & Aiken (1979). Alteration and mineralization of the two rocks are presented in Figure 1, 2 and 3.

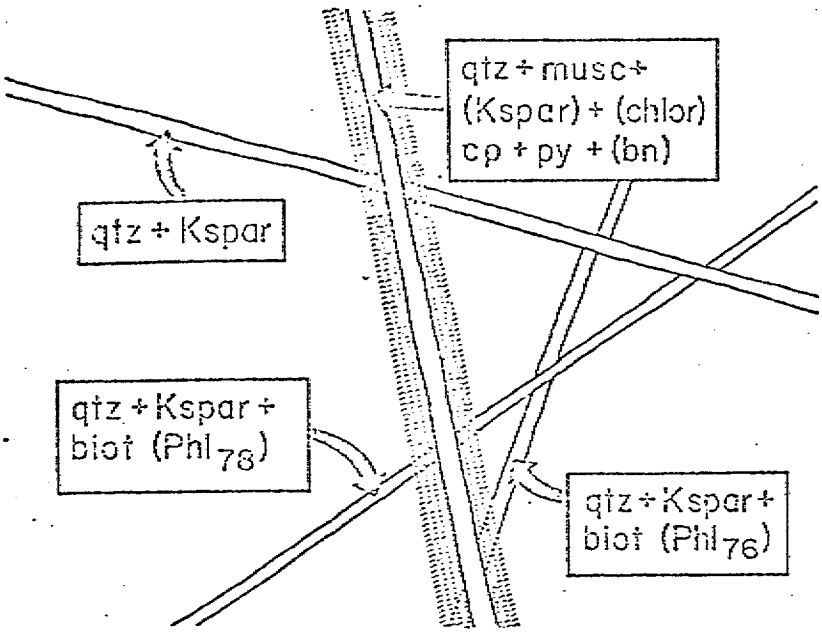

Fig. 1 Paragenetic relations in the Harris Ranch QM.

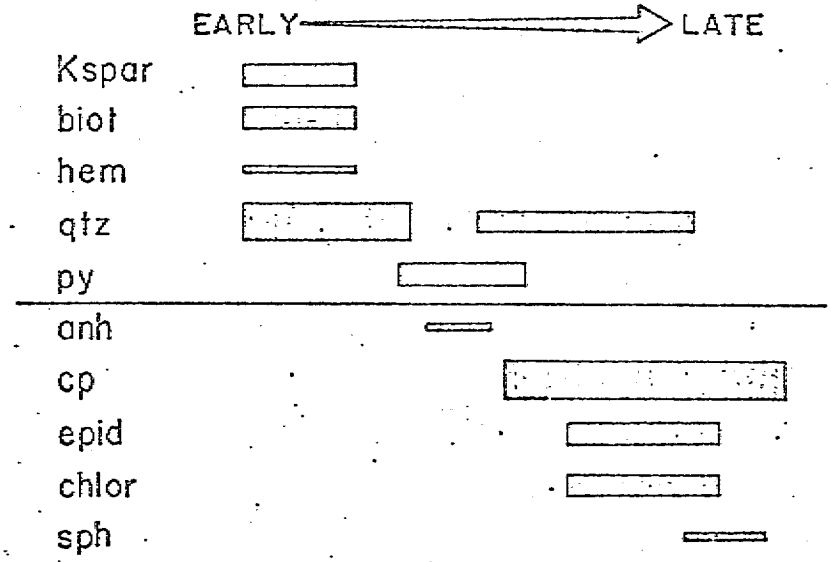

Fig. 2 Paragenetic relations within a single vein in the Harris Ranch.

1) Two assemblages are present in this vein, an early potassic assemblage and later mineralizing event.
2) Quartz-sericite-pyrite stringers and veinlets cut both assemblages.

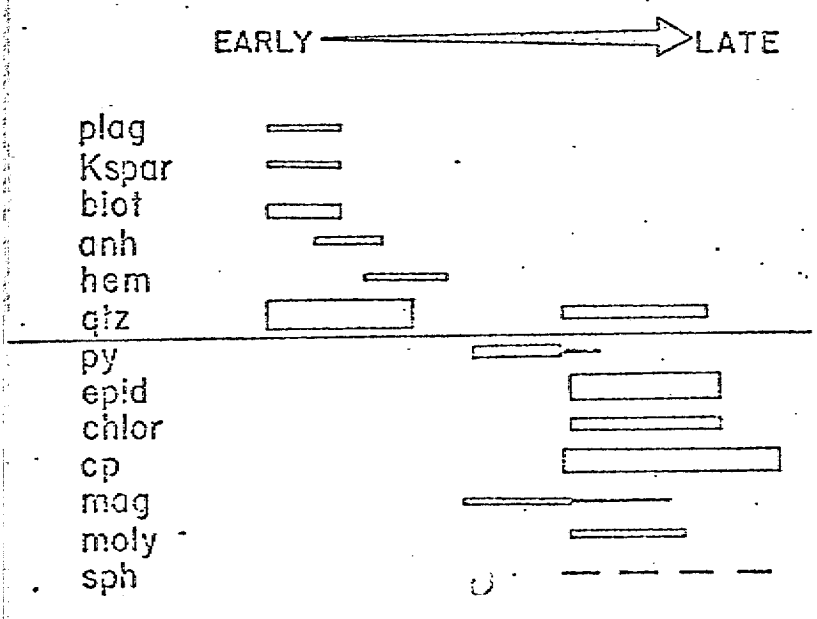

Fig. 3 Paragenesis of alteration and mineralization in the biotite quartz diorite.

1) Two assemblages with sulfides late, as in Fig. 2.
2) Albitic plagioclase and Ca, Fe, Mg phases prominant.
3) All veins studied in diorite show only minor variations of this sequence.

Standard fluid inclusion heating and freezing studies were carried out to determine the temperatures and salinities of hydrothermal fluids associated with the alteration assemblages outlined above. The relative time of a particular inclusion is based on the paragenetic position of the host crystal and the relationship of the inclusion to the host (see Beane, this vol., Fig. 2).

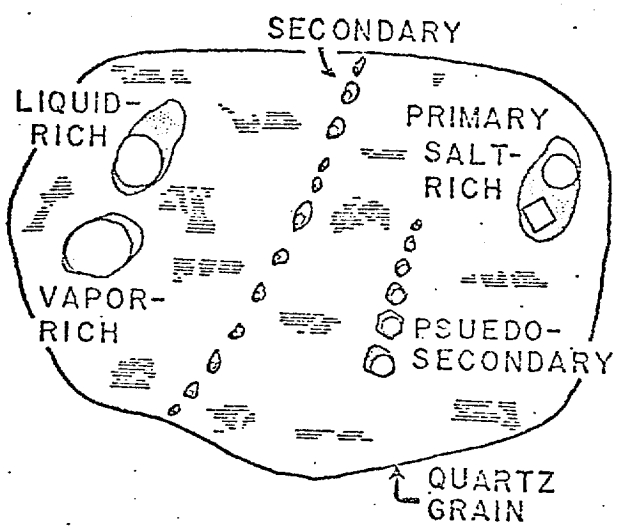

Fig. 4 Schematic diagram of fluid inclusions.

1) Primary and psuedo-secondary inclusions contemperaneous with crystal growth.
2) Secondary inclusions later than crystal growth.
3) Three compositional types seen in this study: L > V, V > L, L+V+S.

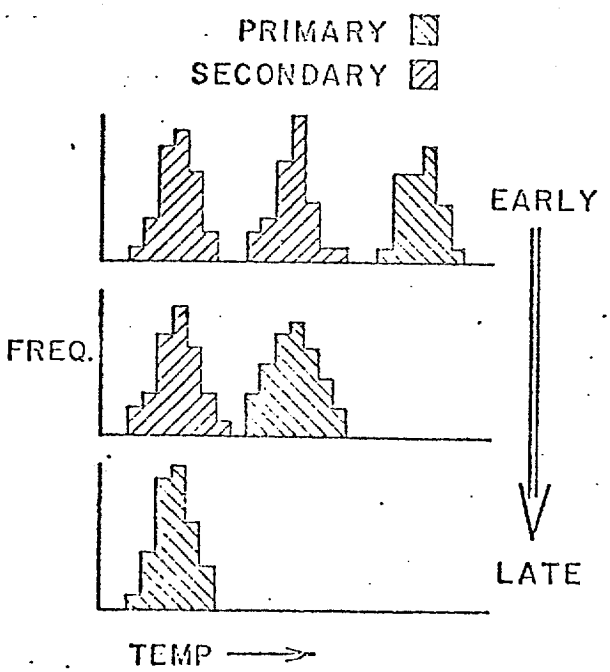

Fig. 5 Hypothetical histograms from three cross-cutting veins.

1) Each vein contains a peak of primary homogenization temperatures characteristic of that vein.
2) Secondary temperatures reflecting later fracturing events occur in earlier veins.

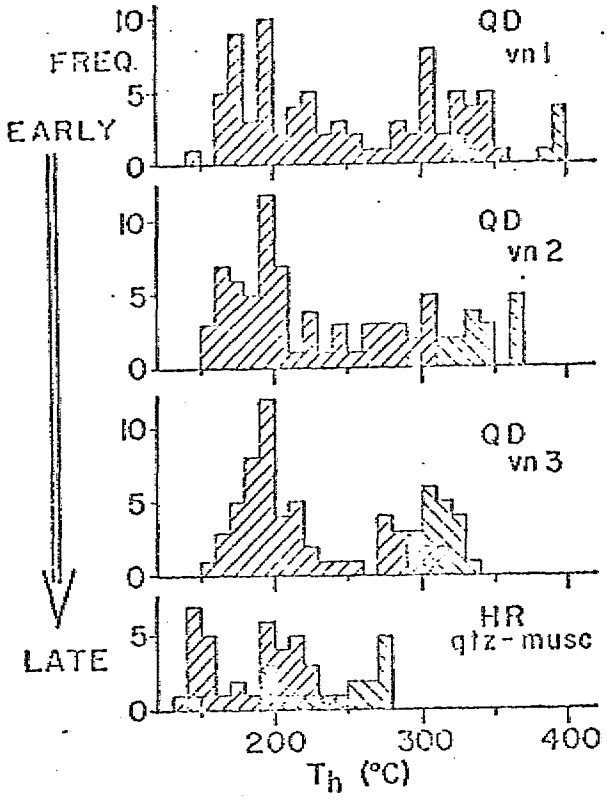

Fig. 6 Homogenization temperatures from veins in the quartz diorite and Harris Ranch (Preece, 1979)

1) Primary temperatures decrease with time.
2) Vein 1 contains secondary inclusion temperatures correlative with primaries in Veins 2 and 3, and vein 2 has secondaries matching primary temperatures of vein 3.
3) All three early veins contain secondary FI temperatures matching primary FI temperatures of quartz-muscovite veins in the Harris Ranch, even though no veins formed in this temperature range in the quartz diorite.

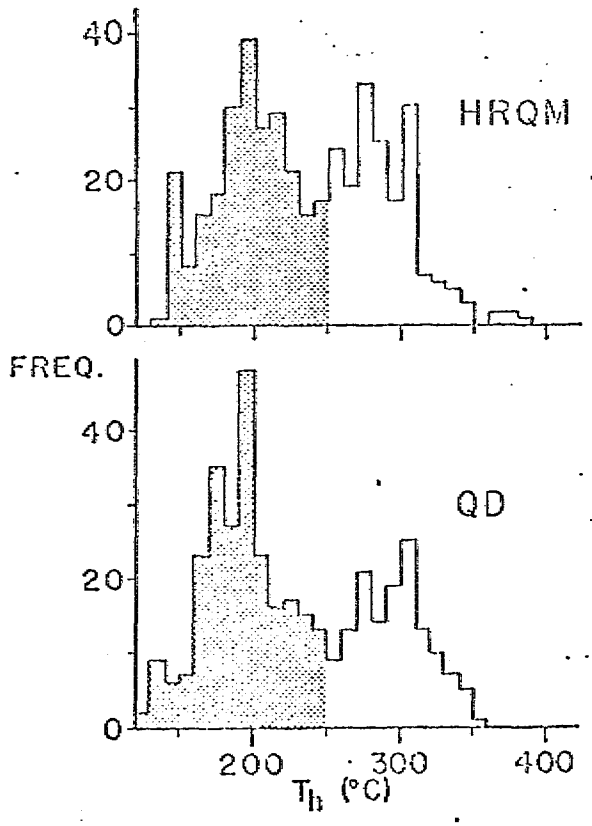

Fig. 7 Secondary inclusion homogenization temperatures in Harris Ranch and quartz diorite (Preece, 1979).

1) Histograms show close similarity
2) Same temperatures form at the same time, indicating no thermal gradient between samples.

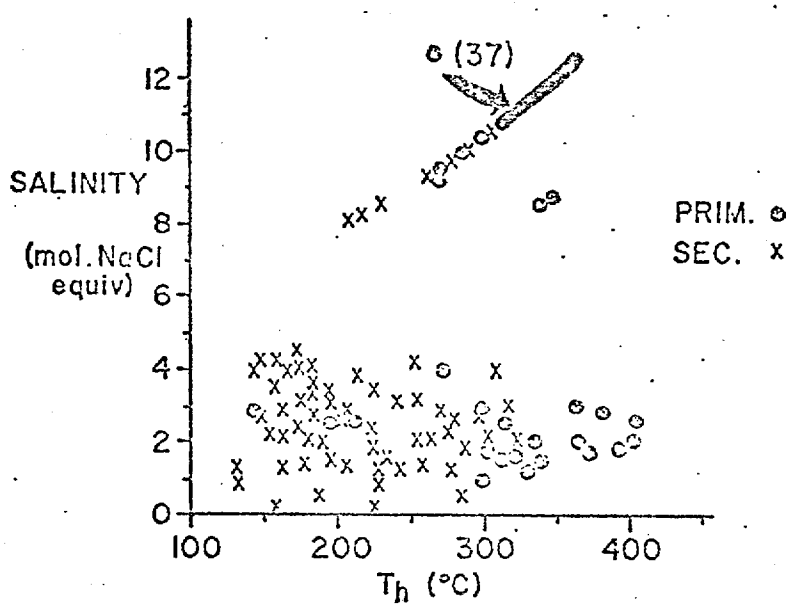

Fig. 8 Homogenization temperatures plotted against salinity (Preece, 1979)

1) Two separate fluids, a high salinity and low salinity, but no significant temperature differences at upper end.
2) Low salinity primary inclusions relatively uniform regardless of temperature.

QTZ MONZ	QTZ DIOR	°C–NaCl (eq)
qtz + Kspar + hem + (biot)	qtz + Kspar + biot + hem + anh	320–360 ~ 40 wt %
qtz + Kspar + hem	qtz + Kspar + alb + biot + hem ↓ epid + chlor + sulf + mag	375–420 2–3 m
qtz + Kspar + hem + sulf	qtz + biot ↓ epid + sulf	300–375 2 m
qtz + Kspar + chlor + (musc) + (sulf)		250–280 2–4 m
qtz + musc + sulf + (chlor)		140–250 2–4 m

Fig. 9 Alteration products and associated fluids (Preece, 1979).

1) Early fluids high salinity-moderate temperature
2) Low salinity fluids first seen at slightly higher temperatures and subsequently cool with time
3) Boiling at ~420°C, indicating 330 bars pressure
4) Mineralization associated with low salinity fluids
5) Different alteration assemblage in chemically distinct wallrocks formed at same time.

This study has shown that the temporal evolution of a hydrothermal system can be deciphered by the use of combined petrographic and fluid inclusion techniques. Although each can give some insight into the conditions of hydrothermal alteration, it is the combination of these two geological tools that provides a powerful lever on the problem of ore deposition.

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GENESIS OF DIFFERENT ALTERATION TYPES AT SIERRITA

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Current concepts of hydrothermal alteration in porphyry copper deposits are based heavily upon a model described by Lowell and Guilbert (1970) in which zones containing characteristics minerals are arranged concentrically about an epizonal intrusive body. The zoning referred to by these authors as typical of a porphyry copper deposit are shown in Fig. 1.

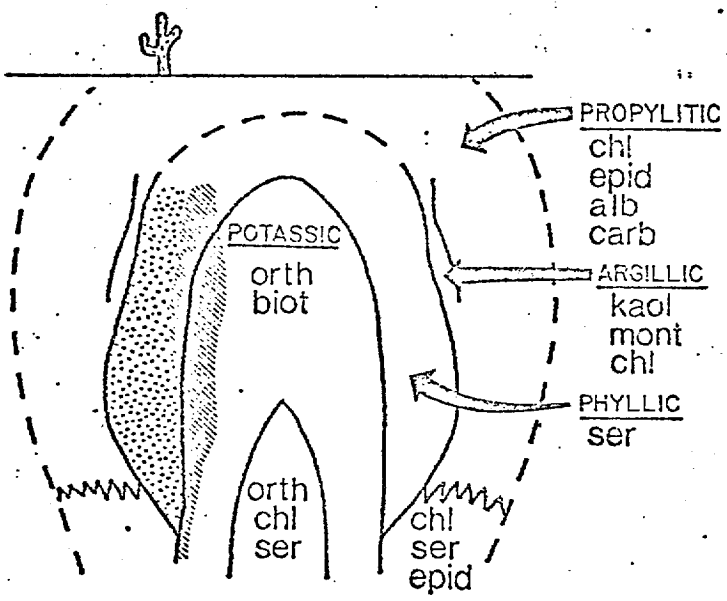

Fig. 1. Schematic drawing of alteration zoning in a typical porphyry copper deposit (modified from Lowell & Guilbert, 1970; Guilbert & Lowell, 1974).

The model is predicated only upon spatial relationships among alteration zones, and relies heavily upon observations at the San Manuel-Kalamazoo Deposit where the intrusive quartz monzonite as well as the intruded granite both contain relatively large amounts of original rock-forming K-feldspar. In the preceeding discussion, Preece demonstrated that by combining detailed

petrographic and fluid inclusion studies, the evolution of alteration minerals at the Duval-Sierrita deposit could be correlated with temperature and salinity variations of the hydrothermal fluid. One of the important results of this work was the temporal correlations of sets of veins between two different rock types as shown in Figure 2.

QTZ MONZ	QTZ DIOR	°C–NaCl (eq)
qtz + Kspar + hem + (biot)	qtz + Kspar + biot + hem + anh	320–360 ~ 40 wt %
qtz + Kspar + hem	qtz + Kspar + alb + biot + hem ↓ epid + chlor + sulf + mag	375–420 2–3 m
qtz + Kspar + hem + sulf	qtz + biot ↓ epid + sulf	300–375 2 m
qtz + Kspar + chlor + (musc) + (sulf)		250–280 2–4 m
qtz + musc + sulf + (chlor)		140–250 2–4 m

Fig. 2. Paragenesis of major alteration minerals and corresponding fluid characteristics (Preece & Beane, 1979).

1. QM:potassic → phyllic
2. BQD:potassic → propylitic
3. Different mineralogies at same time in different rock types.
4. Sulfides appear with specific alteration.
5. Decreasing temperature at constant salinity.

Mineral Stability Relations

The stability of minerals in the K-Al-Si system are influenced by temperature and solution composition as shown in Fig. 3.

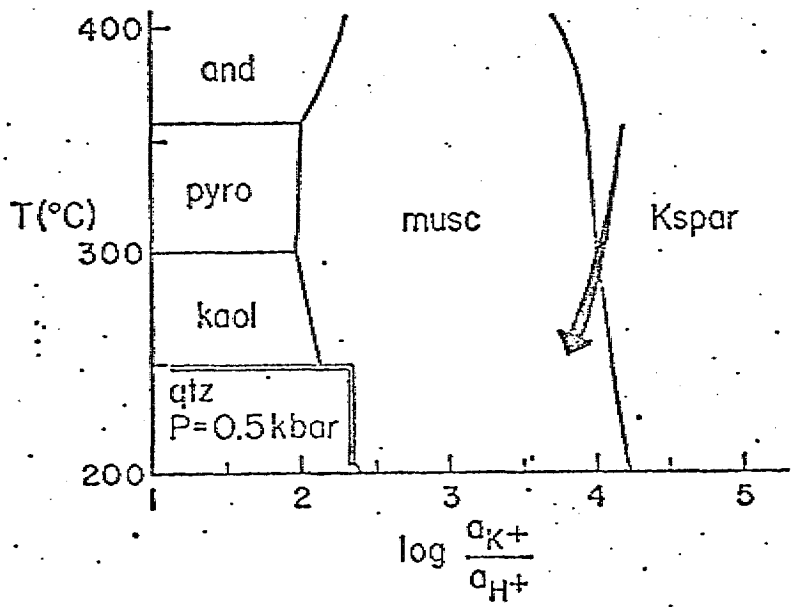

Fig. 3. Stability relations of minerals in the system $K_2O+Al_2O_3+SiO_2+H_2O$ at 500 bars pressure and quartz saturation. Curves are calculated based on Montoya and Hemley (1975).

1. variations with temperature
2. variations in solution composition
3. 280°C crossover at Sierrita

Similar relations may be calculated for the system Ca-Al-Si using data given by Bird (1978) and Helgeson, et al. (1978)

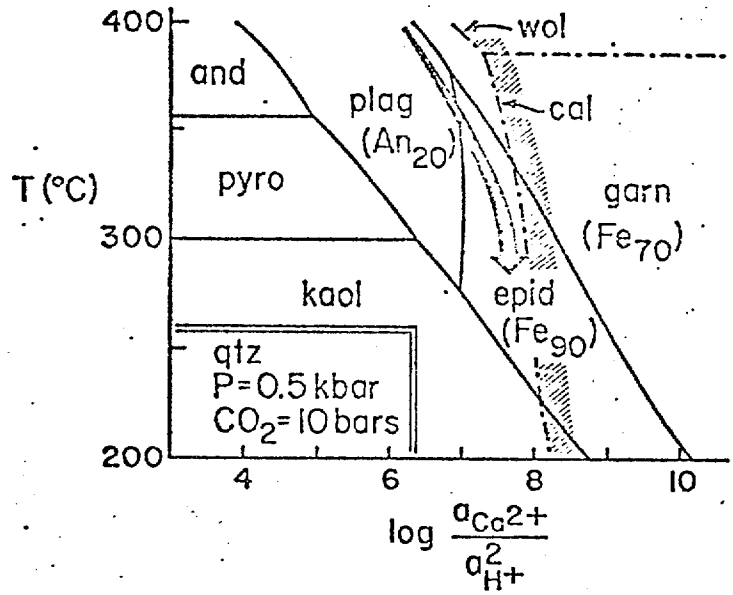

Fig. 4. Stability relations in the system $CaO+Al_2O_3+SiO_2+H_2O$ at 500 bars pressure and quartz saturation.

1. intermediate plagioclase & epidote-compositions from Sierrita
2. Ca/H limits
3. 375°C crossover at Sierrita

Corresponding diagrams may be drawn for the Na-Al-Si and Mg-Al-Si systems. To look at interrelationships between two cations temperature must be fixed. K vs. Ca and K vs. Mg are shown at 300°C and quartz saturation in Fig. 5a and 5b, respectively.

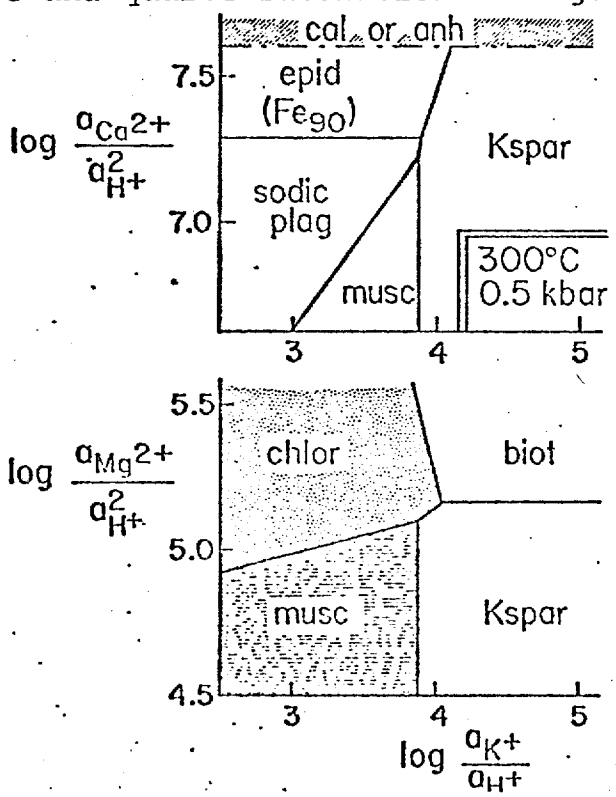

Fig. 5. Stability relations at 300°C and quartz saturation. 5a) K-Ca-Al-Si, 5b) K-Mg-Al-Si

1. compare Sierrita assemblages
2. Biot → chlorite and K-spar → musc by decreasing K/H

Sulfide deposition is caused, in part, by decreased acidity which can result from several factors (Fig. 6).

ACID CONSUMPTION

$$Cu^{+} + Fe^{2+} + 2H_2S + \frac{1}{4}O_2 \Longrightarrow cp + 3H^{+} + \frac{1}{2}H_2O$$

$$3Kspar + 2H^{+} \Longrightarrow musc + 6qtz + 2K^{+}$$

$$KAlSi_3O_8 + 2H_2O \Longrightarrow K^{+} + Al(OH)_4^{-} + 3SiO_2$$

$$KFe_3AlSi_3O_{10}(OH)_2 + 6H^{+} \Longrightarrow KAlSi_3O_8 + 3Fe^{2+} + 4H_2O$$

$$Ca_2Fe_5Si_8O_{22}(OH)_2 + 14H^{+} \Longrightarrow 2Ca^{2+} + 5Fe^{2+} + 8SiO_2 + 8H_2O$$

Fig. 6

1. Deposition by H^{+} consumption
2. Hydrolysis (dissolution reactions) - feldspars don't involve hydrogen but mafics do
3. Alteration reactions generally involve hydrogen as well.

Development of chlorite instead of muscovite by alteration of biotite (Fig. 5b) has a strong influence on the sulfide assemblages formed (Fig. 7).

PHYLLIC

$$3\,Fe\text{-}biot + 20\,H^{+} = musc + 9Fe^{+2} + 2K^{+} + 6qtz + 12H_2O \Longrightarrow CuFeS_2 + FeS_2,\ FeCO_3$$

"PROPYLITIC"

$$2\,Fe\text{-}biot + 4H^{+} = Fe\text{-}chlor + Fe^{+2} + 2K^{+} + 3qtz \Longrightarrow CuFeS_2 + Cu_5FeS_4,\ CaCO_3$$

Fig. 7

1. Biot → musc releases large amounts of iron, which produces a high iron sulfide assemblage (py+cpy)
2. Biot → chlor generally conserves iron in the silicates so the resulting sulfides are high Cu/Fe (cpy+bn, wk py).

Such potential variations from "typical" zoning have been well documented in the field by Titley (1975) and should be recognized by the exploration geologist.

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SIERRITA MINE TRIP

PLEASE READ

ALTHOUGH WE ARE GOING INTO THIS LARGE MINE ON A DAY IN WHICH OPERATIONS ARE SHUT DOWN FOR MAINTENANCE, THIS IS AN ACTIVE MINE IN ALL RESPECTS. BE CAREFUL

WEAR YOUR HARD HAT AND GLASSES AT ALL TIMES

WE HAVE SELECTED BENCHES AND EXPOSURES WHERE THERE IS ADEQUATE SPACE FOR MOST OR ALL OF YOU TO WORK. BECAUSE OF THE LARGE NUMBER OF PEOPLE, BE EXTREMELY CAREFUL AND AWARE OF EACH OTHER.

WE WILL BE WORKING ON BENCH FACES WHICH ARE GENERALLY SAFE BUT THEY SHOULD BE TREATED CAREFULLY AND WITH RESPECT. AGAIN, THIS IS AN ACTIVE MINE, THESE ARE ACTIVE BENCH FACES, AND THEY HAVE NOT HAD TIME TO STABILIZE.

BE AWARE OF WHAT IS ABOVE YOU. DO NOT WORK UNDER OVERHANGING ROCKS.

IN GENERAL, DO NOT WORK ROCKS LOOSE FROM BENCH FACES. IF YOU MUST, MAKE CERTAIN THAT DOING SO WILL NOT ENDANGER YOURSELF OR OTHERS. BE AWARE OF PEOPLE ABOVE YOU AND BELOW YOU. BE CAREFUL IN MOVING OR DROPPING ROCKS DOWN SLOPE.

THE ROCKS IN SIERRITA ARE EXTREMELY HARD AND TENACIOUS. BE EXTREMELY CAREFUL WHEN YOU ARE BREAKING THEM BECAUSE THEY SPLINTER INTO VERY SHARP FRAGMENTS WHICH MOVE AT HIGH SPEED. BE CAREFUL IF YOU ARE NEAR ANYONE BREAKING ROCKS AND BE CAREFUL OF THOSE AROUND YOU IF YOU ARE DOING LIKEWISE. IF YOU HAVE LONG SLEEVES IT IS ADVISABLE TO ROLL THEM DOWN. YOU ARE REQUIRED TO WEAR LONG TROUSERS IN THE SIERRITA PIT. WEAR SAFETY GLASSES AT ALL TIMES.

HAVE AN ENJOYABLE DAY WITH THESE INTERESTING ROCKS

BUT PLEASE USE COMMON SENSE AND BE CAREFUL.

DUVAL SIERRITA-ESPERANZA MINE
S.E.G. FIELD TRIP

Pit Stop No. 1
Map Reference A, 3850 Bench-West Side
HARRIS RANCH QUARTZ MONZONITE (QM)

Harris Ranch Quartz Monzonite, Jurassic in age. A pre-ore rock and host to mineralization of Laramide age. The rock expresses an underlying biotite-stable alteration which is modified by the alteration of later veins.

The objectives of studies of this outcrop are to identify and differentiate vein alteration types and to establish paragenetic relationships based on geometric characteristics & interrelationships. The alteration is relatively simple if contrasted with that of stops to be made later today. A secondary set of objectives is that of evaluation of orientations of different vein sets. Because of distinctive directions of some of the vein types a basis for correlation of different alteration types in other rock types here can be tentatively assessed on similar orientations.

The general sequence of veins is: bi-qz; qz-or-ep-chl-cpy-py; qz-or-ser-cpy-py; qz-ser-cpy-py; and a variety of qz-sulfide types; gyp-zeol-cal-clay.

Pit Stop No. 2
Map Reference B, 3400 Bench-West Side
Cretaceous, BIOTITE QUARTZ DIORITE (BQD)

Biotite Quartz Diorite, a host to mineralization. This biotite-rich rock is not a porphyry but its chemical and mineralogical composition contrasts with that of other igneous rocks of the orebody and as a result, somewhat different mineral assemblages occur as vein-wall selvages.

The objectives of study of this exposure are similar to those of stop 1. However, the alteration is more complex. A paragenetic sequence can be established and a chemical progress proposed from comparison of veins with different alteration minerals. Here, too, vein orientations can be measured and an assessment made of both orientation of vein types and of "density" of fracturing.

Alteration progresses from development of pervasive biotite through successively, qz-or vein types, orthoclase vein types incl. qz and epidote, qz-ab-or-ep-sulfide vein types, qz-ser-cpy-py vein types, qz-sulfide types and late gyp-zeol-cal-clay veins.

Pit Stop No. 3.
Map Reference C, (?)3800 Bench-North Side
QUARTZ MONZONITE PORPHYRY (QMP)

Quartz Monzonite Porphyry (Laramide) which is a host to mineralization and probably a progenitor to the mineralized system. Two "phases" or "types" or porphyry are recognized in the Sierrita - Esperanza orebody. One is a more-or-less typical seriate crowded porphyry with orthoclase, quartz, and plagioclase phenocrysts. The other is an unusual porphyritic rock with large (1-3cm) phenocrysts of orthoclase and is most common in the Esperanza orebody.

Objectives of study of this rock are to evaluate still another vein alteration assemblage, controlled again by wall rock chemistry, of this orebody. Paragenetic data can be determined as well as evaluation of the systematic nature of fracturing and its density.

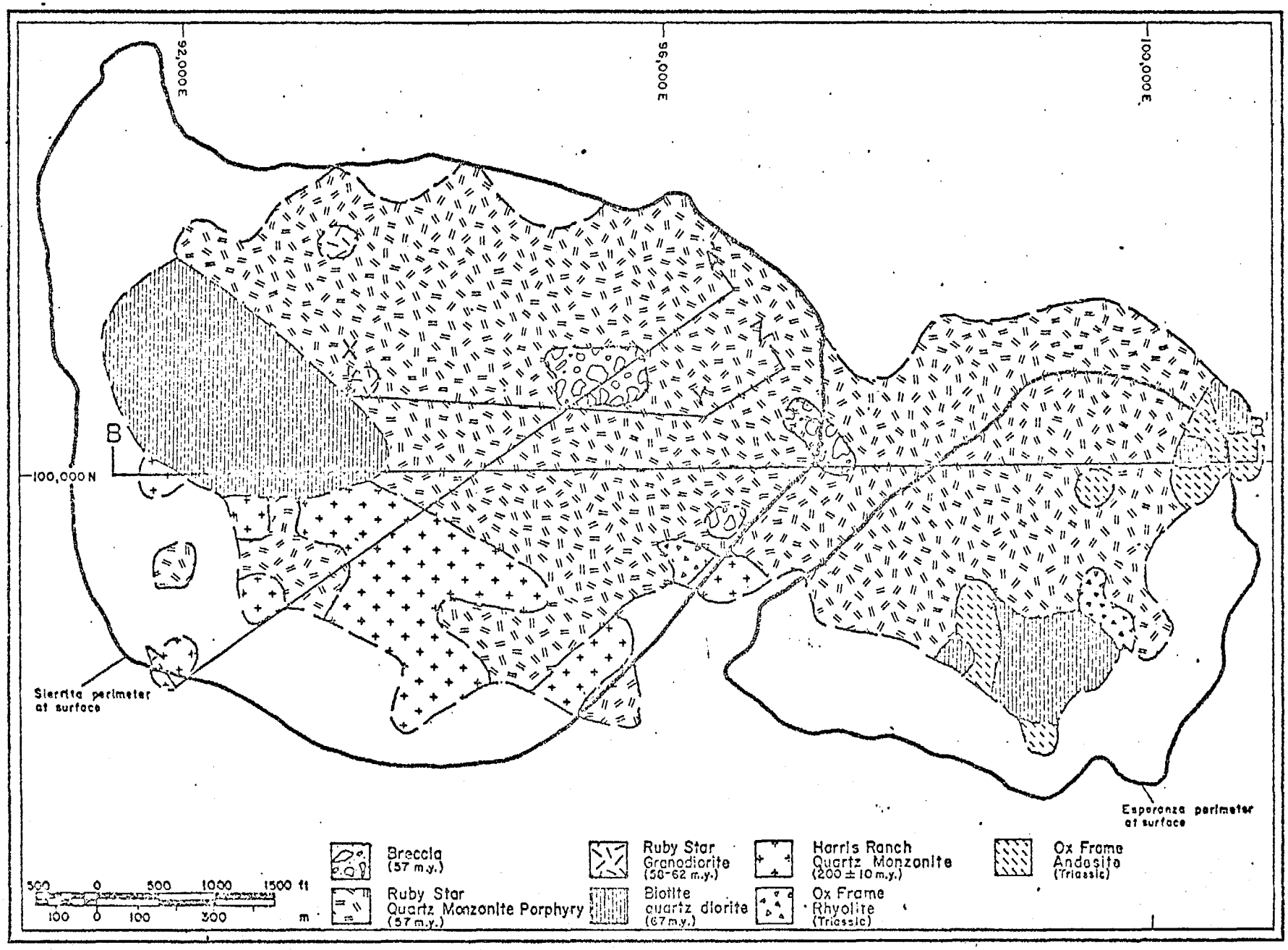
A variety of vein types occur in this rock and probably expresses the greatest complexity to be observed. The general sequence is about the same as seen in the other rock types but the diversity in vein-wall mineralogy is generally much greater than that of the rocks of the previous stops. If possible, try to separate and distinguish sets of veins based on orientation, mineralogy, crosscutting relationships, etc., and measure composite lengths of each type in a 50 cm square for comparison to rocks to be observed at stop 4.

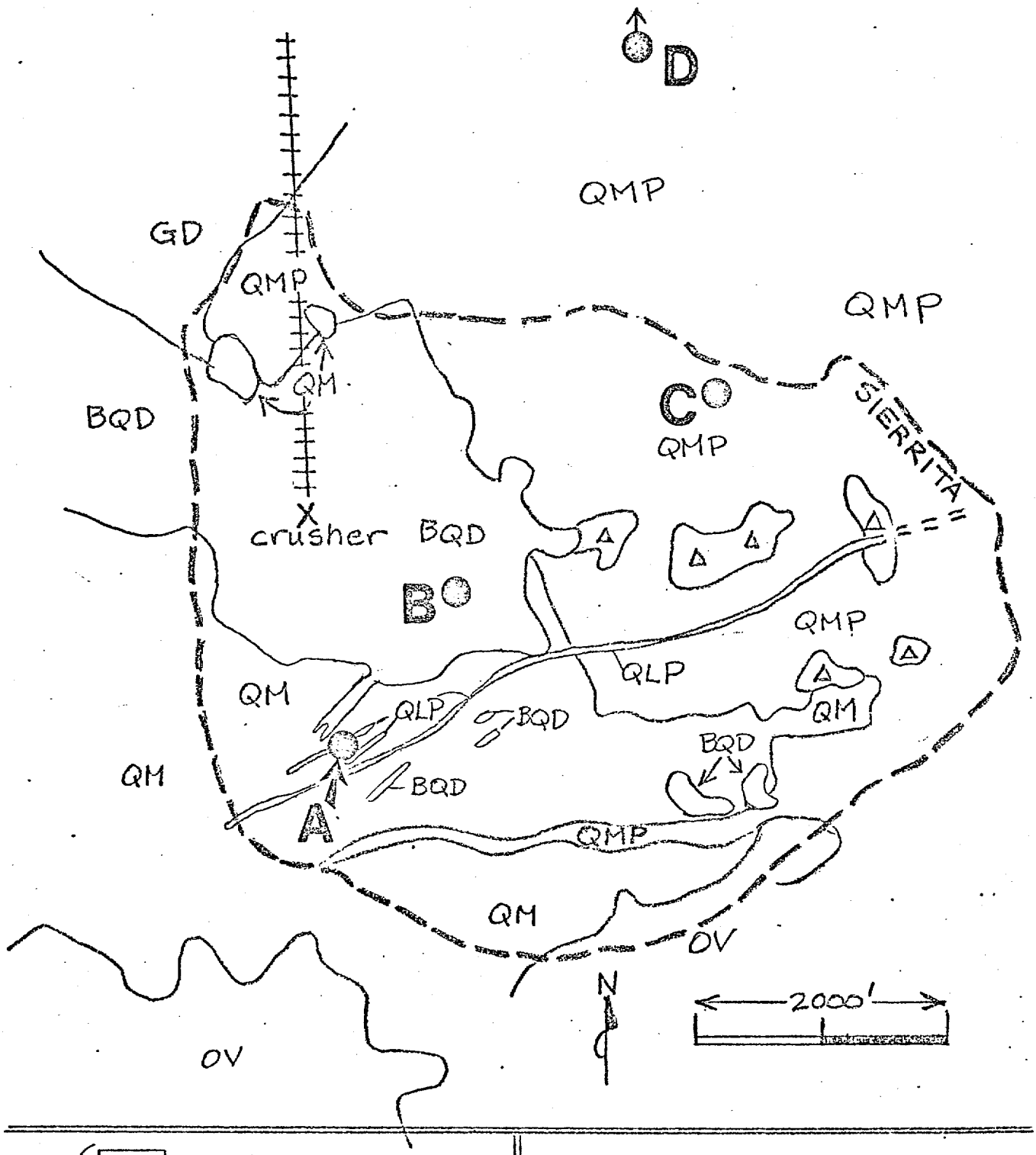
Stop No. 4
Map Reference D, approximately 1.5km north of the Sierrita Pit Edge
RUBY STAR GRANODIORITE (GD) or QUARTZ MONZONITE PORPHYRY (QMP)

A short (¼ mile about) walk along exposures of fractured and veined host rock outside of the pit. The terminus of the walk will be onto a large flat exposure of fractured and veined porphyry in which the systematic nature of fracturing can be observed and measured. Although the "density" of veins in the host remains about the same as at pit stop 3, the dominant mineralogy of most, as deduced from capping interpretation is that of qz-mt-sulfide with lesser numbers of qz-or, qz-or-ep, and qz veins.

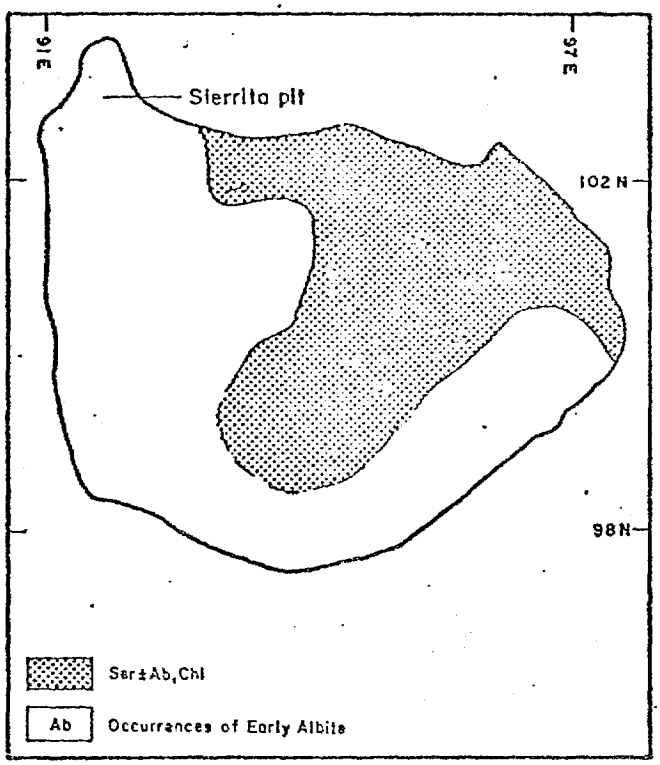
It is noteworthy that the expression of the surface along this traverse is not greatly different from that expressed in this rock type above the Sierrita orebody. The preservation of rock texture and the absence of large volumes of completely leached and oxidized rock must be, at least in part, the result of the absence of any major late "swamping" of the system by fracture-controlled quartz-sericite-pyrite alteration.

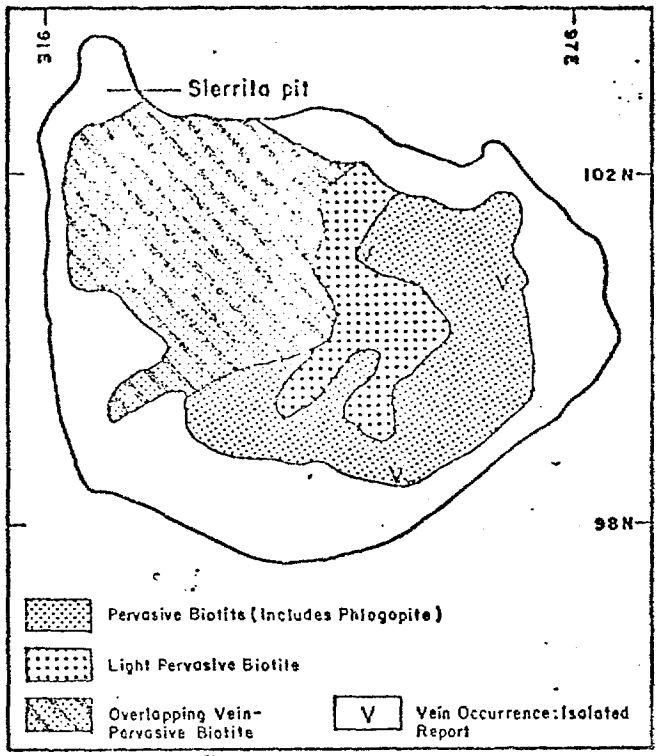
If time permits, on the way out (north) unfractured exposures of the prophyry will be briefly examined, about 1.5 km north.

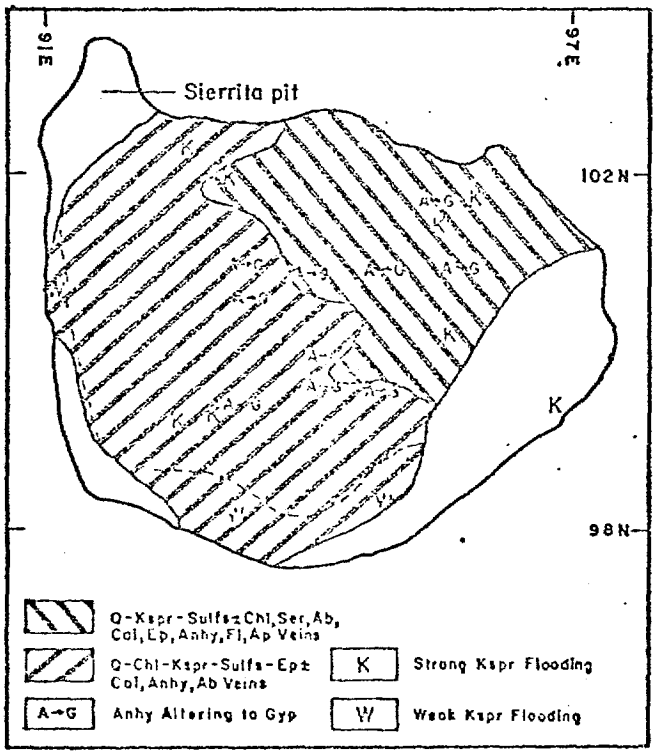

92,000 E
96,000 E
100,000 E
100,000 N
B
B'
Sierrita perimeter at surface
Esperanza perimeter at surface
Breccia (57 m.y.)
Ruby Star Quartz Monzonite Porphyry (57 m.y.)
Ruby Star Granodiorite (58-62 m.y.)
Biotite quartz diorite (67 m.y.)
Harris Ranch Quartz Monzonite (200 ± 10 m.y.)
Ox Frame Rhyolite (Triassic)
Ox Frame Andesite (Triassic)
500 0 500 1000 1500 ft
100 0 100 300 m

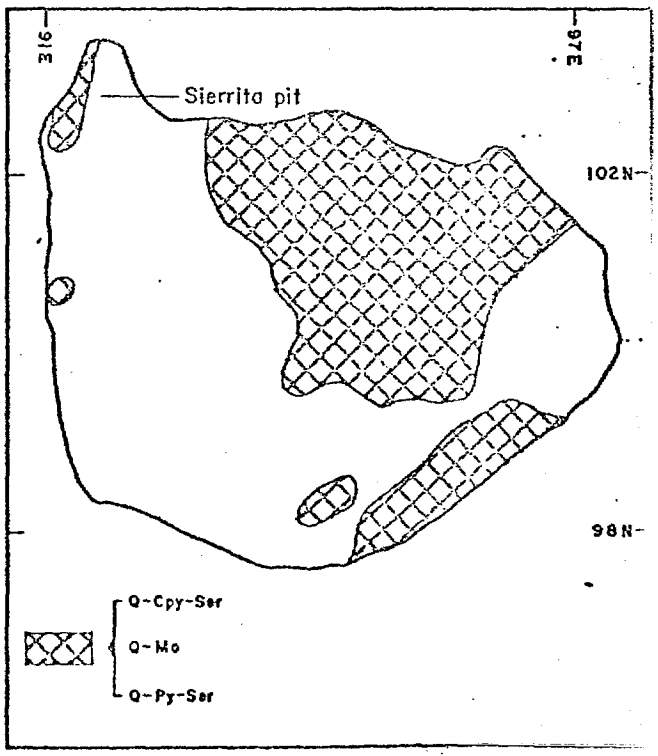


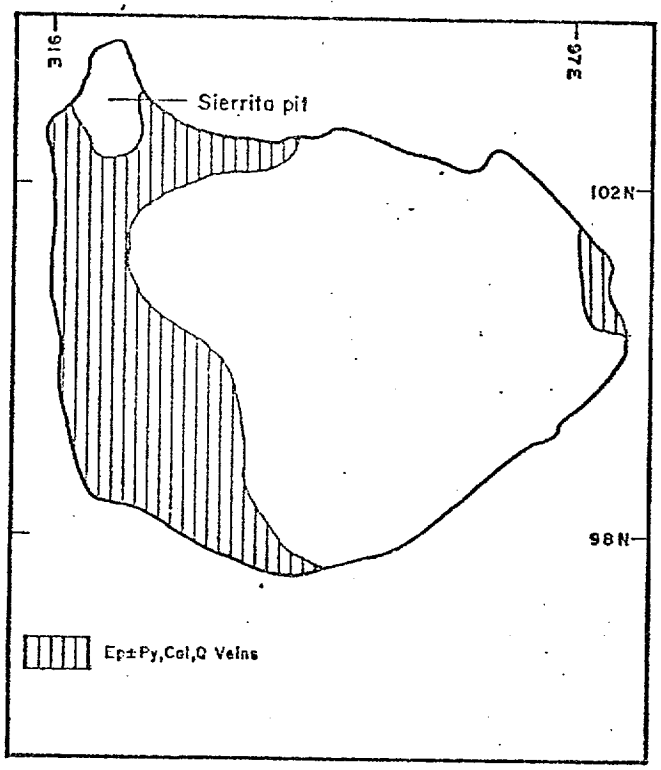
TK	QLP	qtz lat ppy	
	QMP	qtz monz ppy	
	GD	Ruby Star granodior.	
	BQD	biot qtz dior	
JR	QM	Harris Ranch qtz monz	
TR	OV	Ox Frame volc – rhy tuff andes	

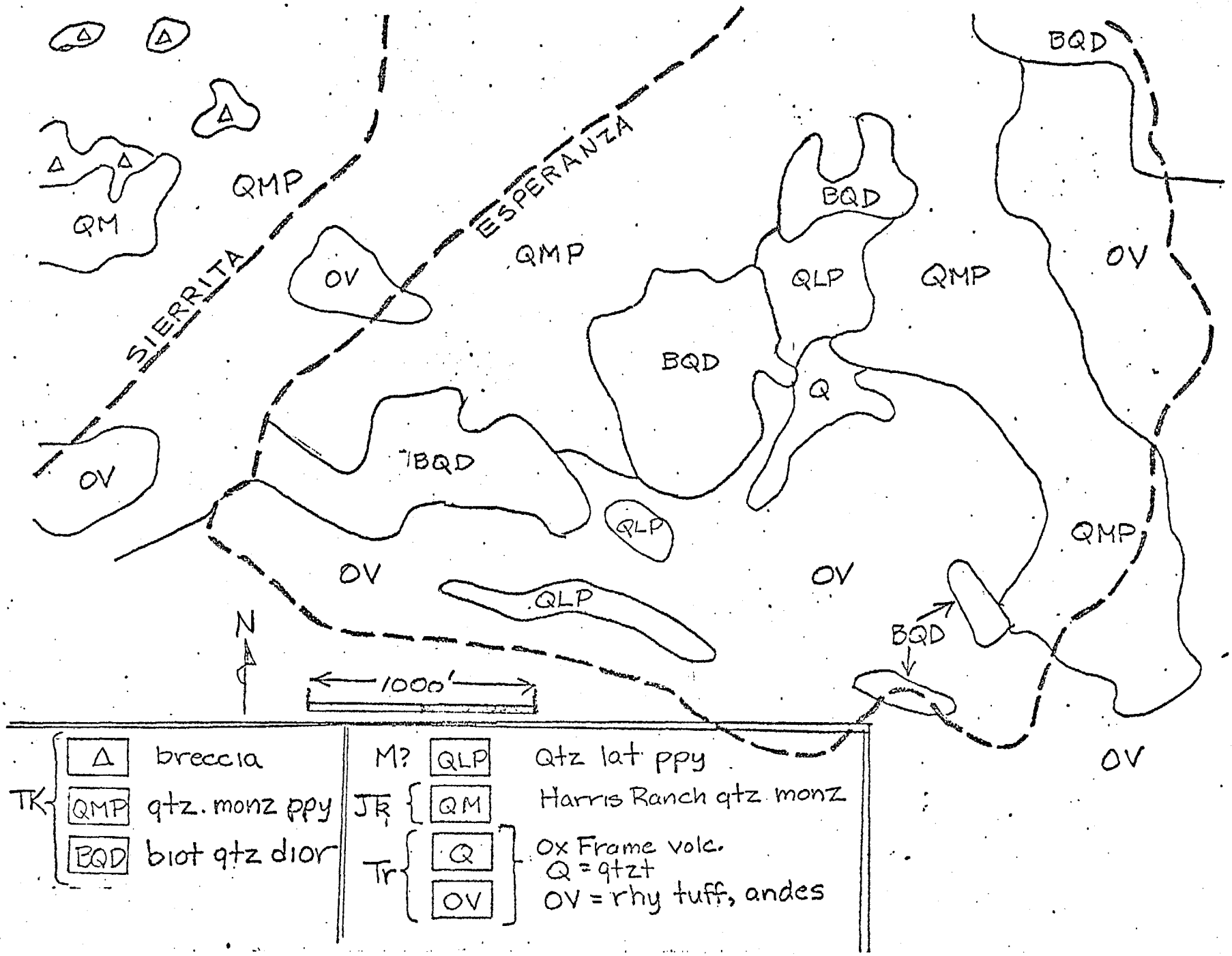

91E
97E
Sierrita pit
102 N
98N
Ser±Ab,Chl
Ab
Occurrances of Early Albite

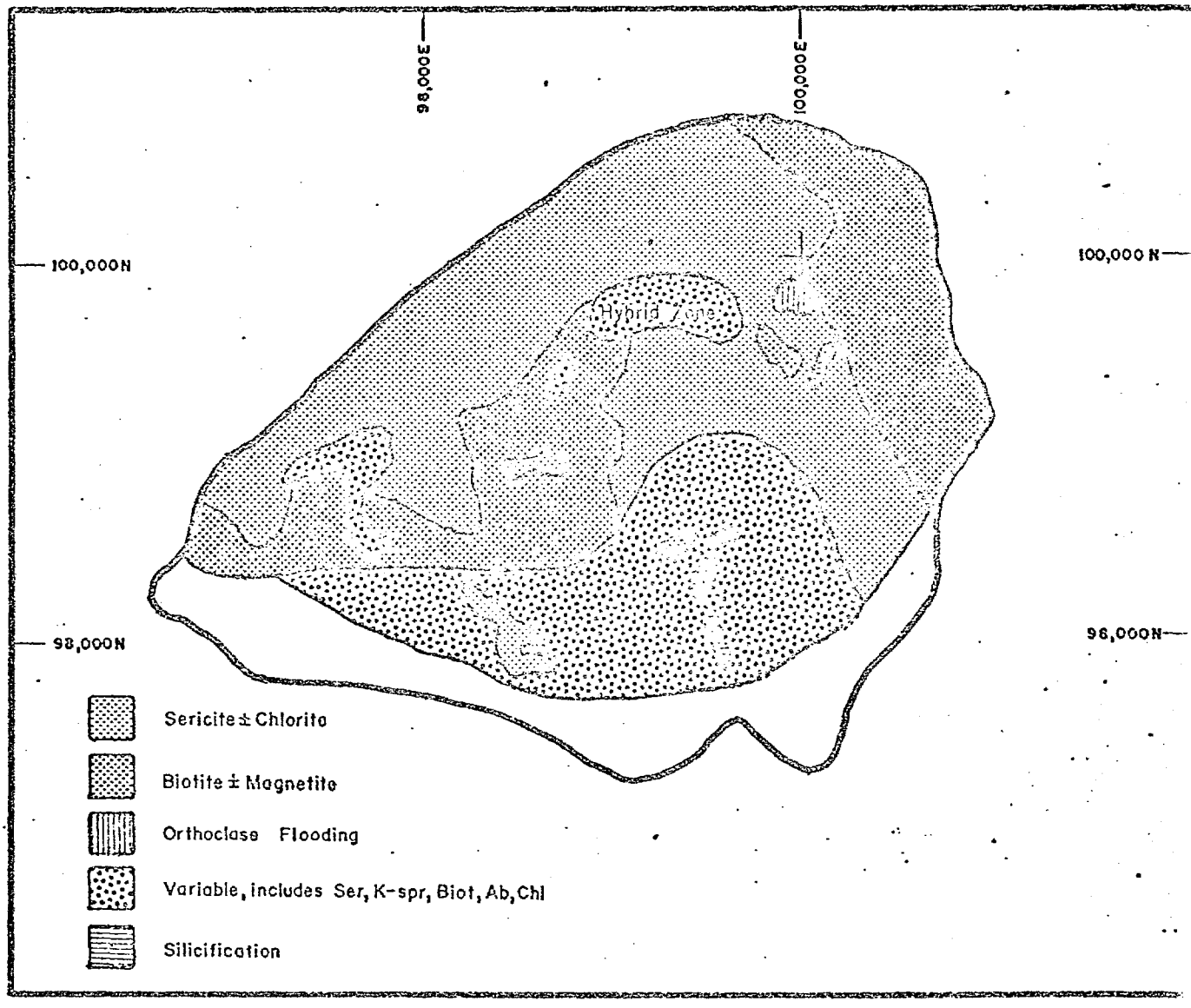

91E
97E
Sierrita pit
102 N
98N
Pervasive Biotite (Includes Phlogopite)
Light Pervasive Biotite
Overlapping Vein-Pervasive Biotite
V
Vein Occurrence: Isolated Report

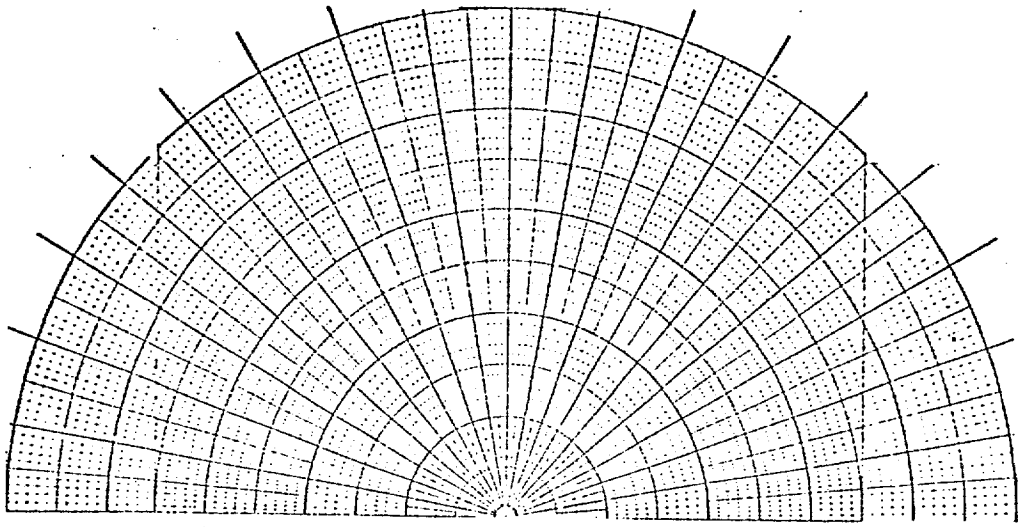

91E
97E
Sierrita pit
102 N
98N
K
Q-Kspr-Sulfs±Chl,Ser,Ab, Col,Ep,Anhy,Fl,Ap Veins
Q-Chl-Kspr-Sulfs-Ep± Col,Anhy,Ab Veins
A→G
Anhy Altering to Gyp
K
Strong Kspr Flooding
W
Weak Kspr Flooding

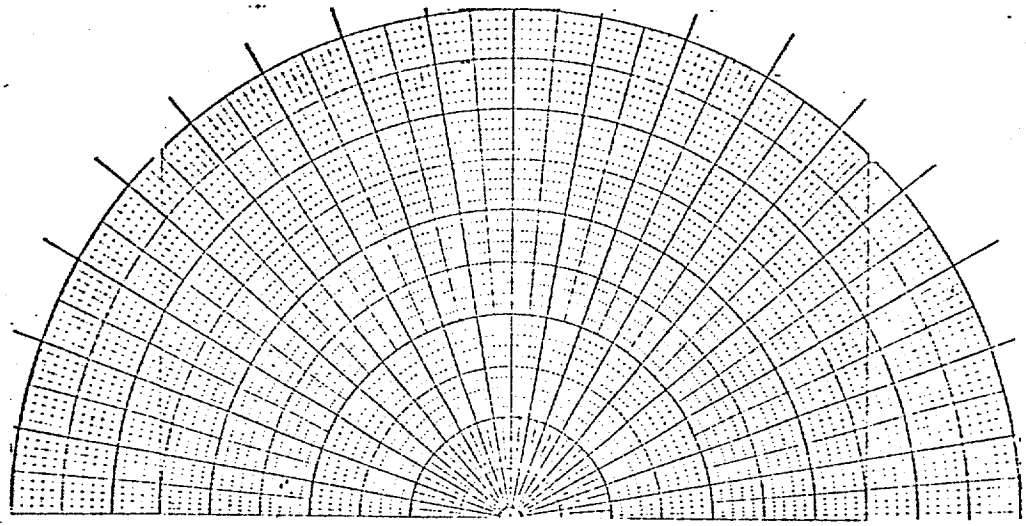

91E
97E
Sierrita pit
102N
98N
Q-Cpy-Ser
Q-Mo
Q-Py-Ser

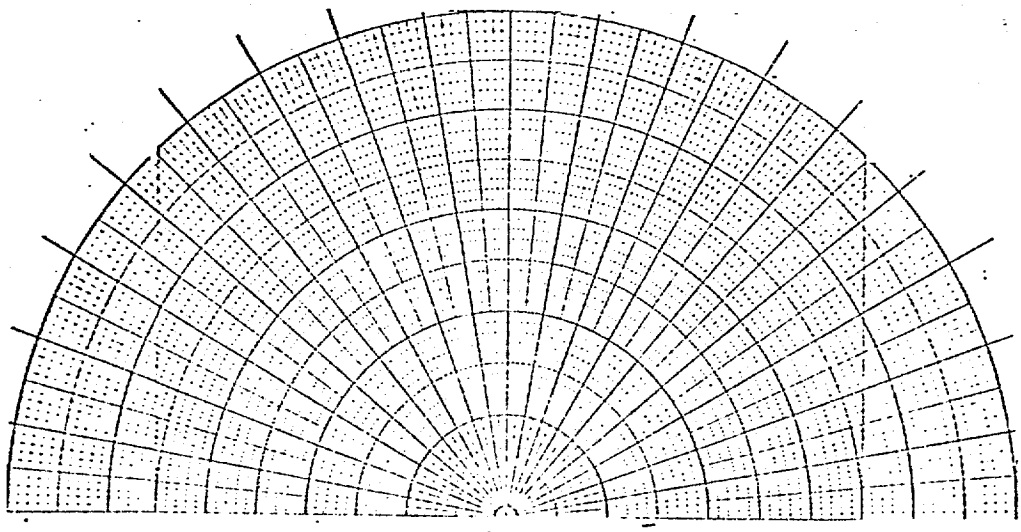

316
326
Sierrita pit
102N
98N
Ep±Py,Cal,Q Veins

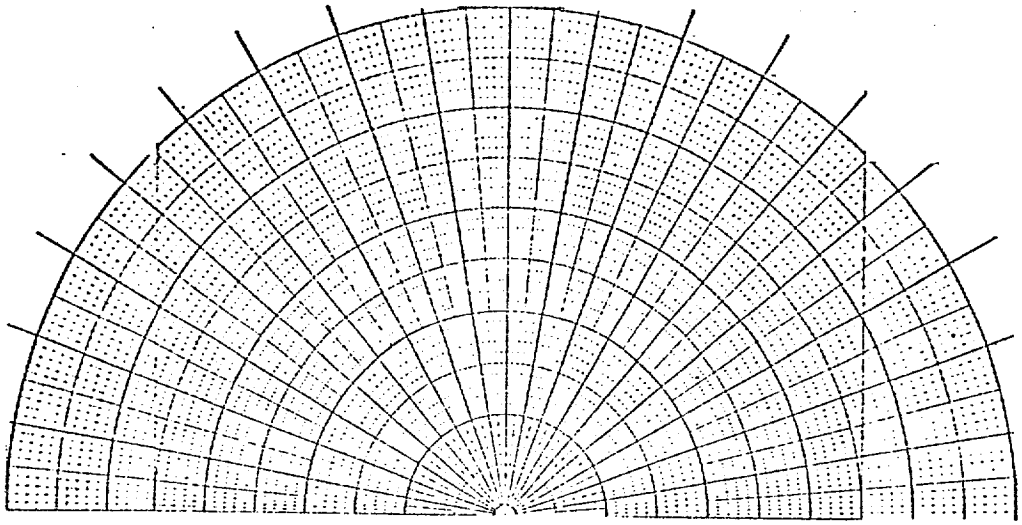

SIERRITA
ESPERANZA
QMP
QM
OV
BQD
QLP
Q
N
1000'
TK
Δ breccia
QMP qtz. monz ppy
BQD biot qtz dior
M?
QLP Qtz lat ppy
JK
QM Harris Ranch qtz monz
Tr
Q
OV
Ox Frame volc.
Q = qtzt
OV = rhy tuff, andes

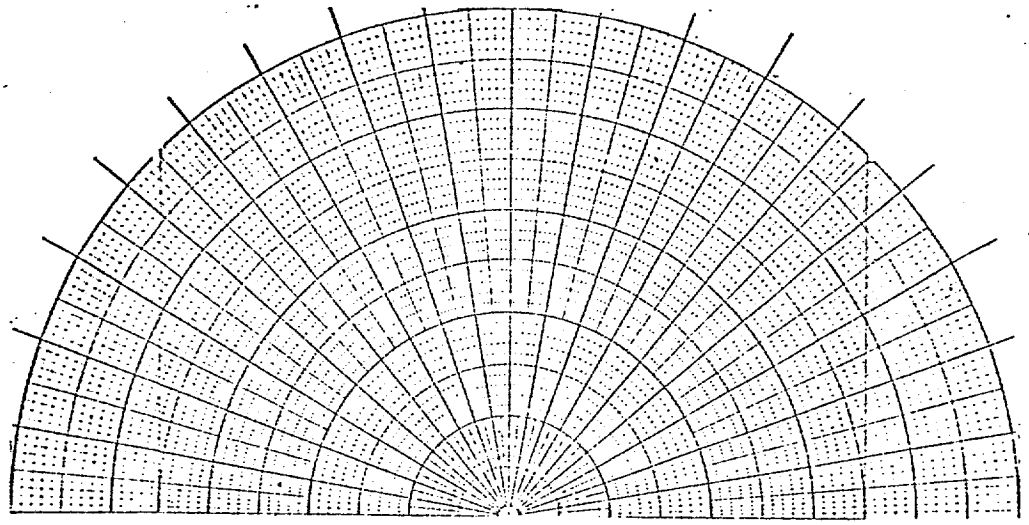

98,000E
100,000E
100,000N
100,000 N
Hybrid Zone
98,000N
96,000N
Sericite ± Chlorite
Biotite ± Magnetite
Orthoclase Flooding
Variable, includes Ser, K-spr, Biot, Ab, Chl
Silicification

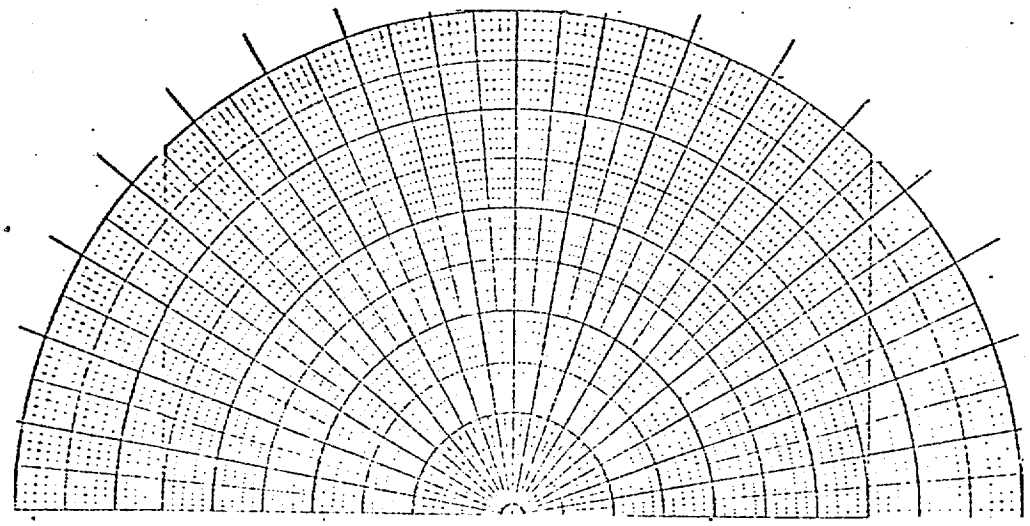












ROCK TYPE _____

MINERALOGY	STK	DIP	WIDTH V	WIDTH H	REMARKS

MINERALOGY	STK.	DIP	WIDTH V	WIDTH H	REMARKS

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GEOLOGIC ROAD LOG — SILVER BELL-NORTH SILVER BELL

Follow the country road west of townsite. Beyond corrals, occasional outcrops of Amole sediments, Recreation Redbeds. Then outcrops of Silver Bell alaskite with occasional Qmp.

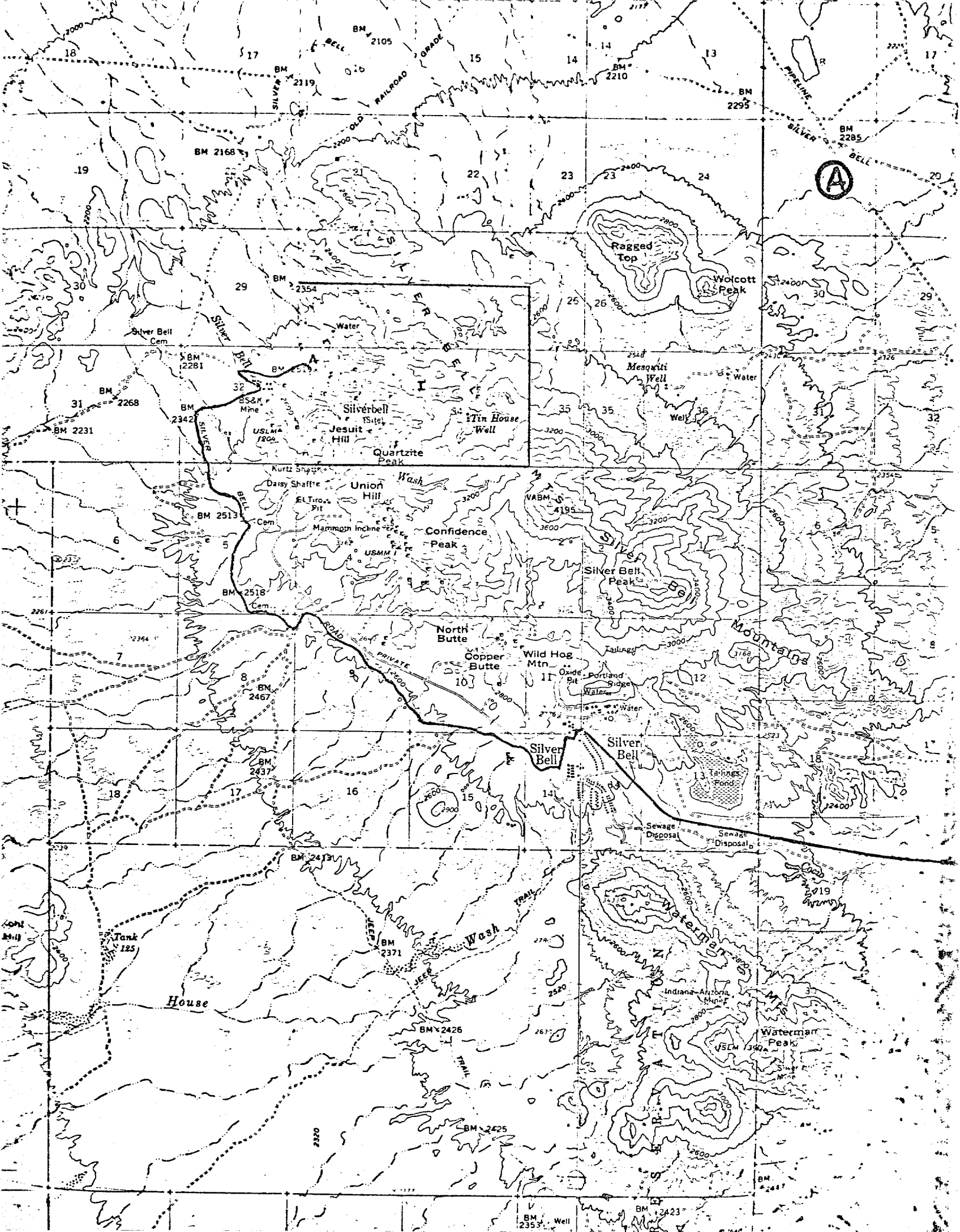
At 3.5 miles is a pre turn-of-the-century smelter site, with foundations and slag, a unit which served early (pre-SASCO smelter, 1906) Pb-Zn-Cu-Ag interests, was served by railroad from the North.

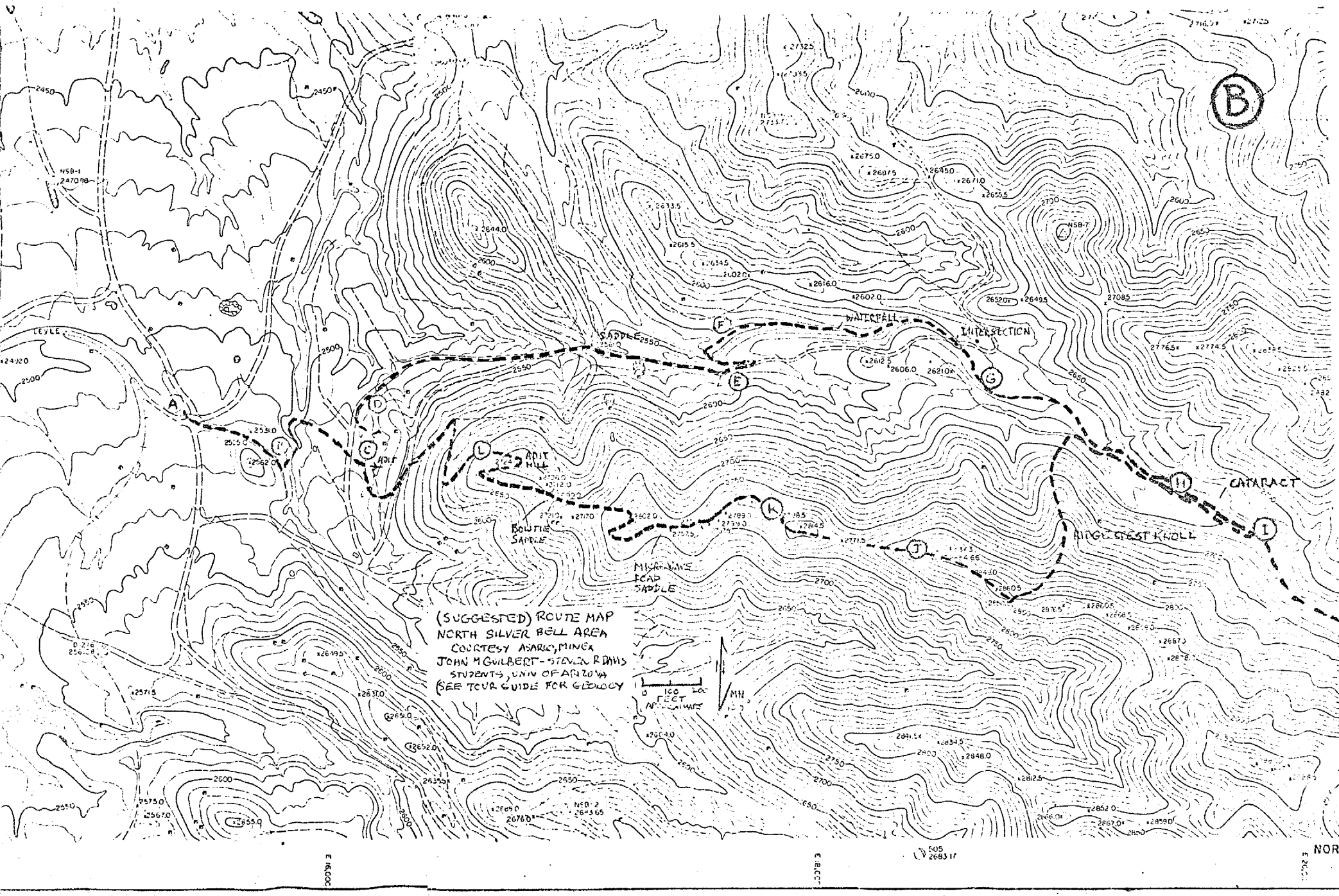
For the next few miles - the Santa Rosas (see county map) are due west, the South Comobabis to the south in the distance. In the middle distance are two Papago Indian preserves, Koht Kohl (to left, upper Paleozoic) and Ka Kohl (to right, mid-Tertiary volcanics). To the northwest are the Slates (Lakeshore) and the Vekols (Vekol).

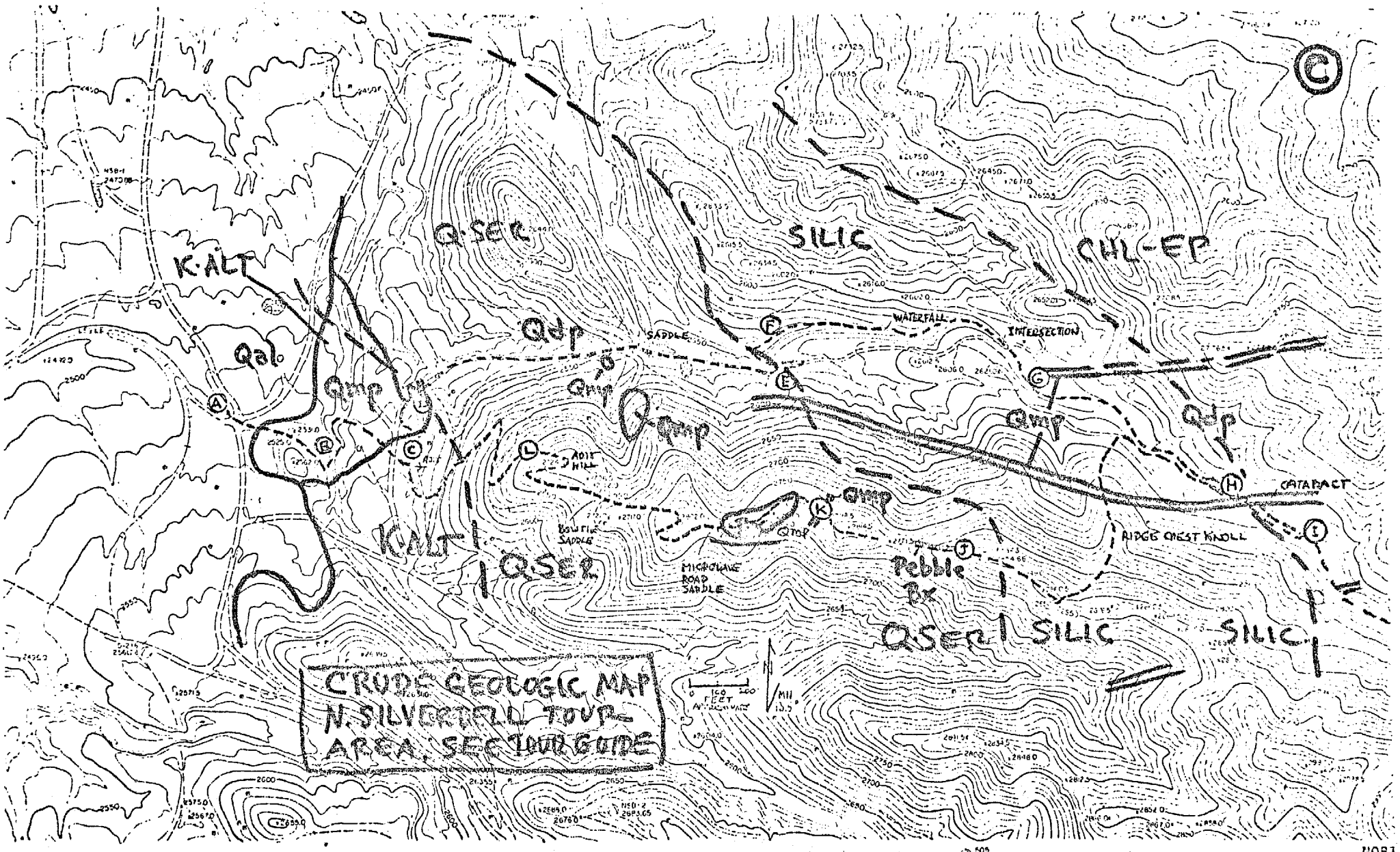
The road curves back, heads NE past the Atlas Mine, a BS & K property of veins of sphalerite-pyrite, minor chalcopyrite-galena in hydrothermally skarnified Paleozoic limestones.

At 6.5 miles and 20 minutes out of Silver Bell, the road is on the old RR grade through thick caliche.

At 7.0 miles, go through gate on RR grade. The West Silver Bell Mountains are to the left in a spectacular saguaro forest, the North Silver Bell property is immediately ahead.


A
Ragged Top
Wolcott Peak
Mesquiti Well
Water
Silverbell Site
Jesuit Hill
Tin House Well
Quartzite Peak
Union Hill
Wash
Confidence Peak
Silver Bell Peak
Silver Bell Mountains
North Butte
Copper Butte
Wild Hog Mtn
Portland Ridge
Tailings
Silver Bell
Tailings Pond
Sewage Disposal
Waterman Mts
Waterman Peak
Indiana-Arizona Mine
Jeep Wash
Tank
House
Silver Bell Cem
Silver Bell Road
Old Railroad Grade
Pipeline
Private Road
Jeep Trail
BM 2168
BM 2105
BM 2119
BM 2210
BM 2295
BM 2285
BM 2354
BM 2281
BM 2268
BM 2231
BM 2342
BM 2513
BM 2518
BM 2467
BM 2437
BM 2413
BM 2371
BM 2426
BM 2425
BM 2423
BM 2353
Well


(SUGGESTED) ROUTE MAP
NORTH SILVER BELL AREA
COURTESY ASARCO, MINEX
JOHN M GUILBERT - STEVEN R DAVIS
STUDENTS, UNIV OF ARIZONA
(SEE TOUR GUIDE FOR GEOLOGY
WATERFALL
INTERSECTION
SADDLE
CATARACT
RIDGECREST KNOLL
ADIT HILL
ADIT
ROUTE SADDLE
MINEVANE CAP SADDLE
100 200
FEET
MN
B
A
C
D
E
F
G
H
I
J
K
L


CRUDE GEOLOGIC MAP
N. SILVERTON TOUR
AREA, SEE TOUR GUIDE
K-ALT
Q-SER
SILIC
CHL-EP
Qal.
Qdp
Qmp
SADDLE
WATERFALL
INTERSECTION
CATARACT
RIDGE CREST KNOLL
BOWTIE SADDLE
MICROWAVE ROAD SADDLE
Pebble Bx
FEET
MILS

North Silver Bell Tour Guide by John M. Guilbert (U of A) and Steven R. Davis (ASARCO)

The North Silver Bell (NSB) area is jointly controlled, in 1979, by Minerals Exploration, Inc. (Union Oil) and ASARCO, Inc. It has long been recognized as a northwesterly extension of the Silver Bell (SB) system. As such, it provides an extraordinary display of first order PCD characteristics at intermediate to shallow levels (probably not more than 1-1.5 km) consistent with Silver Bell proper and of an interaction of hypogene and supergene phenomena. Here you will see epizonal activity manifested by pebble dikes and breccias, which are the upward forerunners of Qmp dikes, and Qmp dikes which themselves flare 200 to 300 feet down to merge into a Qmp stock. You will see potassic alteration, with ~1000 ppmCu and 50 ppmMo, yield laterally (not temporally) to phyllic and then propylitic alteration assemblages, with variable silicification. You will see capping over secondary ores, and characteristics of weathering of different alteration and litho types. Geologic maps showing geology, alteration assemblages, Cu-Mo-Pb-Zn, total sulfide, vein-veinlet-structure relations, silicification, trace element variation, and supergene effects show conventional patterns.

The field tour will be self guided, so that ample time for mapping, contemplation, comparison, and discussion may be apportioned. The 'stops' are all relevant and interesting, and the overall tour about 6-8 km long, so don't indulge yourself too much at any one locale.

The vehicles will enter the area along the old arcuate railroad grade evident on the contour map. We will park at Point A. Take water, notetaking and camera gear, and protective wear with you - you won't want to return to the parking area until late afternoon.

The overall direction of the tour is to the east from Point A along Tin House Wash, then southerly toward the SB mine proper, then westerly along either Breccia Ridge or North Silver Bell Wash, or both.

The rock types at NSB include major dacite porphyry and quartz monzonite porphyry, and minor andesite. The 'dacite porphyry' is predominant, outcropping over about 75% of the map area. It is locally better-termed rhyodacite porphyry (granodiorite equivalent) or even quartz latite porphyry (quartz monzonite equivalent). It may well be a large sill, or even a thick extrusive unit. To the northeast it has lower lithic fragment content and abundant biotite, and maybe part of a stock. Here at NSB the dacite porphyry (field term) has many lithic fragments and low biotite and appears more sill-like, and is perhaps even a thick extrusive body. It fractured readily, and its ratio of veinlet to disseminated sulfide is high. It appears distinctly quartz porphyritic ('quartz eye porphyry'), fractures relatively abundantly and closely, shows little or no biotite, and has sparse phenocrysts of K-feldspar. It contains about 20% rounded 'quartz eye' phenocrysts, 30-40% plagioclase and K-feldspar phenocrysts, and 40-50% aplitic quartz and K-feldspar groundmass. It is an excellent 'reactant' and recorder of alteration effects, and its homogeneity facilitates area to area comparisons. The alteration pattern extends over a 3000 meter east-west 'half distance'.

Proceed about 200 feet east into RR grade cut.

POINT B is the RR cut and the nearby creek bed to the north. The RR cut is in Laramide quartz monzonite porphyry (Qmp), part of a major stock and dike system (to the east) which intrudes the dacite porphyry (Dp). The cut is distinctly potassically altered; excellent q-K-feld veins, predictably with minimal biotite (low Fe-Mg). Low total sulfide and fracture permeability means no or minor supergene enrichment, but rather low-pyrite oxidation and the production of 'copper oxide phases' - chrysocolla, principally. The point is that goethite not jarosite, is the principal limonite, with chrysocolla and 'spotty dendrites' of melaconite. The copper stays in the outcrop - these average 1000 ppmCu, 50 ppmMo, not unlike those at El Arco, and not unlike the grassroots exposures referred to at Sierrita.

Go from the cut down into the wash of North Silver Bell Creek - the potassic alteration is far more obvious here in Dp - with prominent q veining and K-feld flooding, with disseminated py-cp. The stockwork effect is well developed, and again the outcrops are not completely leached, although they are oxidized. Supergene enrichment underlying these outcrops is low grade.

Proceed eastward to adit area.

POINT C. The 'new' portal is in sericitized Dp. A vesicular andesite dike slashes through - note that it is faulted, downdropped to the eastern, mountain-ward side, unusual in this Basin and Range terrane. Note 'spotty' high-Cu dendrites and quartz-veinlet silicification.

(We can't go underground in the adit. It goes - 10^{0} for 315' N87^{0}E, levels and forks, one drive 300' NE, one 200' SE. It samples the enriched blanket terrane under the hill before you, shows excellent structure control of sec cc on py, moderate tonnages of ~0.5% Cu, and Mo).

The old adit 60-70' N of the new adit shows quartz veining and sericitization, excellent fracturing, highly visible quartz eyes characteristic of Dp - get used to them. You are already east of the K-alt center, into superimposed phyllic alteration.

(From here, you can either proceed up Tin House Wash (THW) to Points D-L, or reverse the itinerary by proceeding DUE EAST beyond the New Adit toward Point L on the drill pad up on the hill and reading the trip log 'back to front'. All points are identified and color-coded -- you can approach them in random order if you prefer).

Follow the road northeasterly about 150'.

POINT D. Here we move out of 'stocklike' (to west) Qmp into Dacite porphyry cut by Qmp dikes. Get used to distinguishing the two, and compare with El Tiro occurrences. Several small dikes of Qmp cut Dp before Point D, and the stock 'cupola' is exposed to NW of road behind you. Here a 3' red flag between two stones defines a dike. Uphill, red flagging marks a contact, Dp to W (downhill), Qmp to E (uphill). Qmp shows plag laths, few q eyes, well-developed biotite books, generally subdued rounded weathering. Dp has fine GM, prominent abundant q eyes, <u>rare</u> bi, 'cherty' lithic fragments, and prominent fractures.

Walk uphill along road, in Dp. Churndrill hole cuttings (CDHc), though, are Qmp, more abundant at depth. K-alt, K-feld flooded, py, minor cp and mb. The pink flag in the palo verde tree (step upstream into wash a few feet) is on silicified (silic) Qmp in potassic alteration. The major Dp-Qmp contact is between here and Tin House Saddle -- sericitized Dp is general in and beyond the saddle. Hill immediately north of Saddle is K-alt.

Continue east along Tin House Wash road. Pause 30-40' beyond (east of) saddle. Note hills to north in middle distance. The anomalous red is hematite after and over a chalcocite blanket. Elsewhere, yellows and oranges are jarosites and goethites. Residual hematite box works in phyllic alteration of Dp make the brick red color. Proceed along road. CDHc here are Dp with dissem fg py, minor mb, some sec cc. Hole would probably go into Qmp at depth. One hundred feet beyond pass, the mine dump shows sericitized (ser) Dp, q-mb veinlets (vlts). The greenish stain is nontronite and (probably) ferrimolybdite. Proceed uphill along road to blue flagging past float of phyl and prop Dp, perched gravels of mixed rocks, including andesite, syenodiorite.

POINT E. The blue flaggings delimit a spectacular outcrop (OC) of randomly oriented fractures, a classic stockwork (stkwk). The distant flag is a real photopoint. Generally, primary q fills centerlines, with ex-sulfides, of veinlets in prevasively ser Dp. Cse hypogene ser flanks vlts. OC oxidized, hem flooding, alu nite in vlts, probably some supergene arg (kaol.). Excellent envelope development. Streak the jarosite - the light streak means kaol or alun admixture. Portentious OC. High structure density. Remember Sierrita. Note texture of Breccia Ridge to south. 10-20' beyond second flagging in road is N60W fault gouge in Dp — alunite, jarosite, clays.

(If you stay on the road to its intersection with the wash, you cross a gravel bank with fabulous Sonoran flora -- saguaro, prickly pear, ironwood, palo verde, staghorn and teddybear cholla, hedgehog, and many wildflowers of a sun-drenched hillside. But you miss out ------).

Double back northwesterly down tributary wash here (at fault). Excellent natural OC of Dp, ox and ser. Jar-goeth q-ser vlts weathered in clear relief. Another photostop 30' from Tin House wash, but there are more. Upon reaching THW, there are classic Dp OC's for 50' downstream. Have a look, but head upstream 100' past slabs of caliche.

POINT F. The streambed here is probably structure-controlled -- it runs N65E. Magnificent textbook stkwk Dp. Stream polished at creekbed, another photostop. High color contrast, transported goeth-jar flooding, clear ser envelopes, q and heavy suls to 1" in fracs. Probably once sec cc here. Bank under tall saguaro strongly frac and jtd. About halfway along stop, Dp adit with Cu stains. Inspect it and its frac density, and compare with OC above. Out of stream, natural non-stream-polished OC. Above that, drill pad CDHc of ser Dp, few tenths % cc on py, some ox. Qmp deep, if present at all. Prowl this area -- pervasive phyllic alt Dp, texture, including fragments, obscure.

Proceed upstream. N80W streambed. About 150' beyond F is N70W-85°S prominent fault zone in ser Dp. Flt bx, mylonite under red flag in ironwood. Follow THW upstream. Its box walls are N75-85E, 80-85S vlts and jts common in NSB and SB, cut by N35E-65NW. Heavy silic-ser at bend, weaker q-ser but

strong flt-jts at waterfall. Still N85E. (Above waterfall, excellent flora -- yellow-flowered brittlebrush, purple lupine, California poppies, clumps of miniature fishook cactus, flowering hedgehog, whitish-barked ironwood, green palo verde; 100' above falls, staghorn cholla (pronounced 'choya') on S bank, teddy bear cholla on N.) Dwarf-shrub flowering acacia in wash is a 'copper flower'. Flt bx 40' above falls.

Over next 200', to road intersection with wash, frags showing up in Dp -- less pervasive alt, phyl level diminishing. Strong copper staining in OC at intersection means py diminishing relative to, for example, Point F.

Up the wash, 50' past road - THW intersection, is andesite dike. Same as in SB pit, 19.5-22 my dike event. Cu ox stains and paint late. Near Dp stkwk, lim is jar > goeth.

Another 50' upstream is a boulder of fresh Qmp -- with minor dissem py! Dp here less alt.

Green flagging 200' upstream marks Point G.

POINT G. Qmp dike in Dp. We are now far enough east that Qmp is only dike-form and, as will be seen, it channels alt-min easterly into less-alt Dp. Here the blue and green flagging on the 'tuning fork' saguaro is over alt Dp near its contact,with Qmp under yellow and green flagging in creosote bush. Proceed to east-two sets of green flagging, one in the rill, mark a narrow (3-6') Qmp, low-relief, mod-ser dike.

On up T.H. Wash, less-ser Dp, ep-chlor coming in. (Ignore pink flagging between Points G and H until return). Go 300-400' upstream to white flagging.

POINT H. Series of low OC of Dp, still silic (q vlts, μvlts). Ser down dramatically, orig textures evident. Careful exam reveals chlor vlts and impregs. Plag white to greenish, kaol-ser to chlor. No ep. Dp weakly prop., silic., erratic here.

Continue 300-400' upstream. Green flagging on S side demarcates Qmp dike, spheroidal weath , heavy ox, ser, ~ 80' wide. Dp ser at margins, propyl 10' beyond. Alt-min carried well east of last descrip (propyl Dp).

100' farther along THW, green-blue flagging on Dp (jar ± alunite-kaol), green-yellow on Qmp dike (heavy lim, goeth-hem). Both ser, an eastward 'prong' travelling along Qmp. Nearly fresh (NF) - prop Dp on either side. Sharp color-change a few feet upstream is return to Dp.

Upstream 100' is grotto-waterfall to left (N) behind mesquite. Plunge-pool and low plunge is in Dp, clear contact above first cataract, heavy-lim (jar) Qmp above.

Upstream 150' from TH Cataract (!), 350' from bend,is orange flagging of Point I.

POINT I. Weakly propyl. Dp, rock grayish, greenish cast. Still well frac, mod. q vns, but fewer. Ep vlts, some chlor, bleached. Variable chloritization-epidotization continues for 1000 feet beyond here, generally with chlor-ep, ep-chlor-cal, ep-cal zones. At the base of Point I sign are pieces of ep-veined, bleached Dp, and much darker, NF Dp. Note that the OC here resembles the epveined bleached material--the OCs are importantly altered. There are no more formal stops beyond here, but feel free to press on upstream toward the B mont l-gn-bar-fl occurrence, (probably mid-Tertiary). Between

here and there, prop yields to NF. For example, 200-250' beyond Point I (in wash under green flag in dying mesquite) are strong epidote clots and veinlets with K-feld.

Feel free to turn S anywhere along THW, from here or to the east; cover country, go uphill, generally working west (back down-stream) toward Breccia Ridge. Or—head down THW, veer left down wash at Point H sign, and follow pink flagging uphill to South.

Upslope from THW, first grade crosses Qmp dike—look at alt-min-ox. First knoll is Dp, sparse frac, weak ser, well east of phyllic alt. Continue to knoll.

Ridge Crest Knoll (pink and yellow flagging) in goeth-jar-al, hem-jar, mod.-structured Dp. Probably some cc; fracs pred N70W. Heavy alunite on S side of knoll—1/2" vlts. Facing due N here (the mid-distance peak beyond color anomaly), color contrasts to W, N, and E are clear--less hem, more goeth across canyon, no cc=propyl. Qmp dike low on NW near hill; trace Qmp dike from Point G in THW up hill to E. Two Qmp dikes are joined by a Qlp one.

Is this a copper province? Due W on skyline, the distant round knob with the nipple is Vekol Peak, site of Vekol deposit. Nearer and next to N are Slate Mts at Lakeshore mine. Through notch just W of N is Casa Grande Mt--ASARCO's Sacaton mine may be visible. Casa Grande West is west of Sacaton. Yes!

Follow pink flags up to skyline saddle, (where Silver Bells(?) are in bloom, with lupine, California poppies, brittlebrush). 50 feet SE of saddle is a knoll with a thin pebble--breccia dike with Dp and qtzite pebbles which projects to Point J. SB obvious; mines and prospects down to SE near road to microwave tower are along another Qmp dike.

Follow Breccia Ridge to west. Note that N70W jt direction yields progressively to stockwork. Structure more pron. westerly--well devel near Survey Beacon, leached vlts, stkwks. 20' from Beacon on crest is pebble dike marked with orange flagging.

POINT J, white flagging. Nearby orange flagging traces clear-cut pebble dike 1-2 feet wide, 50 feet long, well-rnded pebbles, traceable precisely along ridge crest. Almost certainly 'leading edge' of Qmp dike 200-300' below. Excellent fracture net-stkwk here, alun vlts. Mod. leaching.

Proceed W along ridge. Old prospect pit--ironwood tree prob. 100 years old means Silver era prospect. Cu stain in shear. Some prospects contain 30-foot saguaro, indicate a +150 year age of the prospect. Some of these early pits must have been dug by Indians or early Spaniards.

100'east from lowest saddle or ridge (orange and pink flag) is excellent breccia dike zone, round and angular frags. We are approaching breccia pipes--structure, alt, and min will augment westerly. Look west to next hill and its hem stain, part of the augmentation. Move over to it, note pron. incr. in q veining-silic. Look west from here (yellow-green flagging), another picture stop, of shatter and true breccia pipes. The topographic arc low on the S side of the prominent pipe-hillock is a Qmp dike. Breccia bottoms in Qmp and is cut by Qmp dikes.

POINT K (red flagging) is right on a 3' Qmp dike which clearly cuts shatter bx . Nearest prominent knoll (20-30') is shatter bx . Look at it -- 'frags' not rotated. Walk across next 2 knobs past shatter breccia knoll 30-40 feet from Point K to pipes of true intrusive breccia -- rock flour; rotated frags of Dp, basement. Blue flagging=division between shatter and true bx at last knoll -- red circle outlines 18" Dp bx clast with 1/2" q veins ending at clast margin, clearly a rotated intramin frag. Study bx continuing along N side. Cu stains. Bx=vent—fissure pipe complex, Qmp against bx on S side. Proceed down to saddle with Microwave Tower road. Several Qmp dikes cut through here--pink flagging on miniature fishook cactus is precisely above Qmp (right)-Dp (left) contact. Dp increasingly ser, but ox Cu present--not strongly pyritized-leached. Nontronite, spotty dendrites indicate 500 ppmCu.

From Microwave Road Saddle, proceed west along old road with pink flagging. Note increasing silic, flooding, geometrically like K-alt; we are nearing a return to Adit Hill and Point C. Note K-alt-K-feldspar-q-flooding coming in to end of road, with increasingly interesting limonites, both qual and quant. At end of road, turn back to NE and go to top of hill.

On NW side of hilltop is a small prospect pit in Dp with strong silic, ser, and 'Golden gertie' limonite, that 80% jarosite-20% goethite mix that bodes so well. Relief limonite on ex py-cc vlts. Stockwork, 'spotty' high-Cu-Mn-ox dendrites, Qmp dike nearby. This area one of pervasive ser, minimal vlt control. 10'N of Survey Station (1'E of Anchor) is nice turgite. 25' NE of Survey Station are heavy Cu-stained vlts. The whole hill is silicified with ser variable from 30 to 100%, mod. vlt. density. From here look west-the RR cut of Point B is clearly visible. It's orangey goethite, as it should be, from oxidation of biotite, magnetite, and sparse suls. But the nearer Adit Hill (above Point C, the adit) is anomalously goethitic-it should be redder, more hematitic-except that its sec cc blanket isn't (after all) very rich.

Proceed downhill, through bleached ser, hem-goeth-jar-stained Dp to Bowtie Saddle. In saddle, Qmp (we're near the Qmp stock area) and Dp are Cu-stained, sericitized, and show spotty high-Cu dendrites. Look at these excellent road cuts.

From Saddle, continue along road with gentle downgrade to west and pink flags, approaching west face of Adit Hill. Strong jarosite (higher pyrite) relict textures, patchy hem after cc, abundant Cu stains, higher q-silicification, mixed potassic-phyllic alt. Jarosite and Cu definitely increase to west; CDHc are Dp with q-mb. Road hooks to N at its end, adit in sight below.

Note here that the dumps from the adit are jarosite-stained in near pile, earliest-dumped and first-excavated; then hematite-stained material. More distant dump area is 'ore piles' of slightly greenish "post-mine" oxidized, cc-enriched "ore", q.v.

Proceed from 'hook' in road uphill to hilltop and green-white flagging. Enroute, K-alt and ser obvious, ser younger. Mod-low structure density, mod. jarosite. Qmp summit, moderate structure density, jarosite-goethite stain not too impressive.

Walk downhill to NW to Drill Station, Point L.

POINT L. This OC is in Dp-the wall of the bulldozer cut is an excellent exposure of a K-alt silicified stockwork, with veinlets with q-sulfide centerlines, now with jarositic limonites, 'spotty' dendrites of more than 500 ppmCu, but with minimal Cu ox stains. CDHc here are mixed-Dp > Qmp, but clearly Qmp is at depth (latest CDHc). Ser-silic frags, py common, with some moly and minor cc.

From here, walk due west down hill to Adit portal (Point C). Capping propitious, but not 'classic'. Hematite, jarosite, goethite on q-ser vlts obvious, but quantitatively subordinate. Walk over this hillside carefully-it is at boundary between potassic and phyllic and is underlain by only marginally subeconomic 'ore'.

The loop has been closed. The tour has travelled from potassic into superposed phyllic of first low, then total extensiveness, diminishing eastwardly (except along sub-outcrop Qmp stocks-and outcropping Qmp dikes) to chlor, chlor-ep, chlor-ep-cal propylitic, then back into the nucleus via an increase from fractures to shatter box to true intrusive breccia, with a shift from prop to phyllic to potassic and with corresponding change in qualitative and quantitative limonites.

ASARCO

Southwestern Exploration Division

April 6, 1978

TO: Geologists

FROM: F. T. Graybeal

Porphyry Copper Compilation

Attached is a handwritten list of all known porphyry copper mines and prospects in Arizona assembled by Mr. Sell with minor assistance from myself. Please note that this list has certain deposits underlined in red and for each listed deposit there is attached an ASARCO Exploration Record Sheet giving the name and location of that deposit. For each deposit underlined in red it will be your responsibility to see that the files and recent literature are scanned for the appropriate information required. Please confine your comments to a single sheet if at all possible, but be as complete as the literature or files allow. You will note that some sheets have been partially completed -- you may retain or modify this information as you see fit. If possible under section 33 you should remark on the potential for related limestone replacement (Cu, Pb,Zn) or disseminated precious metal deposits. Be particularly careful to mention 1) alternate interpretations of zoning or structure and 2) subjects for which information is lacking.

If you are uncertain as to the name or location of the deposit see Mr. Sell. Some of the deposits are cross-listed by several names so don't do the same deposit twice. In reviewing the list if you notice an omission check with Mr. Sell to see that it's not listed under another name before filling out an Exploration Record Sheet. For Section II I suggest confining your reference list to three entries including a simple reference to Asarco file data if any is available.

The purpose of this exercise is to compile a porphyry copper map of the Southwest USA, to provide a quickly available general reference on all significant deposits which can be readily updated, and to reveal deposits for which information of potential exploration significance is present or lacking. This index will also be available for various statistical studies if justified. Please deliver the completed forms to Mr. Sell -- handwritten is fine. I would attach a relatively low priority to this work.

F. T. Graybeal

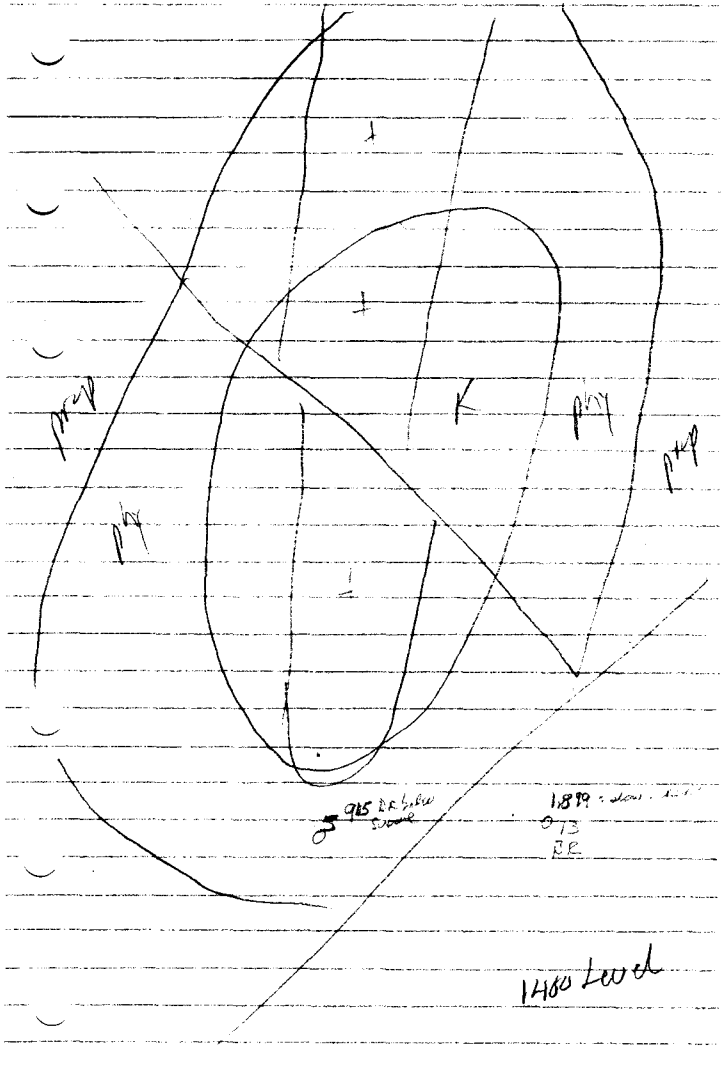
F. T. Graybeal

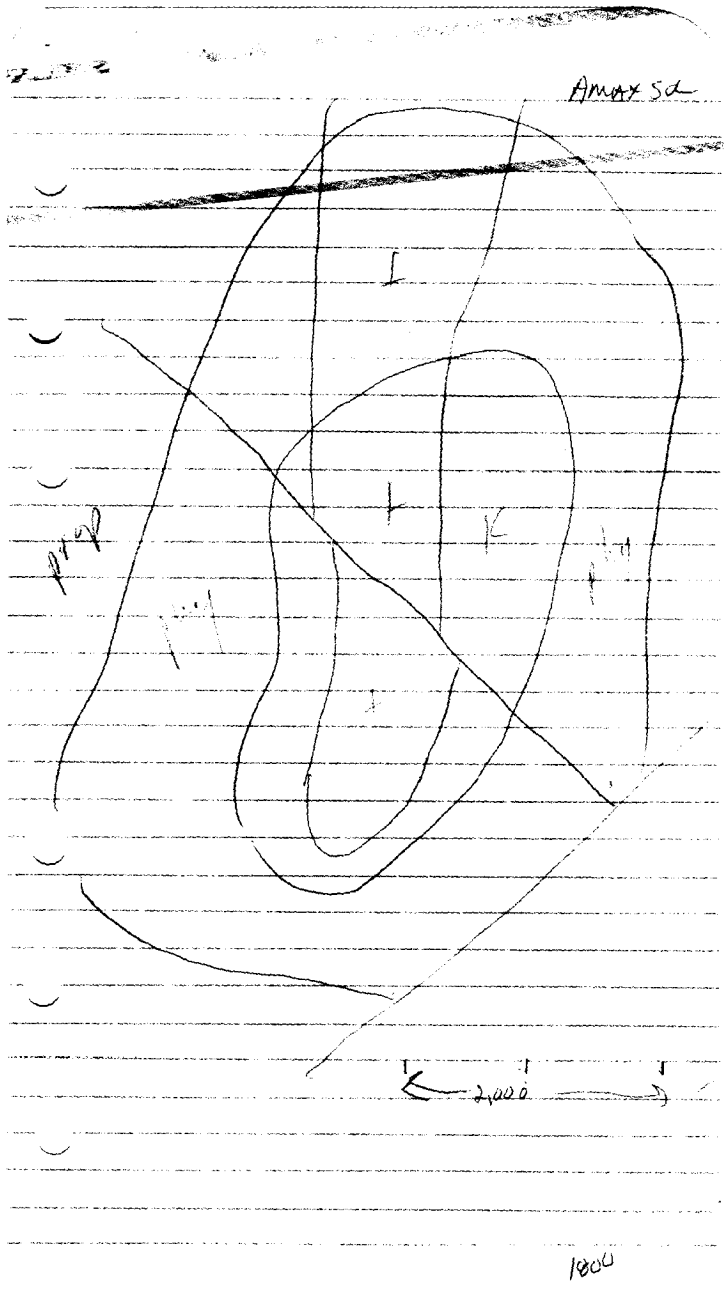
FTG:lb
Att.

cc: JDSell

Porph Cu - Arizona

AMAX SQ




Amax Sd
I
K
2,000
1000

Sec Property
Graham Co, Arizona

WLK
per
Graham Co Arizona

AMAX - A holes
PD - B
Quit - 2

Drilling
Premin. 10,000
Total 25,000

Bk high near NS thru Sol VABM
drops off again quickly to East
[illegible] drilling + 3,000 in gravel

Sulfides 700-1,200' below surface
elsewhere + 2,000' to sulfides

Colgrd 6 8 sec age

[illegible] valley
Most drilling is 2000' NS 6,000' EW

PD shows narrow trough 1,000' wide trends NS
so their look plans 1400' & 1800' centered

~~[illegible] NS trend~~

Shows as zone system
central zone 1-3% Py K
phyllic 3-8% Py
prop 1-5% Py

33,952 PO drilling $450,000

41,987' drilling

SC-16 2563' depth test K core
term in PC schist

Sec 4 L.C. indicates superior enrich
veins seeds oriented core N20W 28°SW

Cuadrilatero of rectangular dolt extension
at Sotfield and Dos Pobres, only local
at SOL

SOL 54 mT .14
Sandiez 80 .36
Sotfield 26 billion .2
Sansom 50 .52
Dos Pobres 400 .72

Temperature +70° Centigrade

AMAX - MILLER ALPRAISAL

~~JHC~~ a real example of over kill

~~JHC~~ DKK

ASARCO

Southwestern Exploration Division

October 7, 1976

copy WLK file
Pegpin Arizona

FILE MEMORANDUM

Sol Property
AMAX Exploration
Graham County, Arizona

Charlie Miller of AMAX called on 6/8/76 concerning a possible joint venture of their Sol Prospect. On 6/11/76, W. L. Kurtz, F. T. Graybeal, and J. D. Sell inspected the Sol data, but not the core, in the AMAX office. This memo is from the inspection and conversations.

The Sol Prospect is 15 miles E and NE of Safford along the Morenci highway and is covered by 512 unpatented claims. The surface geology is post-mineral basalt and gravel cover with some valley lake beds. The post-mineral cover varies from 200 to 500 feet in thickness. The target area was found in 1971 with a gravity anomaly and follow-up IP work. Drilling since that date has been: AMAX 4 holes, Phelps Dodge 12 holes, and Quintana 2 holes. All but one penetrated the valley fill deposits and most holes were between 2 and 3 thousand feet in depth. The deepest hole was 3600 feet with a bottom hole temperature of 70°C. A bedrock high extends north-south under the Sol VABM and drops off quickly to the east. An Exxon hole to the east bottomed in gravels at a depth in excess of 3000 feet.

The drilling has defined a steeply dipping, thousand-foot-wide granodiorite dike trending N10°E. The dike cuts a sequence of metavolcanics and volcaniclastics which strike N20°W and dip SW. The bedrock suface dips to the SW.

Centered on the south end of the granodiorite is an elliptical potassic zone 3000 x 4500 feet elongated N10°E, containing 1-3% pyrite; surrounded by a phyllic zone 4000 x 7000 feet with 3-8% pyrite; followed by a propylitic zone of 1-5% pyrite. The alteration zone of interest is 6000 x 9000 feet, containing 1-8% pyrite. Copper within the zone assays between 0.05 and 0.06% copper. The best ten-foot run in the potassic zone returned 0.46% copper while the best ten-foot run in the phyllic zone returned 0.68% copper.

The alteration is dominantly sericite-carbonate-chlorite-epidote with or without quartz. Although coarse breccia and retrograde alteration is extensive at KCC Safford and PD Dos Pobres, they are only locally developed at the Sol Prospect. The anomalous mineralization is near the phyllic-potassic contact and within the metavolcanic-volcaniclastic sequence. Molybdenum is anomalous in the phyllic zone. Inferred mineral resource at Sol is 54 million tons at 0.14% copper with a 0.10% cutoff.

AMAX and PD drilled 41,967 feet of rotary and core footage. Of this PD in 12 holes drilled 26,460 feet at a total cost of $420,000.00.

Two age dates have been determined. Hole SOL-4 sampled weakly mesozonally altered granodiorite with less than 4% secondary biotite. The whole rock K-Ar date is 60.7±2.4 m.y. Hole Sol-6 sampled sericitized metavolcanics at a depth of 1,558 feet. The age of sericite K-Ar is 67.5 ± 2.9 m.y.

The Sol alteration zone is the second largest in the Safford district. The phyllic zone is similar to the KCC zone but not to the PD zone.

Other tonnage-grade figures for the district include:

KCC Safford	2 billion tons at 0.20% copper
PD Dos Pobres	400 million tons at 0.72% copper
ICC Sanchez	80 million tons at 0.36% copper
San Juan	50 million tons at 0.52% copper

James D. Sell

JDS:lb

cc: FTGraybeal
WLKurtz

Form Revised 3/8/75 by J.H.C

ASARCO EXPLORATION RECORD

☐ FIELD EXAMINATION ☐ LITERATURE SEARCH ☐ ASARCO FILE ☒ AMAX Submittal

Section I General Indexing

① Name(s) of Property or Area: SOL Owner: AMAX						② Country: U.S.A.	③ State or Province: Arizona	
						④ Co. or Map Sheet: Graham Co.	⑤ File or Core No.: Aa-7A.12.0	
⑥ Latitude	⑦ Longitude	⑧ Mer.	Tws.	Rng.	Sec.	⑨ Examined by	⑩ Date	
32° 48' 30" N	109° 32' W	G&SR	7S 7S	27E 28E	24 19	WLK, FTG, JDS	6/11/76	
						⑪ Office: Tucson	⑫ Field Days: One	

Typed: 10/8/76

Section II Sources of Information

⑬ References

Author	Date	Title	Publications	Vol. No.
Files of AMAX submittal, 1976				

Section III Appraisal

⑭ Recommendations
- ☐ Action Now
- ☒ Too Low Grade
- ☐ Too Small
- ☐ Ownership Problem
- ☐ Access Problem
- ☐

⑮
- ☐ Past Producer
- ☐ Producer
- ☐ Mineral Deposit
- ☒ Prospect
- ☐
- ☐ Geologic Concept
- ☐ Geochem Anomaly
- ☒ Geophy. Anomaly
- ☐

⑯ Production

Commodity	Tons	Grade

⑰ Reserves ☐ Measured ☒ Estimated

Commodity	Tons	Grade
Copper	54 million	0.14%

⑱ Num. Drill Holes 18
Approx. Total Footage 42,000+

⑲ Excavations

⑳ Spectro. Analysis Attached

㉑ Assays Attached

㉒ Geochem Results Attached

Section IV Geologic Data

㉓ Commodity or Contained Metals: Copper

㉔ Ore Minerals - Major: Minor: Chalcopyrite

㉕ Host Rocks - Major: Granodiorite, metavolcanics Minor:

㉖ Age of Host Rocks: Gd, wholerock 60.7 ± 2.4 my — Metavolc. sericite 67.5 ± 2.9 my

㉗ Nature of Exposures: Completely covered by alluvial fill or Quaternary basalts.

㉘ Alteration: Potassic core → phyllic → propylitic

㉙ Total Extent: phyllic 4000 x 7000 ft., elongate N10°E.

㉚ Structure: ±1000 foot wide granodiorite "dike" centered on alteration pattern, but continues into propylitic zone.

㉛ Ore Occurrence: Phyllic zone contains 3-8% pyrite; "ore" on contact of gd-metavolc. with some 54 million tons of 0.14% inferred.

㉜ Age of Mineralization: ±60 my

㉝ Conclusions and Recommendations: Very large alteration zone with very low copper values associated with moderate to high pyrite values. Top of sulfide 700-1200 feet below surface with around 500 feet of leached capping. Capping thickness increases to NE.

(For additional space use extra sheets)

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

VOL. 69 | AUGUST, 1974 | No. 5

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SOCIETY OF MINING ENGINEERS of AIME

345 EAST 47TH STREET, NEW YORK, N. Y. 10017

PREPRINT NUMBER

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REGIONAL CHARACTERISTICS OF SOUTHWESTERN NORTH AMERICA PORPHYRY COPPER DEPOSITS

J. David Lowell
Consulting Geologist
Still, Lowell & Still
Tucson, Arizona

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This paper is to be presented at the AIME Annual Meeting - Chicago, Illinois - February 25 - March 1, 1973.

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REGIONAL CHARACTERISTICS OF SOUTHWESTERN NORTH AMERICA PORPHYRY COPPER DEPOSITS

INTRODUCTION

A number of excellent papers have been written dealing with the geologic setting of the Southwest Porphyry Copper Province, and the writer has borrowed extensively from Anderson (1966), Jerome and Cook (1967), and Cooley (1967). The paper has profited from review by Arthur R. Still, J. H. Courtright, J. D. Sell and L. Clark Arnold. Assistance in preparation of illustrations and compilation of geologic data was furnished by Diane Wright.

DISTRIBUTION OF DEPOSITS IN WESTERN NORTH AMERICA

The term "southwestern porphyry deposits" is sometimes used to describe the Arizona-New Mexico-Sonora deposits, or may include all of western U. S. and Mexico deposits. Figure 1 shows the distribution of deposits in North and South America. The porphyries in central Mexico consist of wide-spaced occurrences scattered along a linear belt which appears to be a continuation of the belt that extends northwestward from South America into Central America. Projected northward this belt passes into a roughly oval cluster in northern Sonora, southern Arizona and southwestern New Mexico which is shown in detail in Figure 2. The northwesterly-trending belt emerges from the north edge of the cluster as a string of scattered occurrences and extends through the Copper Basin, Bagdad, and Ithaca Peak deposits toward the Yerrington deposit in Nevada. Ely and Battle Mtn., Nevada, and Millford and Bingham Canyon, Utah, are somewhat east of the trend. Farther to the east are the porphyry molybdenum deposits of the Colorado Mineral Belt including Climax and Urad-Henderson, and farther south the Questa, New Mexico, porphyry molybdenum deposit. Butte and Heddleston, Montana, constitute an outlying porphyry copper district approximately 500 miles north of Bingham Canyon.

[redacted]

[redacted]

~~Circulate~~ I didn't obtain Apollo satellite coverage that took in the Globe Region - G.J.S. Then Starting - there is more better quality photos you obtained?

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EXPLORATION DEPARTMENT
120 BROADWAY, NEW YORK, N.Y. 10005

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JOHN J. COLLINS
DIRECTOR OF EXPLORATION

AIR MAIL

September 18, 1973

Mr. W. L. Kurtz
Asarco
Tucson Office

Satellite Photos

Dear Mr. Kurtz:

Herewith is the NASA photo which appeared on the back of the "Exploration Issue" of Asarco News. The overlay is notable to me for the clarity of the Devil's Canyon Fault which runs through our Superior East area and far to the north and to the south. Probably this is a major old structure which has been reactivated, and I think you are taking it into account in planning our Superior East drilling. Did Staargaard map and comment on it?

Also I am impressed by the large semi-circular patterns - igneous centers? Why don't you order the prints from the three other cameras to see if other features appear. Al Giesecke may find some items of interest to his structural analysis.

Regards,

John J. Collins

John J. Collins

cc: AGiesecke

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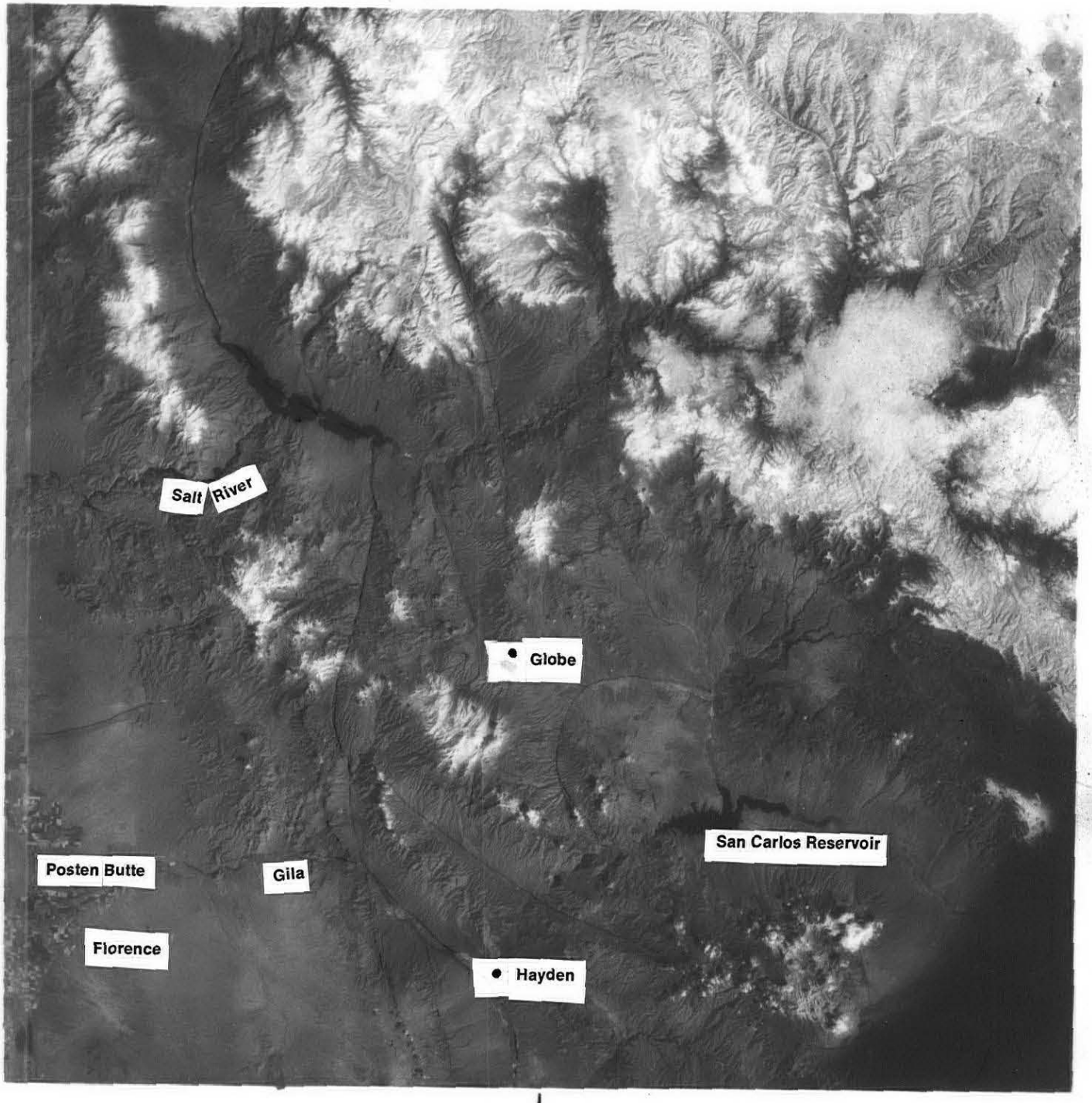

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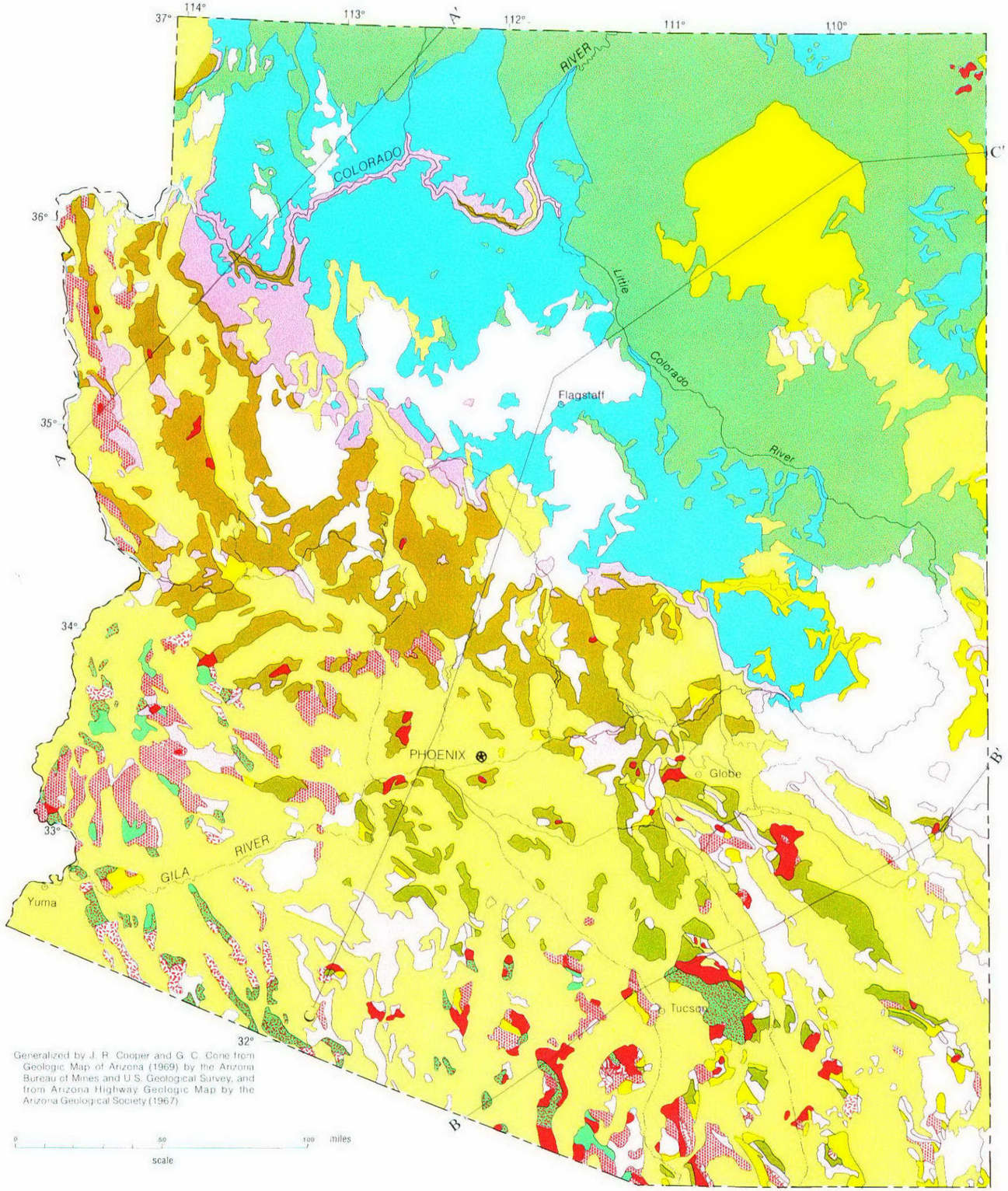
MANNED SPACECRAFT CENTER, HOUSTON, TEXAS

APOLLO 9 EARTH-SKY (S065) VIEW----Black and white infrared photograph of the Globe, Arizona, area, including Roosevelt Lake and San Carlos Reservoir, taken on March 12, 1969, by one of the four synchronized cameras of the Apollo 9 Earth Resources Survey S065 Experiment. At 11:29 a.m. (EST) when this picture was made the Apollo 9 spacecraft was at an altitude of 125 nautical miles, and the sun elevation was 33 degrees above the horizon. The location of the point on the earth's surface at which the four-camera combination was aimed was 33 degrees 32 minutes north latitude, and 110 degrees 44 minutes west longitude. The other three cameras used: (A) color infrared film; (B) black and white film with a red filter; and (D) black and white film with a green filter.

110% + 91



EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

CENOZOIC

QTs — Quaternary and upper Tertiary (Pliocene) sedimentary rocks, mostly unconsolidated; includes scarce lava and silicic tuff

QTv — Quaternary and upper Tertiary volcanic rocks, mostly basaltic in composition

Ts — Middle Tertiary (Miocene and Oligocene) sedimentary rocks; locally include lava and tuff

Tv — Middle Tertiary volcanic rocks of silicic to basaltic composition; includes related intrusive rocks

MESOZOIC

Ks — Cretaceous sedimentary rocks

TRv — Lower Tertiary to Triassic volcanic rocks; includes some sedimentary rocks

Mesozoic sedimentary rocks

JTRs — Jurassic and Triassic sedimentary rocks

PALEOZOIC

PIPs — Permian and Pennsylvanian sedimentary rocks; shown only on Colorado Plateau

M€ / Pz — Mississippian through Cambrian sedimentary rocks on Colorado Plateau; all Paleozoic sedimentary rocks in Basin and Range province

PRECAMBRIAN

Yp€ — Younger Precambrian sedimentary rocks and intrusive diabase

Op€ — Older Precambrian rocks of all types, including schist, gneiss, and fine- to coarse-grained igneous intrusive rocks

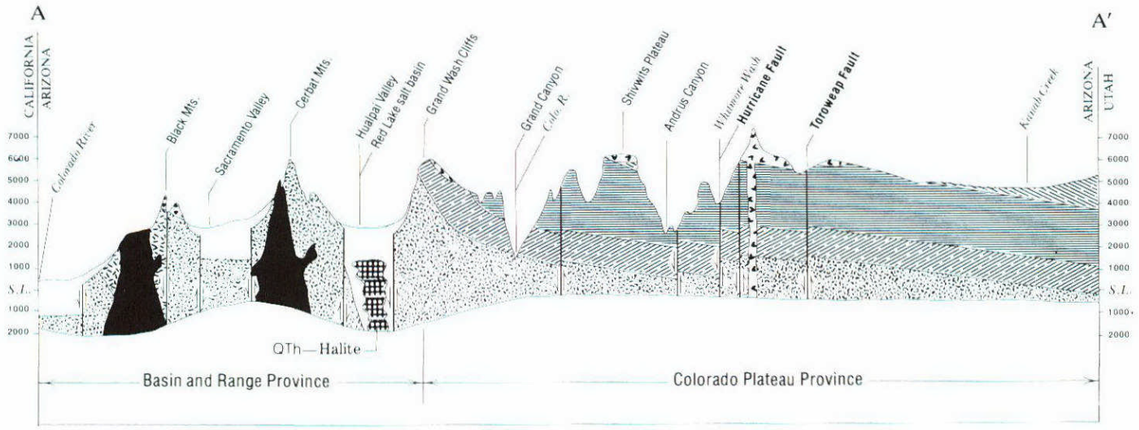
OTHER METAMORPHIC AND INTRUSIVE IGNEOUS ROCKS

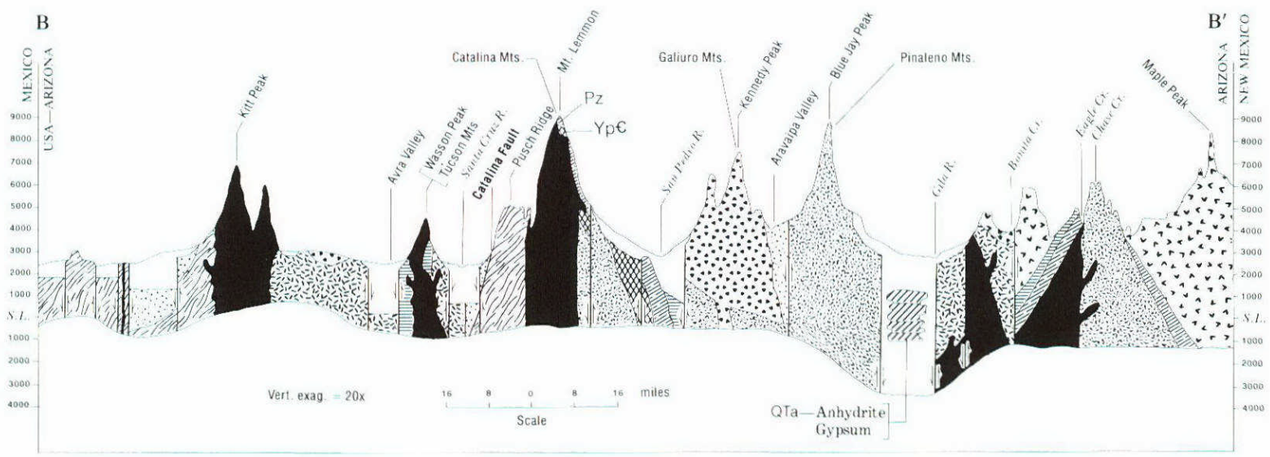
TKu — Tertiary and Upper Cretaceous intrusive igneous rocks

TM2 — Post-Paleozoic gneiss and schist

JTR — Mid-Cretaceous to Triassic intrusive igneous rocks

GEOLOGIC MAP and CROSS-SECTIONS of ARIZONA





EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

CENOZOIC

QTs — Quaternary and upper Tertiary (Upper Miocene-Pliocene) sedimentary rocks, mostly unconsolidated; includes scarce lava and silicic tuff

QTh / QTa — *Evaporites*
QTh—Halite
QTa—Anhydrite
Gypsum

QTv — Quaternary and upper Tertiary volcanic rocks, mostly basaltic in composition

Ts — Middle Tertiary (Miocene and Oligocene) sedimentary rocks; locally include lava and tuff

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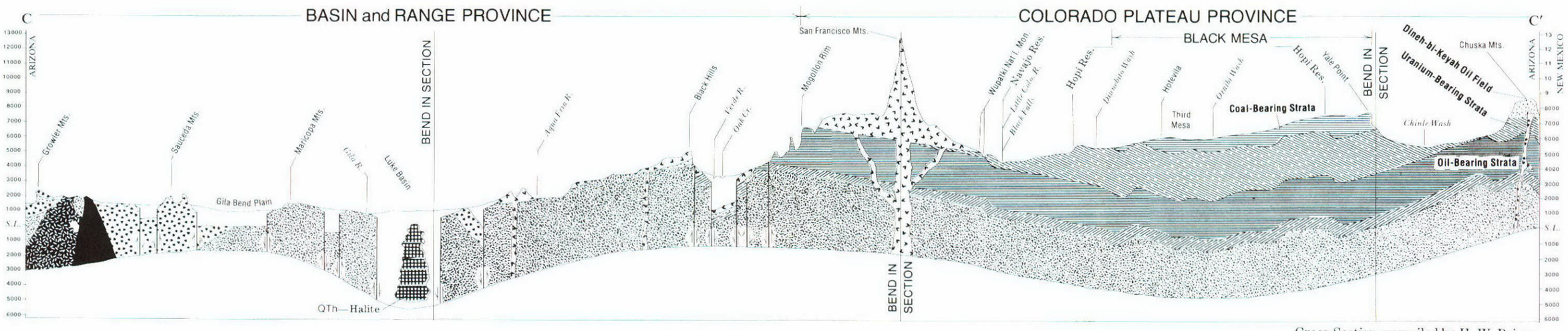

Cross-Sections compiled by H. W. Peirce

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COVER PAGE

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SEP 1 1978

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Title of Paper

Some Geological Criteria applicable to the search for southwestern North American porphyry copper deposits.

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Joint Meeting MMIJ/AIME 1972, Tokyo

INTRODUCTION

During the past decade, porphyry copper deposits have been discovered in southwestern North America at a rate of more than one a year. Since 1953, the discovery date of Pima, at least 20 deposits have either been newly discovered or "rediscovered" because of changed economic conditions. Perhaps significantly, only one of these discoveries (Sacaton) has resulted in establishing a new mining district. Because of this great number of deposits in the southwest (more than 30 including those in Mexico) the region is unique. (Fig.1). There now exists in this part of North America a wealth of exposure of geology and developed information about the porphyry copper deposit that is unrivalled, and the region has become one from which fundamental information about the porphyry copper deposit has developed.

This paper will briefly outline and discuss some of the important characteristics of southwestern North American porphyry copper deposits that may relate, or are known to relate, to their exploration and recognition in the field. Certain of these characteristics can be compared against western Pacific porphyry types. The features considered include those which may be viewed on a regional scale and which relate to the regional environment, and those which may be useful when regional search has defined an area for closer study and evaluation.

At the outset, it should be emphasized that adherence to, or consideration of, any proposed set of criteria or to any model should be undertaken only with full realization that such criteria or such models may be established in only a general way. Vagaries of nature may modify or obscure some of the characteristics to some degree in almost every deposit and certainly in different regions. Thus, certain of the properties of southwestern porphyries that are described in the following pages should be tested in other regions before consideration of them as criteria of widespread applicability. As a further point, the diagnostic criteria by which the porphyry copper deposit is described and recognized are also subject to change with time. The porphyry copper deposit is an excellent example of a mineral body type for which the characteristics considered important in ore search have changed in response to changing economic conditions. As lower and lower grades of mineralization become ore, those properties of the low grade portion of an orebody assume increasing importance, in both geological and geophysical interpretations.

PORPHYRY COPPER DEPOSIT CHARACTERISTICS

Probably the best known and most exhaustively studied group of porphyry copper deposits in the world occurs in the American southwest. From this region has has come the wealth of information that has spread almost world-wide and that has become the standard for comparison and evaluation of prospects and properties. As this paper utilizes, as a basis for discussion, the deposits of southwestern North America, it is necessary to outline some of the general characteristics of those bodies, particularly those characteristics of importance in geological and initial economic evaluation.

The first to attempt a serious generalization of the various geological and economic features of the porphyry copper deposit was Parsons (1933) who later (1956) correctly noted that it was impossible to define them. Recently, models treating certain of their distinguishing features have been proposed by James (1971), Rose (1970), and by Lowell and Guilbert (1970). In the Wilson Volume (Titley and Hicks, 1966) Jerome described many of those features of the deposits which he considered critical to the explorationist.

In the tabulation which follows, I have listed some of the general characteristics which might apply to the known deposits in the American southwest, but not necessarily to porphyry copper deposits outside of this region. Where known or appropriate, I have attempted in a few instances to compare or contrast these properties with deposits elsewhere.

A. All tend to be large orebodies although there is considerable variation in that size. They range downward from the billion ton category to the 33 million tons at Castle Dome.

THIS B. They all tend to be of low copper grade but considerable variation in grade exists. The data of Lowell and Guilbert (op. cit., p.391) suggest a grade of hypogene ore of 0.41% on the average. Grades of copper lower than this are being mined but with sufficient molybdenum to upgrade the low copper value to economic tenor. At this juncture, distinction must be made between the grade of copper which is being mined and the grade of copper which is being sought or which has been found in as yet undeveloped deposits. Leaming as cited by Peters (1970) has revealed that the discovery period for the copper deposit (exploration through evaluation time) ranges upward in duration from 3 years. In addition to this, the time to get to production, if work is continued, may be more than two additional years. Consequently, in any given year it is difficult to determine what minimum grade at discovery is necessary for production 5 to 7 years hence. The grade considered economic has been steadily dropping and Lowell (1970) has presented the results of some studies related to this problem.

C. All appear to bear some spatial relationship to calc-alkalic porphyritic intrusive igneous rocks. Such a spatial relationship implies a genetic tie between the porphyries and the copper but such a relationship is not always demonstrable.

D. Economic copper mineralization is not necessarily restricted to the rocks of intrusive igneous origin. Earlier it was recognized (Parsons, 1933) that both intrusion and host rock were important hosts for ore mineralization and that fact was the basis for arrangement of subject matter in the Wilson Volume. From the data of Lowell and Guilbert (op. cit. p.390) it can be determined that about 85% of the deposits involve copper in wall rocks, in about 60% of the deposits over 30% of the copper occurs there, and in the "typical case" almost 40% of the copper occurs in preore host rocks. Because the two environments commonly respond differently to the process of copper deposition, it is important that the two be separated and recognized. One is the copper-bearing intrusion which may contain both syngenetic and epigenetic mineralization and for which I have suggested the term Intrusion Porphyry Copper Deposit. The other is the epigenetic orebody which occurs in the host rock to the intrusion or in certain of the breccia bodies and for which I have suggested the term Wall Rock Porphyry Copper Deposit. Many, if not most, deposits are composites of the two types.

E. They all contain, on a bulk basis, low sulfide concentrations, probably averaging 2-4% (volume) sulfides in the ore zone. There is considerable latitude in this figure, however, and some bodies may contain as much as 10% or as little as 1%.

F. Most of the orebodies which have been studied in some detail reveal an extremely important geological characteristic. Minerals and metals are zoned. Studies made of hypogene zoning in intrusion porphyries such as that at Kalamazoo reveal this variation in sulfide and silicate mineralogy. Less clearly understood, but nonetheless of equivalent importance are the zoning patterns in wallrocks other than the calc-alkalic mineralogical equivalents and the zoning patterns produced by supergene alteration. On district-wide scales as well as deposit-wide scale, base and precious metals are zoned as well as the non-sulfide alteration minerals. This property of zoning, if recognized, properly interpreted, and understood is probably the most important of the features which the exploration geologist can utilize in the field in ore search.

The features described above are considered important ones at this particular time. There are other characteristics of these bodies, however, that have been important historically but which the changing economics of copper mining have modified to varying degrees in the American southwest. Among such properties of the porphyry copper deposit have been secondary enrichment and fracturing. Although both fracturing and enrichment are highly desirable features and the potential for their existence should not be overlooked, particularly in less well explored parts of the world, their inclusion as necessary distinguishing features now must certainly be questioned.

Most of the deposits of this region whose discovery and start of exploitation predate 1950 had enriched blankets of supergene copper minerals. Indeed, Parsons (1933, p. 343) noted that secondary enrichment was "the most important geologic phenomenon in the Porphyry story." At least two reasons for this can be suggested. Economics of the time required the high grade ore of the enriched blanket. As a lower grade of copper is now economic, the requirement for enrichment is somewhat lessened although one cannot deny the fact that it is still extremely desirable to find an enriched body. Another factor may have been that the process of oxidation and enrichment develops a striking color anomaly at the surface and consequently the orebodies which were first mined from the porphyries were easily discovered.

Many of the bodies of hypogene ore, particularly in some of the intrusion porphyry copper deposits, occur in strongly fractured rock. No data of which I am aware allows a confident statement regarding the variation of grade with fracturing. Perhaps significantly, however, as lower grade mineralization is recognized as ore to an increasing degree, less fracturing may be expected because many of these ores are syngenetic in intrusions and occur in less fractured parts of the body.

SOUTHWESTERN NORTH AMERICAN PORPHYRY COPPER DEPOSITS IN TIME AND SPACE

Porphyry copper deposits of southeastern Arizona and adjoining Mexico and New Mexico were formed in two discrete periods of time and in recognizable preore settings. Closely similar origins, together with the common environment and distinct times of formation are sufficient common characteristics to allow definition of a metallogenic region. Deposits of this part of the American southwest have been considered a specific and definable part of the copper deposits of the western United States and Canada and considered to represent the Sonoran Copper Subprovince.

The Subprovince is polycyclic. The older time of ore deposition is represented, so far as is now known, only at Bisbee where Creasey and Kistler (1963) obtained dates of 163 my (K/Ar) and 176-178 my (Rb/Sr). Parenthetically, it should be noted that this age of about 170 my is close to that of some deposits in British Columbia which have been dated and categorized by White, Harakal, and Carter (1968). Little can be stated yet with regard to the significance of this time of copper ore formation but it does seem more than merely coincidence that so closely similar deposits should have formed at the same time in such widely separated locations in North America.

The younger time of ore formation coincides with the time of the Laramide Revolution and was a period during which at least 21 known, dated, deposits were formed in this part of North America. Eight additional deposits appear, on the basis of geological relationships, to have been formed during this time but absolute dates are lacking. The 21 dated deposits appear to have all formed within the time span of 10 to 12 million years between about 55 and 66 million years ago. (Table 1.)

With regard to geological environment, the deposits occur in the Basin and Range Province of southwestern North America, a region whose physiographic features appear to date from the mid-Tertiary. It has long been recognized (Ransome, 1915, Mayo, 1958, Schmitt, 1966) that ore districts of the southwest occur in a belt of intense structural deformation. This belt, the Texas Lineament or Zone, trends WNW and, although definition of its boundaries vary with different authors, it appears to include within its borders most of the porphyry copper deposits of the region. Major problems exist, however, in attempting to apply any analysis of structures within this belt to the genesis of ore deposits which are included in it. Because the belt includes a variety of mineral deposits of different types, different apparent controls, and strikingly different ages, and because the belt of structural deformation includes structures which apparently originated and greatly modified the region <u>after</u> copper mineralization of the Laramide, extreme caution must be used in application of the concept of such tectonics on other than a gross regional scale. On the regional scale, Schmitt (op.cit.) noted that the southeastern Arizona ore districts occur in an area coinciding with the intersection

of the Jerome-Wasatch and Texas Zones.

Preliminary results of an analysis of the nature and distribution of Mesozoic pre-porphyry copper deposit rocks allow an interpretation of the preore stratigraphic setting and suggest a basis for inferring a preore tectonic pattern. Anderson (1966) was the first to point out that in a general way some of the porphyry copper deposits of this region seem to cluster around a Lower Cretaceous basin. The exception to this generalization is Bisbee which, although relatable to other preore features, predates the time of basin formation. Continued work with rocks of the Mesozoic has revealed that definite preore patterns of sedimentation can be interpreted in terms of structure and that there are definite spatial relationships of deposits with these preore features. Although the spatial relationships can be demonstrated, the reasons for their existence in relationship to the porphyry copper deposits are still not clearly understood. Preliminary results of this work have been reported (Titley, 1970).

A considerable body of geological information has developed during the past decade regarding the nature of early Mesozoic events of southeastern Arizona. Results of much of this work have recently been published by the U.S.Geological Survey (Drewes, 1971, Hayes, 1970a,b). Rocks of the early Mesozoic (Triassic and Jurassic) which have survived subsequent geological events are mixed volcanic units and clastic sediments of which a larger proportion are redbeds. Consideration of their distribution and the fact that they have protected thick Paleozoic sections from erosion through the Mesozoic and most of the Cenozoic has led to interpretation of a possible NNW-trending fault system which originated and was active in the early Mesozoic and probably at the close of the Paleozoic. Breaks typical of this early set are those at Bisbee which guided emplacement of that early Mesozoic porphyry copper deposit. That certain of the Laramide deposits seem to be distributed at certain locations of these apparently old structural lines attests to some continuing influence of the structures in the emplacement of the porphyry copper deposits.

During the upper part of the Jurassic or the Lower Cretaceous, a major basin evolved in southeastern Arizona and adjoining regions which, through the Lower Cretaceous ultimately accumulated in excess of 12,000 feet of sediments. These strata, the Bisbee Group, are of marine-near shore affinities and are time equivalents of sandstones, arkoses, and related rocks which occur in erratically distributed outcrops surrounding the deep basin. The difference in stratigraphic facies permits definition of a"foreland" area about the deep basin and a broken surface upon which apparently little more than a few thousand feet of arkoses accumulated in isolated localities. The foreland was apparently a site of mountain building and an area from which much material was eroded and transported into the Bisbee basin.

For reasons not yet clearly understood, except for the possible appeal to the tectonics of basin formation, it is on the foreland and its boundaries the nearly all of the Laramide porphyry copper deposits occur. Axes of thickened sedimentary rocks, interpreted to represent deeper parts of the basin, have been recognized. These axes, of NNW trend, parallel the western border of Bisbee Group rocks and can be projected onto the foreland where they coincide with lines drawn through groups of deposits. (Fig. 2). Within the deeper part of the basin, no discoveries of porphyry copper deposits of Laramide age have been reported, even though intrusions both younger and older than those which are related to the foreland porphyry copper deposits occur there. It would be unwise to imply that no porphyry copper deposits of Laramide age occur in the basin and some may yet be discovered - but at this particular point in time the Lower Cretaceous foreland and its associated structures have been the productive sites.

A distinctive suite of Upper Cretaceous preore rocks occurs in southeastern Arizona and the rocks are found chiefly on the Lower Cretaceous foreland although they are not totally restricted to it. The suite tends to be dominantly volcanic and, although not all exposures have been thoroughly studied or reported, andesites or andesite breccias and lahars probably predominate with lesser amounts of dacitic or rhyolitic ignimbrites. Sandstones or other

sedimentary clastic units are usually subordinate and occur in some exposures. Our knowledge of distribution of these rocks is far from complete but the location of some of them is shown on Figure 3. Their distinguishing features were first noted by Courtright (1958) and possible correlations and a discussion of their potential significance were noted by Richard and Courtright (1960). Studies of the chronology of one group of exposures were reported by Bikerman (1967).

These rocks occur either closely associated with porphyry copper mineralization or near deposits in many districts. They closely predate but are not known to postdate mineralization in those areas where they have been studied. There are areas on the Lower Cretaceous foreland where they occur but are not yet known to be related to porphyry copper mineralization. The close preore age of these rocks together with their distribution suggests a tantalizing hypothesis involving their close genetic tie to the ore-forming process. However, at this time, conclusive evidence that they were genetically related precursors has not been established.

Ajo (New Cornelia) occurs in a location where its affinities to a preore environment can not be determined from evidence presently available but Ajo and other deposits of western Arizona, Utah, and adjoining Nevada bear curious spatial relationships to other sedimentary lines (Fig. 4). Lines corresponding to miogeosynclinal facies as depicted by Hamilton and Meyer (1965) occur in potentially significant positions with respect to deposits near the western side of the Cordilleran trough. These deposits, of varied age (Table 1.), unlike those of southeastern Arizona and the Sonoran Subprovince exhibit no consistent, as yet recognizable, pattern of time-space relationships. One can not fail to be impressed, however, by their positions as they relate to these older lines.

ZONING CHARACTERISTICS

Zoning in southwestern North American porphyry copper deposits is expressed in two basic ways - Chemical Mineralogical and Physical. These features of zoning are found in virtually all of the intrusion and composite porphyries and in most of the wall rock types. The tendency toward this regular and systematic distribution of effects, and perhaps causes, of mineralization in the porphyry copper deposit gives rise to many characteristics whose recognition and proper interpretation are of extreme importance in ore search.

Fracturing

Although there are undoubtedly many physical properties of rocks which might be relatable to the systematic variations in alteration minerals in the porphyry copper deposits, to the exploration geologist, the most obvious and easily recognized significant property is that of fracturing. Two properties of fracturing are commonly measured - intensity, and orientation.

It was earlier noted that I know of no data that permits a confident statement relating variations of copper value with fracture intensity. Noteworthy, however, is the situation, generally recognized, that in many bodies, the content of sulfide minerals increases in a way that seems to correspond to frequency of fracturing; but also noteworthy is the fact that high sulfide content does not necessarily correspond to a high grade of copper. Because moderate to intense fracturing occurs in the porphyries of southwestern North America, and can be so quantized, and because it can be related to sulfide zoning and silicate alteration in certain instances, it is an important phenomenon to seek and recognize in prospects in the early stages of reconnaissance exploration.

Results of studies which have been carried out in some of the porphyry copper deposits of Arizona (Heidrick and Rehrig, 1969, Rehrig and Heidrick, 1969) have revealed that mineralization in the bodies is correlative with the direction of fracture orientation. From the analysis of several thousands of measurements of veins, dikes, faults, joints, and fractures in five porphyry stocks, it was determined that orthogonal ENE to E and N to NW joints

and fractures occur with mineralization and that, in the bodies studied, the ENE-trending breaks are the ones most commonly mineralized. Significantly, these directions do not seem to bear any consistent relationship to the geometry of the stocks in which they occur. There are not sufficient data to allow extension of these observations to other areas but it does not seem unreasonable, from the basis of other analogies, to suggest that patterns of breaking may exist in other porphyry copper Subprovinces or Provinces which show a consistent relationship to mineralization.

Hypogene Alteration and Zoning

In order that alteration and zoning be properly described and understood in the southwestern North American porphyry bodies it is necessary that two types of alteration or alteration processes be recognized. Because the rocks encountered at depth have not been modified by surface processes, excellent work has been carried out in the study and definition of the zoning and alteration in them. The patterns revealed are the result of hypogene processes. When these rocks are exposed at the surface they undergo further changes which develop supergene minerals and which modify the zoning developed by the primary processes.

Because the literature contains a wealth of data related to hypogene zoning, this discussion will briefly review its major characteristics and underscore certain points which I feel important to ore search.

The best studied of the southwestern porphyry copper deposits for which published information exists is San Manuel-Kalamazoo. There, Lowell and Guilbert (1970) have detailed the results of a study of alteration phenomena and metallization. In this body, a composite type, alteration and metallization apparently occur in about equal parts in host rock and intrusion. The granite which composes the host rock to the porphyry is mineralogically similar to the intrusion and consequently little or no interruption of the alteration process took place (or can be recognized?) because of wall rock contrast. The result is a zoning pattern that is distinct and is implied to be concentric and symmetrical in plan normal to the long axis of the orebody. Other potentially significant features of the alteration pattern there merit comment. One is the fact that high sulfide content does not necessarily correspond to high copper value, a point noted earlier in this paper, and a point that is extremely important in the interpretation of geophysical data. In many bodies, it is becoming increasingly obvious that high primary copper values occur in zones of low total sulfide. Another point is that although the alteration envelopes are interpreted as closing, the high grade protore shell does not; consequently, continued deep exploration through zones of phyllic alteration in an orebody of this nature may not necessarily find what may be sought, particularly in those cases in which the mineral body has not been tilted as at San Manuel. A third point deserving of some comment is the absence or questioned presence of a zone of hypogene argillic alteration, in this orebody. The problems of origin of minerals of the argillic zone have been reviewed by Rose (1970) and by Meyer and Hemley (1967) and it is sufficient here to point out that the problems related to observed argillic alteration of the porphyries have not been resolved, especially in the hypogene zone.

Rose (1970) has reviewed and presented the alteration patterns at several porphyry copper deposits in this region. The alteration patterns depicted by Rose reflect the predicted departure from the high symmetry implied at San Manuel - chiefly as the result of varying response of differing wall rock types to the alteration process. Although these patterns depart from the high symmetry, they still manifest lower orders of symmetry and, importantly, still reflect orderly zoning. Many problems in the interpretation of hypogene alteration still exist. Among the most important ones are those treating alteration in wall rocks whose mineralogy contrasts strongly with the parent intrusion. The calc-silicate suite can pose difficult problems in interpretation which may be only partially solved in exploration by knowledge of original composition of the carbonate rock suite and understanding of rock geometry. Zoning of the calc-silicate alteration patterns is poorly understood, although Gale (1965) and Perry (1969) have made considerable head-

way in studies at Mission and Christmas, respectively.

One further aspect of hypogene zoning deserves comment, particularly within the context of western North American porphyries but as well in relation to some of the porphyries of the western Pacific. The hypogene zoning patterns which have been detailed have been those of deposits which either were deeply covered at the time of formation and which occur in a nearly isotropic wall rock environment or those of deposits which have been unroofed by removal of a thick cover subsequent to formation of the copper body. Unknown are the manifestations of hypogene alteration zoning produced by a very shallow intrusion. Geologic data from deposits in the American southwest permits the interpretation of intrusion to shallow crustal depths in some instances. In view of the apparently young age of some of the western Pacific porphyries, however, the evidence for a shallow depth of formation of copper bodies is much more compelling. For this reason, the possibility that hypogene alteration patterns may be telescoped should be considered in any evaluation of the two dimensional alteration patterns worked with in the field. Either or both, variations from the calc-alkalic host rock type and a shallow level of intrusion have the potential for distorting and compressing the zoning pattern considered typical. The characteristics of propylitic alteration about deep porphyries seems distinct in that environment but these characteristics become diffused in many deposits or prospects by apparent superposition on propylitic alteration types, of silicate, oxide, and sulfide minerals of both phyllic and potassic zone affinities.

Supergene Alteration and Zoning

The copper-seeking exploration geologist has worked for decades at the surface where supergene effects predominate and may obscure the otherwise distinguishing features of hypogene alteration. These supergene alteration effects occur at, and directly below, that level at which assessment of subsurface geology is based, that level at which most geochemical prospecting data are acquired, and that level from which many geophysical techniques of ore search are initiated. Notwithstanding this importance, the supergene zone is the one about which perhaps the least is known and it is certainly the most poorly understood of the various manifestations of porphyry copper alteration. The lateral extent, or depth, to which supergene effects have reached is extremely variable as are the various ways in which the alteration may be manifested.

Many deposits of the American southwest have been characteristically altered by surface processes and the economic importance of the resulting enriched blanket has been great. The features of the leached capping which occurred above the enriched zones have been well studied and the results widely applied. A similar assessment of the importance of supergene effects may be extended for most, if not all, of the known porphyries of South America. At the other extreme, however, many deposits of southern British Columbia reveal little or no enrichment and weak (by comparison) effects of surface-related alteration. Deposits and prospects of the western Pacific and Australia reveal a broad spectrum of supergene effects which range, even in individual prospects, from fresh pyrite and other sulfides at the grass roots to deep and complete lateritization.

Few, if any, rules can be stated now regarding supergene processes and effects. Nonetheless, there are certain features of primary mineralization and alteration which may, and are tentatively believed to, influence the nature and pattern of alteration that is produced by the surface environment. Some of the more important or potentially important facts and phenomena are discussed below together with possible potential significance to deposits of the western Pacific.

The time at which supergene alteration and enrichment took place is unknown. It is a fact that may not be widely recognized but the present-day processes do not seem to be enriching so much as they are destroying the enriched blankets of deposits in western North America. As Richard and Courtright have noted at Silver Bell (1966, p.162), the zone of enrichment seems to bear no relationship to the present-day position of the water table but does seem to be related to an older time during which the existing landforms were developed. Fragments of oxidized capping are known to be present there in

nvolcanic and sedimentary units tens of millions of years old (Richard, pers. comm.) The idea that it is the arid environment which produces the conditions necessary for oxidation and enrichment can not be verified at Silver Bell, nor can it be in most of the deposits of that region. As Livingston, Mauger and Damon (1968) have noted, enrichment of the southwestern North American deposits took place prior to their being covered and protected by rocks of mid-Tertiary age. The climatic-physiographic conditions which existed at the time at which those supergene processes took place are unknown. The chief effects of the present day climate have been that of restricting or reducing vegetation which has resulted in the exposure at the surface of the splendid color displays developed by the oxidizing process.

The mineralogic-lithologic requirements for enhanced supergene effects to be developed are believed to be generally recognized. Little or only weak enrichment, and its accompanying supergene alteration, is developed in zones of low permeability and/or low pyrite content in host rocks of quartzo-feldspathic composition. The presence of a large pyrite content, together with permeability provided by intense fracturing may accelerate the process and the absence of either or both may restrict it. Insufficient data regarding the process of capping development from calc-silicate rocks containing dissemination sulfides exists upon which to make any generalizations but in the few exposures in which such ores have been exposed to the present or ancient surfaces of weathering, it seems that the effects of oxidation may be considerably more restricted than in the calc-alkalic suite. Whether this may be due to lower sulfide content, less permeability, or different silicate mineralogy is unknown.

Problems of interpretation of phyllic and argillic alteration in the hypogene zone are severely compounded by the results of supergene alteration which is imposed upon that rock-alteration suite. Rose (1970, p.920) has premised his discussion of alteration and zoning on a recognition and clear distinction which is recognized between alteration effects in the two environments. He has noted the wide acceptance for a supergene origin of kaolin and the possibility that chlorite, montmorillonite, and sericite may be formed in that environment as well. I have observed changes in the abundance and character of mica and clay-like minerals in the shallow parts of drill holes above hypogene alteration from prospects in both the western hemisphere and the western Pacific. For these reasons, I have suggested (Figure 5 and explanation) a hypothetical zoning pattern which might develop above a typical hypogene pattern of alteration. The zoning is consistent with observation and is consistent as well with low temperature and pressure data for orthoclase, H-mica, and kaolinite as outlined by Garrels and Mackenzie (1971, p.370). Progressive neutralization of strong acids derived close to the surface takes place by reaction as they move downward through the supergene system. This gives rise to zones in which kaolinite and H-mica are stable.* I should reassert that the interpretation is one which is hypothetical and, although the model of San-Manuel Kalamazoo primary zoning has been used, does not reflect the history of the deeply buried Kalamazoo orebody. I do suggest, however, that some serious consideration be given to the model or at least to the potential stability of the minerals and mineral zones present and that considerable care be exercised in attempts to extrapolate alteration mineralogy derived from surface altered samples to the effects of hypogene alteration.

SUMMARY

The foregoing has outlined certain of the characteristics of regional distribution and certain of the intrinsic properties of southwestern North American porphyry copper deposits. Particularly emphasized have been those features

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*Dr. James Anderson (pers. comm., 1969, 1971) has developed an interpretation of vertical supergene zoning which is similar in some respects to the features shown on Figure 5. He has included in his interpretations of zoning, additional silicate alteration products which are not shown in the clay-mica assemblages I have depicted.

of environment which may be important to understanding of regional occurrence and control. At this stage of understanding, a preore environment can be described but its cause and effect relationships remain a matter of intelligent speculation. As a starting point I have suggested that basin-related tectonics may have set the stage for the Laramide events by initiating structural weaknesses and developing lines or zones of increased permeability along which the younger magmas rose to give rise to the volcanic rocks and copper-bearing porphyritic intrusions.

On a more positive point, results of this work have resulted in clarification of certain problems whose solution may contribute to a better understanding of porphyry copper genesis. That there appear to be real associations of certain ages of copper-bearing intrusions in certain preore environments seems well-established as does the fact that coeval but copper-barren intrusions occur in adjacent regions outside of the environments. Present research is now being directed toward a greater understanding of the origin and significance of these time-geographic-chemical differences.

Recognition of the possibility of the regional and temporal zoning, for whatever reasons, of southwestern North American porphyry copper deposits and its potential use as an exploration tool must be supplemented by an appreciation of the internal zoning of structure and sulfide-silicate mineral assemblages. Two processes which may produce zoning are hypogene and supergene, and the results of supergene processes may strongly modify and obscure the original hypogene products. Although hypogene zoning is becoming rather well understood in the deposits of North America and certain supergene effects are generally recognized, these characteristics of the deposits of the western hemisphere should be extended to deposits of the western Pacific only with considerable caution.

Ages of many western Pacific porphyries are quite young compared with most western hemisphere deposits. Although rates of uplift and erosion can not be determined for certain, the Pacific porphyries have the potential for having been formed at much shallower levels than those of the western hemisphere. Although not conclusive, many lines of evidence are permissive of this interpretation. If the implications of shallow depths of formation are correct, the "typical" hypogene alteration zoning depicted for the western hemisphere porphyry type may not be applicable in western Pacific bodies because of the potential for a much greater interplay between primary ore fluids and near surface waters. Telescoped primary zoning may be developed and, under very near surface conditions, may be indistinguishable at this state of our knowledge from alteration types considered as supergene in the western hemisphere. Because of the possibility of epizonal intrusions and "epithermal" conditions many otherwise complex alteration patterns may yield to understanding if the effects of "overprinting" of alteration types, and the potential significance of mineralogical variations of wallrocks are recognized.

ACKNOWLEDGEMENTS

Many individuals and groups have supported aspects of the studies reported in this paper. Because the interpretations are based upon data and ideas from so many fields of study, I would be remiss not to acknowledge the contributions of many individuals who have been interested in these problems and who, from time to time have offered data and advice. My colleagues at the University of Arizona, Drs. J.W.Anthony, J.M.Guilbert, W.C.Lacy, E.B.Mayo, H.W.Peirce, J.S.Sumner, and R.F.Wilson have been continuing critics. Present and former graduate students, T.L.Heidrick, P.A.Handverger, W.Butler, and Drs. F.T.Graybeal and W.H.Rehrig, have all offered constructive criticism of various aspects of the field studies and interpretations.

Data and ideas regarding the Mesozoic in the southwest, presented in an earlier manuscript and part of which is summarized in this paper, have benefitted from a critical review by Drs. Charles A.Anderson and Philip T. Hayes of the U.S. Geological Survey. Neither, however, concurred with all of the interpretations presented in that work. Colleagues from industry and who have been involved in the search for the copper bodies have proffered suggestions and have asked the appropriate questions - particularly Messrs. G.A.Barber, C.P.Miller, Harold

Courtright, James Eidel, and John Ruckmick. Some of the ideas regarding supergene alteration have been rewardingly discussed with Dr. James A. Anderson.

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TABLE 1.

TABULATION OF ABSOLUTE AGES
FROM PORPHYRY COPPER DEPOSITS
IN SOUTHWESTERN NORTH AMERICA

Sonoran Subprovince

Deposit	Age (my)	Source
Castle Dome	62	(1)
Copper Cities	63-64	(1)
Inspiration	58-60	(1)
Ray	60-63	(1)
Morenci	55-62	(1)
Safford (KCC)	62	(1)
San Manuel	65-69	(1)
Kalamazoo	65-69(?)	Same as San Manuel(?)
Silver Bell	63-67	(1)
Esperanza	61-63	(1)
Twin Buttes	54	(1)
Pima	59	(1)
Mission	59	(1)
Sacaton	65	Damon, Pers. Comm.
Lake Shore	66	(2)
Christmas	62	(2)
Cananea	59	(2)
Nacozari (La Caridad?)	54	(3)
Santa Rita	58-63	(4)
Copper Creek	68	(6)
Sierrita	61,140(?)	(1, 5)
New Cornelia (Ajo)*	62-63	(1)
Bisbee	163-178	(6)

Unknown but probably Laramide from stratigraphic or other evidence are: Vekol, Rosemont, Helvetia, Tyrone, Poston Butte, Red Mountain, and Safford (PD).

Western Arizona, Nevada, Utah
("Cordilleran" Region)

Bagdad	71-73	(1)
Mineral Park	72	(1)
Bingham	45-49	(4)
Ely	121	(4)
Yerington	111	(4)
Copper Basin	Unknown	
Battle Mountain	Unknown	

Sources: (1) Data compiled from various sources by Livingston, Hauger and Damon, (1968); (2) Damon and others, (1965); (3) Damon and others, (1968); (4) Data compiled by Jerome and Cook, (1967); (5) Damon and others, (1966); (6) Creasey and Kistler, (1962).

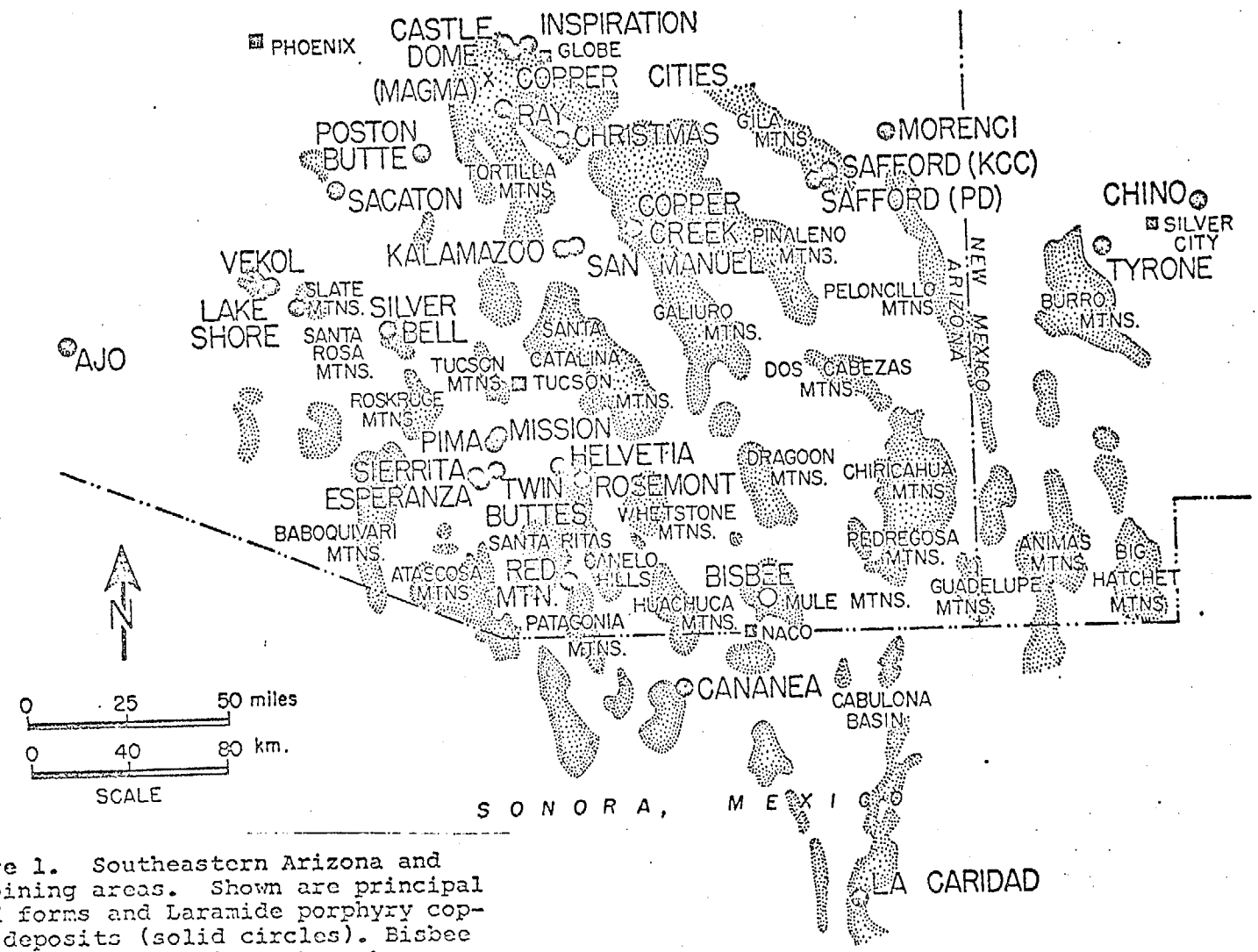


Figure 1. Southeastern Arizona and adjoining areas. Shown are principal land forms and Laramide porphyry copper deposits (solid circles). Bisbee (Triassic-Jurassic) is shown by open circle on this and subsequent figures.

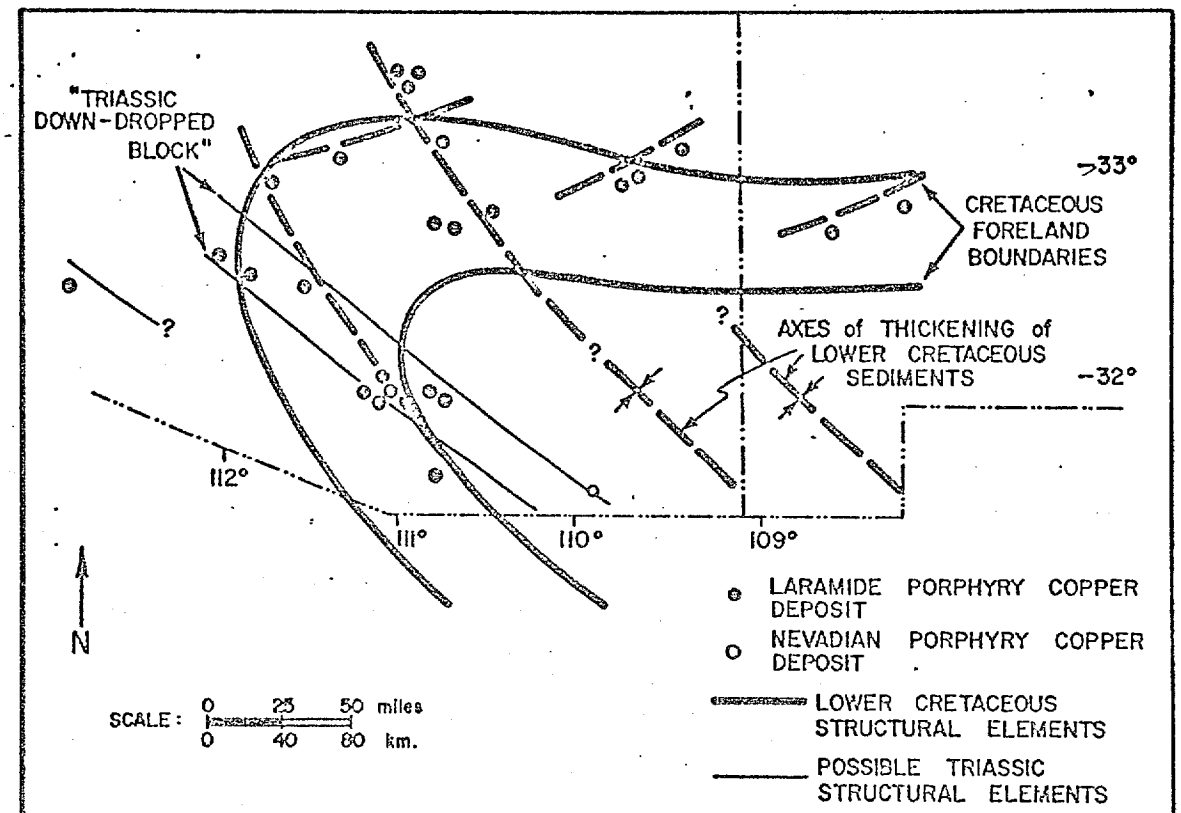


Figure 2. COMPOSITE MAP of INFERRED MESOZOIC STRUCTURAL ELEMENTS

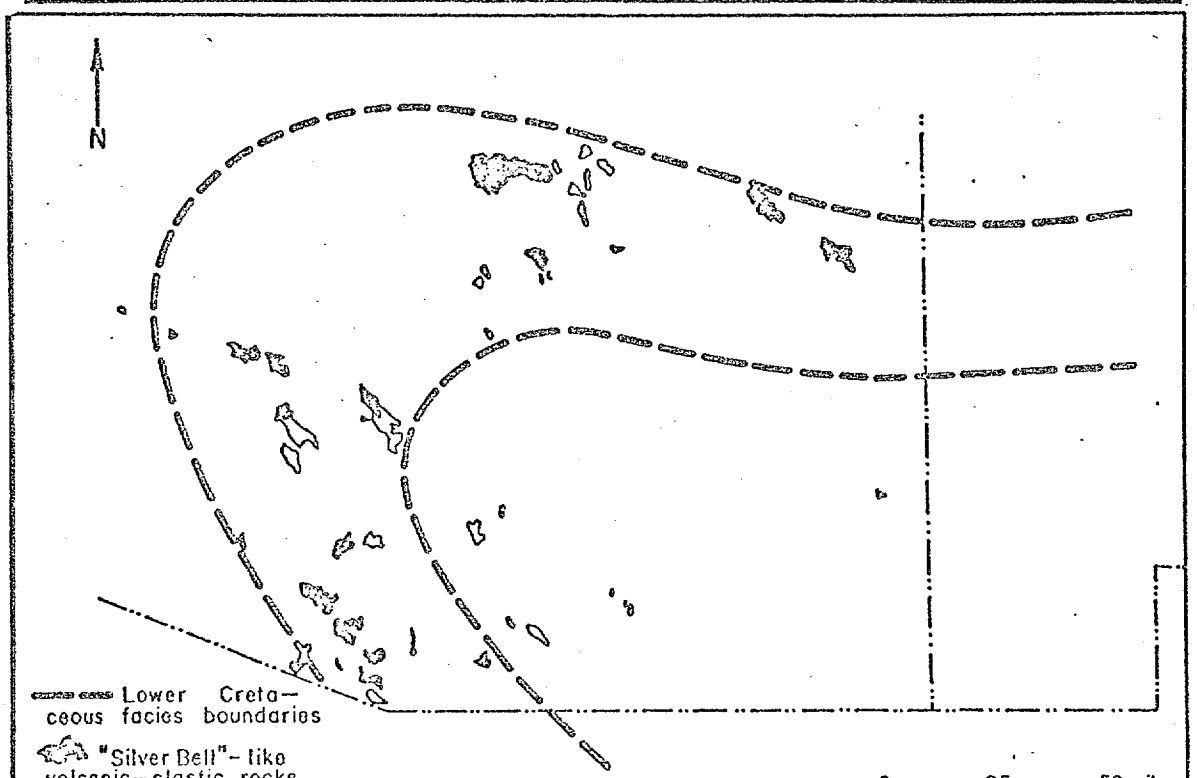


Figure 3. DISTRIBUTION of SOME UPPER CRETACEOUS VOLCANIC and CLASTIC ROCKS, SOUTHEASTERN ARIZONA and ADJOINING AREAS

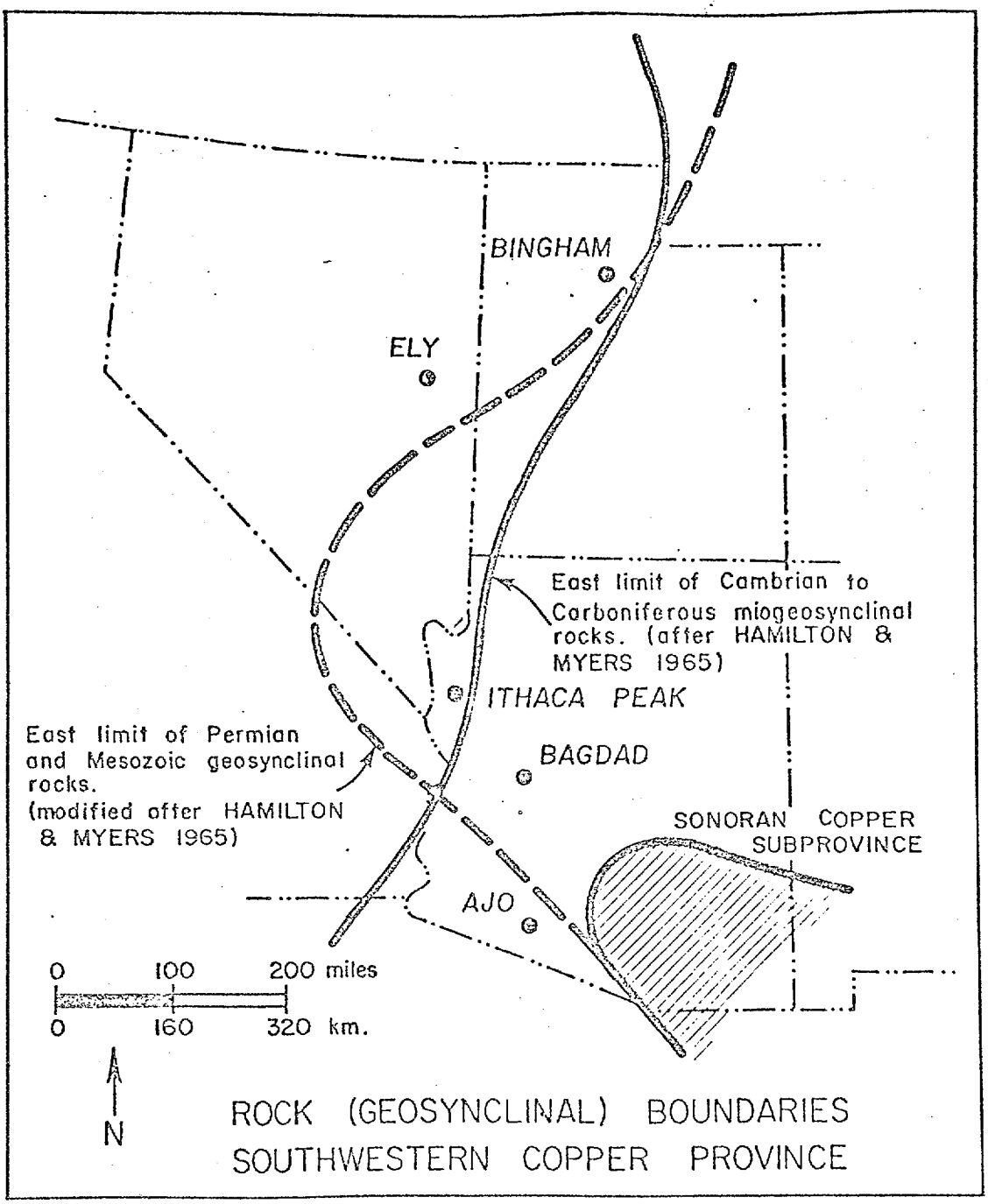

BINGHAM
ELY
East limit of Cambrian to Carboniferous miogeosynclinal rocks. (after HAMILTON & MYERS 1965)
ITHACA PEAK
BAGDAD
East limit of Permian and Mesozoic geosynclinal rocks. (modified after HAMILTON & MYERS 1965)
SONORAN COPPER SUBPROVINCE
AJO
0 100 200 miles
0 160 320 km.
N
ROCK (GEOSYNCLINAL) BOUNDARIES
SOUTHWESTERN COPPER PROVINCE

Figure 4.

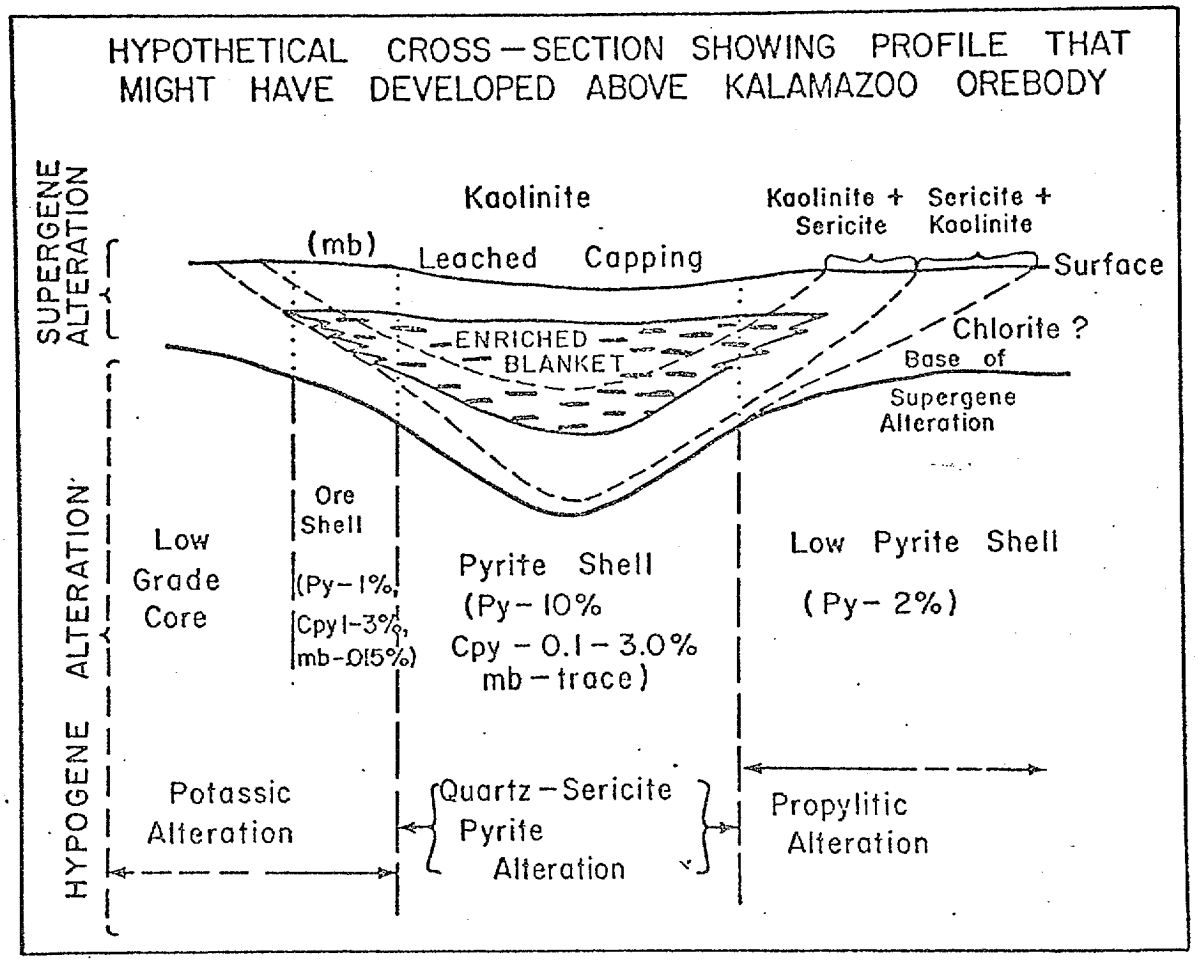
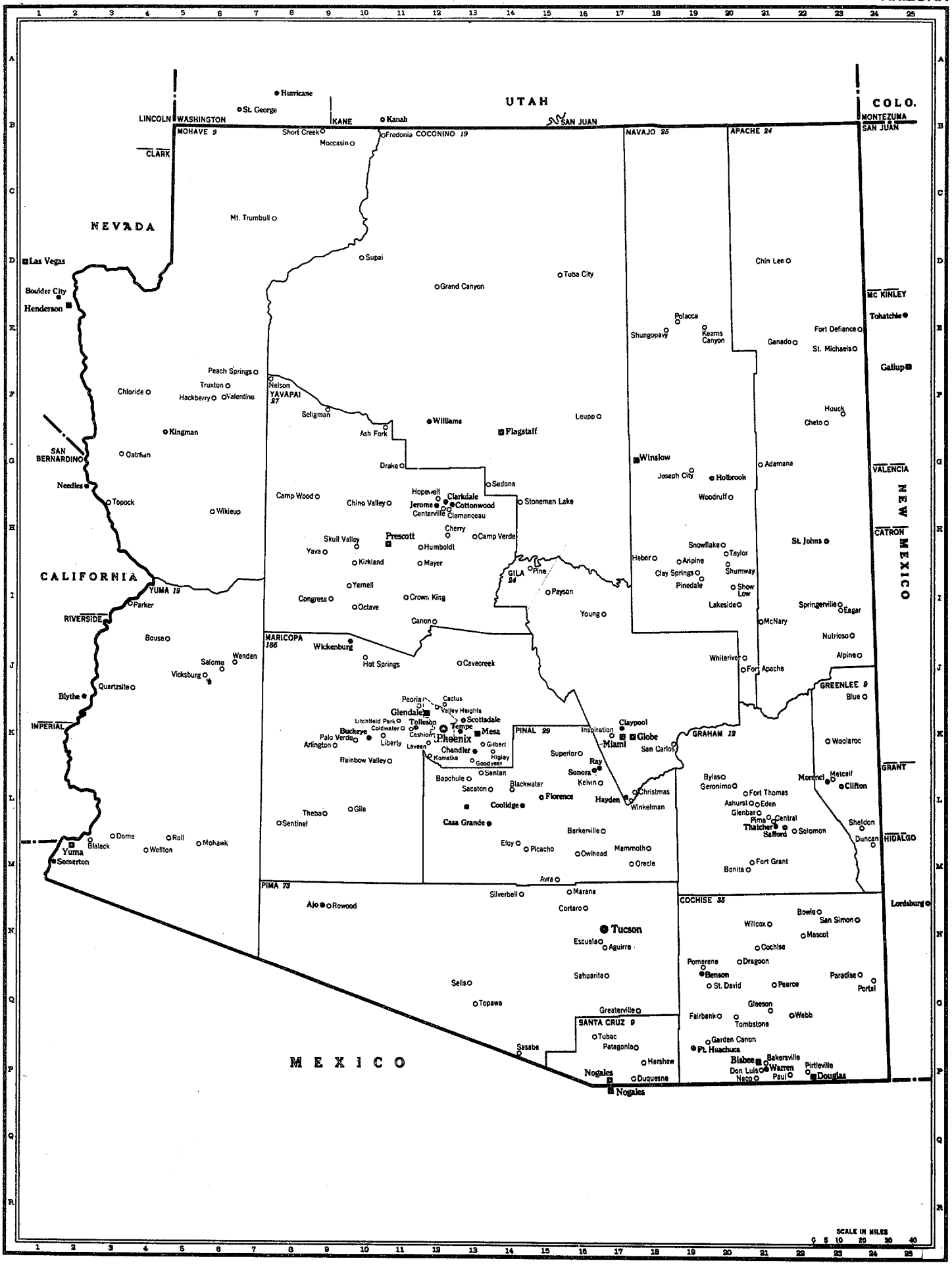


Figure 5. The hypogene alteration zoning depicted by Lowell and Guilbert (1970) is used as a basis for postulation of what might be expressed were the San Manuel-Kalamazoo orebody tilted back to its original vertical position and exposed to those events which produced enriched blankets in the southwestern North American porphyries. I have shown only the three principal alteration zones one one side of the symmetrically altered orebody for this purpose.

The base of the zone of supergene alteration is difficult to determine for certain in many instances but from a megascopic standpoint I have considered it to be that level at which pyrite grains are no longer coated by films of chalcocite. The base is shown in this case as dipping deeply into the zone of hypogene phyllic alteration. Two bases for this interpretation are proposed. First, the zone is high in pyrite and second, the zone tends to be more permeable than those which flank it because of more extensive fracturing. The resulting picture is one of a lateral zoning which is reversed from that ordinarily expected in the hypogene zone. The basis for the interpretations shown is that of composite information noted in numerous drill holes from bodies in the southwest.


UTAH
COLO.
NEVADA
CALIFORNIA
NEW MEXICO
MEXICO
LINCOLN
WASHINGTON
KANE
SAN JUAN
MONTEZUMA
MOHAVE 9
COCONINO 19
NAVAJO 25
APACHE 24
CLARK
YAVAPAI 27
MC KINLEY
SAN BERNARDINO
VALENCIA
CATRON
YUMA 19
RIVERSIDE
MARICOPA 186
GILA 24
GREENLEE 9
IMPERIAL
PINAL 29
GRAHAM 12
GRANT
PIMA 73
COCHISE 35
HIDALGO
SANTA CRUZ 9
Hurricane
St. George
Kanab
Short Creek
Moccasin
Fredonia
Mt. Trumbull
Supai
Grand Canyon
Tuba City
Chin Lee
Las Vegas
Boulder City
Henderson
Polacca
Shungopavy
Keams Canyon
Ganado
Fort Defiance
St. Michaels
Tohatchie
Gallup
Peach Springs
Truxton
Hackberry
Valentine
Chloride
Nelson
Seligman
Ash Fork
Williams
Flagstaff
Leupp
Houck
Cheto
Kingman
Oatman
Needles
Topock
Wikieup
Drake
Sedona
Winslow
Joseph City
Holbrook
Adamana
Woodruff
Camp Wood
Chino Valley
Hopewell
Clarkdale
Jerome
Cottonwood
Centerville
Clemenceau
Stoneman Lake
Cherry
Skull Valley
Prescott
Humboldt
Camp Verde
Yava
Kirkland
Mayer
Pine
Payson
Snowflake
Taylor
Heber
Aripine
Shumway
Clay Springs
Pinedale
Show Low
Lakeside
St. Johns
Springerville
Eagar
Parker
Yarnell
Congress
Octave
Crown King
Canon
Young
McNary
Nutrioso
Bouse
Wenden
Salome
Vicksburg
Wickenburg
Hot Springs
Cavecreek
Whiteriver
Fort Apache
Alpine
Quartzsite
Blythe
Peoria
Cactus
Glendale
Valley Heights
Litchfield Park
Tolleson
Scottsdale
Coldwater
Tempe
Mesa
Buckeye
Cashion
Phoenix
Palo Verde
Arlington
Liberty
Laveen
Chandler
Gilbert
Higley
Komatke
Goodyear
Rainbow Valley
Santan
Inspiration
Claypool
Miami
Globe
San Carlos
Superior
Ray
Sonora
Kelvin
Bapchule
Sacaton
Blackwater
Florence
Hayden
Christmas
Winkelman
Coolidge
Casa Grande
Theba
Gila
Sentinel
Blue
Woolaroc
Bylas
Geronimo
Fort Thomas
Morenci
Metcalf
Clifton
Ashurst
Eden
Glenbar
Pima
Central
Thatcher
Safford
Solomon
Sheldon
Duncan
Dome
Roll
Mohawk
Yuma
Blalack
Wellton
Somerton
Barkerville
Eloy
Picacho
Owlhead
Mammoth
Oracle
Fort Grant
Bonita
Avra
Ajo
Rowood
Silverbell
Marana
Cortaro
Lordsburg
Bowie
San Simon
Willcox
Mascot
Tucson
Escuela
Aguirre
Cochise
Pomerene
Dragoon
Benson
Paradise
St. David
Pearce
Portal
Sahuarita
Sells
Topawa
Gleeson
Greaterville
Fairbank
Webb
Tombstone
Tubac
Garden Canon
Pt. Huachuca
Patagonia
Sasabe
Hershaw
Bisbee
Bakersville
Warren
Pirtleville
Don Luis
Naco
Paul
Douglas
Nogales
Duquesne
SCALE IN MILES
0 5 10 20 30 40

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

March 14, 1963

CONFIDENTIAL

Mr. C. P. Pollock, Exploration Manager
American Smelting and Refining Company
120 Broadway
New York 5, New York

Porphyry Cu General

PORPHYRY COPPER DEPOSITS - ARIZONA & NEW MEXICO

Dear Sir:

Attached is a memorandum with map by Mr. Courtright in which he lists and comments briefly on the known porphyry deposits in the Southwest and arrives at the gambling odds involved in porphyry copper exploration.

He limited his tabulation to the Southwest because there are enough deposits and ore bodies here to provide a sound statistical base.

He concludes that, given a porphyry copper deposit at least one-half mile in diameter, the odds are about even that the deposit will contain a commercial ore body. These odds are far better than any statistics which could be put together for any of the other base and precious metals, wherein the ratio of known deposits to ore bodies might be derived.

This 50-50 chance, of course, does not include the gambling odds for finding a porphyry prospect. In the Southwest these odds are long because the area has received, and is being given, so much exploration attention. These "prospecting" odds are much more favorable in other countries, particularly Latin America, if political and economical conditions are, for the purpose of these comments, disregarded.

The basic gambling odds of 50-50 can be applied in a general way to these other countries, and to other areas in this country, once a porphyry deposit is found.

Yours very truly,

Kenyon Richard

KENYON RICHARD

KR/kw
Attachment
cc: CPPollock(2 extra)
DJPope
KWhiting
RBSprague
AGBlucher

ALL CONFIDENTIAL, W/ATT.

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona
February 18, 1963

FILE MEMORANDUM

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In the following tabulation porphyry copper occurrences are divided into 5 different categories: (1) Productive Deposits, (2) Marginal Deposits (undeveloped), (3) Deposits Currently Under Exploration, (4) Prospects which have been Tested and Proven Sub-Marginal, and (5) Untested Prospects.

1) Productive Deposits

Over 100 Million Tons*	Under 100 Million Tons*
Morenci	Bagdad
Santa Rita	Copper Cities
San Manuel	Silver Bell
Miami-Inspiration	Esperanza
Ray	Christmas
Ajo	Mineral Park (under development)
Cananea (Sonora, Mex.)	Castle Dome (mined out)
Bisbee	
Mission-Pima	

* Production plus potential

2) Marginal Deposits (Undeveloped)

Tyrone..... Reportedly plus 400 million tons @ .70% Cu, chiefly chalcocite. Owned by Phelps Dodge.

Lone Star..... Reportedly 800 million tons @ .55% Cu, mixed sulphides and oxides. Kennecott.

San Juan..... "Large ore body too deep for open pit mining." Owned by Phelps Dodge.

Helvetia..... 14 million tons .80% Cu. Mixed sulphides and oxides. Controlled by Banner.

3) Deposits Currently under Exploration

Sacaton	Asarco
McGee (NW of Esperanza)	Bear Creek
Saginaw Hill (So. Tucson Mtns.)	Anaconda
Red Mt. (Patagonia)	Kerr-McGee
Twin Buttes	Banner
Four Metals	Noranda
Johnson Camp	Cyprus
Chilito	Bear Creek

4) Sub-Marginal Deposits
Proven either too small or too low grade

	Drilled By
Kelvin	Con Coppermines
Copper Creek	Bear Creek & others
Sunnyside	ASARCO
Turquoise	ASARCO, Bear Creek
Red Hills (Texas)	ASARCO, Bear Creek(?)
Poston Butte	ASARCO
Lake Shore	USBM, Shattuck-Denn & Trans Arizona
Pioneer Group	Duval Sulphur & others
Blackwater	Magma Copper
Cerrillos	Bear Creek
Hiltscher	Bear Creek
Steeple Rock	Bear Creek
Madera	Miami Copper
Cactus	Miami Copper
Three R	Con Coppermines (property recently acquired by Anaconda)
Copper Basin	Phelps Dodge

5) Porphyry Copper Prospects - Untested

Rock House (No. of Superior)	Outcrops indicate minor chalcocite enrichment below, but zone too small in size.
Border Pipe (So. of Patagonia)	Mineralized breccia pipe ± 500' in diameter. Outcrops indicate original disseminated pyrite with minor enrichment. Deposit too small to warrant drilling.
Tyndall District (So. Santa Rita Mts.)	Zone of strong quartz-sericite-pyrite alteration several square miles in extent. General character of leached outcrops, plus occasional exposure of sulphides in old adits, indicate little more than traces of either primary or secondary copper.

5) Con't

Tombstone	Zone of alteration one mile or more in diameter lies southwest of this old silver mining district. Outcrops do not appear too promising, but total extent of zone has not been determined. Further reconnaissance planned.
Organ District (Organ Mts.,NM)	Zone of alteration ½ mile wide extends about one mile northwesterly where it passes beneath valley alluvium. Mineralization in exposed portion of zone not sufficiently attractive to warrant exploration. Possibilities under cover highly speculative. A possible application of geophysics was considered at one time; however, the area is now partly within the White Sands Testing Range.

The Productive Deposits listed above (see attached map for location) range in size from 18 million tons (Castle Dome) to a plus one billion tons (Morenci), if future potential is added to past production. With the exception of Castle Dome, which is mined out, nearly all of the mines listed here have a future life of at least 10 years, and at least 50% of them a future life of over 20 years.

Tyrone is included in the group of marginal deposits; however, under different ownership this deposit would likely be in production. Phelps Dodge spent several years in drilling and evaluating and then placed it on the shelf --- presumably because they possess ample resources of lower cost copper elsewhere. Tyrone, with a relatively large tonnage and a grade of .70% copper, would be at least equally profitable, if not more so, than either of Duval Sulphur's two deposits, Esperanza and Mineral Park.

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Reportedly Bear Creek ("McGee" Prospect) has been finding .4 to .5% primary copper in diorite and andesite in ground adjacent to the Experanza.

Red Mt., Patagonia, lies within a large alteration zone which includes the Sunnyside breccia pipe (drilled by Asarco in 1950). Kerr-McGee recently completed driving an incline on the east side, encountering low grade (± .05% Cu) primary mineralization. Reportedly, they plan drilling higher on the mountain.

Chilito produced 91,000 tons of 1.4% Cu. This ore, which consisted of disseminated copper in quartzite, was shipped to Hayden as siliceous flux. Kennecott acquired the property last year.

Banner recently drilled several holes in a gravel covered area southeast of

Twin Buttes. This is the area generally considered to be the probable location of the "roots" of the Mission-Pima zone of mineralization. According to a local contractor, Banner recently cancelled plans for an additional 90,000 feet of diamond drilling at Twin Buttes. The area may still hold exploration possibilities.

Most of the copper ore mined at Johnson Camp came from more or less massive sulphide lenses in the Cambrian Abrigo formation. Disseminated copper occurs, however, in the Cambrian quartzite and in the lowermost part of the overlying limy shale of the Abrigo. During the past few years, 150,000 tons or more of oxidized copper-bearing rock has been mined open pit and shipped to the Douglas, El Paso and Hayden smelters for siliceous flux; and recently, Cyprus completed a series of drill holes in this disseminated copper horizon, reportedly indicating a zone 150' thick and 2000' long of .75% Cu. No intrusive rocks of the porphyry copper type have been found in the area; however, the deposit resembles a porphyry type occurrence in other respects, and an intrusive center of relatively strong alteration-mineralization could exist under the alluvial covered valley east of the mine.

Brief comments on the Untested Porphyry Copper Prospects are included in the foregoing list.

Referring to the attached map, it is to be noted that with the exception of Christmas, mines developed within the past 12 years --- Mineral Park, Mission, Pima, and Esperanza --- all fall within a northwest-trending belt which includes Bagdad, Sacaton, Silver Bell and Cananea. In his report on the discovery of the Sacaton Prospect (Feb. 13, 1961), Mr. Kinnison referred to the aforementioned belt as the Silver Bell zone, and pointed out that the Sacaton area was situated at the intersection of this zone and two cross-trending zones which he labeled "Miami" and "Poston Butte". Since that time, drilling at Sacaton has demonstrated the existence of a major-sized porphyry copper deposit, the full extent of which has yet to be determined. This, and other new discoveries, tend to emphasize certain trends along which the exploration chances may be better; but we must still depend on finding a lead, such as an altered outcrop with evidence of leached sulphide mineralization, or altered boulders derived from a now-buried outcrop, wherever it be located --- on trend, or off.

In 1950 (above mentioned memo of Oct. 4, 1950) there were 12 "commercial" deposits (excluding Tyrone and Pilares) and 10 deposits regarded as either "non-commercial" or as "prospects" with unknown potential. The ratio has changed some in the past 12 years, but the odds still appear very favorable. Today there are 17 "commercial" deposits (including Tyrone), 3 marginal, 16 sub-marginal, 8 currently under exploration and 5 untested. Four of those currently under exploration, Saginaw Hill, Chilito, Red Mt., and Four Metals, should be regarded as sub-marginal on the basis of prior exploration results. Thus, we have a 20-25, or 4-to-5 ratio if the 3 marginal deposits are included with the 17 "commercial" deposits, and all 5 untested deposits are included with the sub-marginal deposits. This ratio has no bearing on the chances of finding a new porphyry copper prospect --- due to the great concentration of exploration personnel in the Southwest for many years, this chance must be regarded as very slim --- but it does suggest that if a new prospect

is found, and the zone of alteration-mineralization demonstrated to be of adequate size (say, a half mile or more in diameter), the odds should be roughly even that the zone will contain a "commercial" ore body.

J. H. Courtright

J. H. COURTRIGHT

JHC/kw
Attachment - Map

Porph Cu General

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Tucson Arizona
February 18, 1963

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File Memo February 18, 1963

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Turquoise	ASARCO, Bear Creek
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Poston Butte	ASARCO, Conco
Lake Shore	USBM, Shattuck-Denn & Trans Arizona Eupiero-Helca
Pioneer Group	Duval Sulphur & others
Blackwater	Magma Copper, Pan Ocean Duval
Cerrillos	Bear Creek
Hiltscher	Bear Creek, Inspiration
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J. H. Courtright

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JHC/kw
Attachment - Map

Economic Geology
Vol. 63, 1968, pp. 943-949

discusses the Nogal or Rialto property
does not discuss the Eagle Creek deposit

Field Work copy
Porphyry Copper
New Mexico

Hydrothermal Alteration and Mineralization of the Rialto Stock, Lincoln County, New Mexico

TOMMY B. THOMPSON

Table 1. Spectrochemical analysis and norm