CLASIFICACION ACTUALIZADA DE YACIMIENTOS MINERALES

Abril, 1981

Lunes 20	9 - 10 horas	Introducción	Ing Miguel Vera Ocampo
	10 - 13 horas	Clasificaciones genéticas recientes	Ing Germán Arriaga García
	13 - 15 horas	Comida	
	15 - 19 horas	Los fenómenos geológicos y los yacimientos minerales Concepto de metalotecton. Intemperismo. Sedimentación. Metamorfismo. Intrusiones. Vulcanismo. Vulcanismo-Sedimentación.	Ing Germán Arriaga García
Martes 21	9 - 13 horas	Los fenómenos geológicos y los yacimientos minerales	Ing Germán Arriaga García
	13 - 15 horas	Comida	
	15 - 19 horas	Consideraciones sobre metalogenia regional. Esquemas modernos. El futuro de la prospección minera	
Miercoles 22	9 - 13 horas	Depósitos de sulfuros masivos vulcanogénicos. Distribución:regional y emplazamiento tectónico. Realción espacio-temporal. Características geológicas generales Depósitos precambricos; Depositos Fanerozoicos. Depositos de sulfuros masivos en ambientes sedimentarios. Depósitos precambricos en ambientes eugeosinclinales. Depósitos misceláneos con posible interpretación singenética	Dr Samuel Romberger
	13 - 15 horas	Comida	
	15 - 19 horas	Depositos de sulfuros masivos vulcanogénicos	
Jueves 23	9 - 13 horas	Depósitos de cobre-molibdeno (Pórfidos cupriferos) Definición general, tonelaje y ley. Distribución mundial y emplazamiento tectónico. Posición dentro del modelo de placas tectónicas. Relación espacio-temporal. Comparación con depositos de sulfuros masivos singeneticos. Características generales. Celsificación en terminos de composición y asociación-litológica-. Formas estructurales, regionales y locales. Mineralización y alteraciones asociadas. Mineralogía de los yacimientos. Oxidación secundaria. Geoquímica. Naturaleza y origen de los fluidos mineralizantes. Descripción general de ejemplos.	Dr. Samuel Romberger

Jueves 23	13 - 15 horas	Comida
	15 - 19 horas	Depósitos de cobre-molibdeno Porfídicos (Pórfidos cupriferos) Dr Samuel Romberger
Viernes 24	9 - 13 horas	Depósitos de materiales base y preciosos, emplazados en rocas volcanicas
	13 - 15 horas	Comida
	15 - 18 horas	Depósitos de materiales base y preciosos, emplazados en rocas volcanicas
	18 - 19 horas	Conclusiones
	19 -	Clausura.

Directorio de Profesores: Curso Clasificación de Yacimientos Minerales

Abril, 1981

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DIVISION DE EDUCACION CONTINUA
FACULTAD DE INGENIERIA U.N.A.M.

CLASIFICACION ACTUALIZADA DE YACIMIENTOS MINERALES

INTRODUCCION

CLASIFICACIONES GENETICAS ACTUALES

LOS FENOMENOS GEOLOGICOS Y LOS YACIMIENTOS MINERALES

CONSIDERACIONES SOBRE METALOGENIA REGIONAL

ING. GERMAN ARRIAGA GARCIA

ABRIL, 1981

" CLASIFICACIONES ACTUALIZADAS DE YACIMIENTOS MINERALES"

ING. GERMÁN ARRIAGA GARCÍA

TEMARIO

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II.- CLASIFICACIONES GENETICAS ACTUALES

III.- LOS FENOMENOS GEOLOGICOS Y LOS YACIMIENTOS MINERALES
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INTRODUCCION

" A LAS DISTINTAS CIVILIZACIONES QUE SE HAN DESARROLLADO EN LA TIERRA, SE LES HA DADO EL NOMBRE DEL PRINCIPAL MATERIAL QUE ELLAS UTILIZARON. ASÍ, SE TIENEN:

LA EDAD DE PIEDRA
LA EDAD DE BRONCE
LA EDAD DE FIERRO

UNA CIVILIZACIÓN SE DESARROLLA Y ESTÁ LIMITADA POR LOS MATERIALES DE QUE ELLA DISPONE. SE PODRÍA DECIR QUE NOS ENCONTRAMOS ACTUALMENTE EN LA FRONTERA QUE SEPARA LA EDAD DE FIERRO DE UNA EDAD DE MATERIALES NUEVOS".

EN UN ARTÍCULO SOBRE LA PROSPECCIÓN DE MATERIALES Y EL DESARROLLO INDUSTRIAL J. SERVANT PRINCIPIA SU EXPOSICIÓN CITANDO ESTAS PALABRAS DEL PREMIO NOBEL SIR. GEORGE THOMSON A PARTIR DE UNA RELACIÓN DE M. PROMISEL PRESENTADO EN 1968. ESTA RELACIÓN ESTABLECE EN 5 PUNTOS LA NUEVA IMPORTANCIA ADQUIRIDA POR LOS MATERIALES NATURALES EN LA VIDA MODERNA:

1) EXPLOSIÓN DE INNOVACIONES EN DIFERENTES MATERIALES QUE SE HA PRODUCIDO EN EL TRANSCURSO DE LOS ÚLTIMOS 30 AÑOS Y QUE SE HA MANIFESTADO EN TODAS LAS CATEGORÍAS DE LA CIENCIA Y LA TÉCNICA MODERNA.

DESDE AUTOMÓVILES HASTA VEHÍCULOS ESPACIALES, LOS DOMINIOS DEL MAGNETISMO, LA ELECTRÓNICA, EN FIN DE TODA LA INDUSTRIA DE TRANSFORMACIÓN, LA INDUSTRIA ALIMENTICIA, ETC.

El problema es el de sacar partido de esta explosión permanente y favorizarla para que se continúe en los años por venir. Es interesante notar que los materiales no-metálicos cada día utilizan en una relacion mayor con respecto a los materiales metálicos.

El ritmo de producción de los aceros tiende a disminuir en comparacion con los materiales no-metalicos que se producen con un incremento exponencial. Esta nueva expansión en la producción de materiales cerámicos, vidrio o plásticos exige una serie atencion de paises como el nuestro tan preocupado siempre en la explotacion de metales.

2) El Reconocimiento de las necesidades sociales. Este hecho marca numerosos problemas por la carencia de los materiales para estas necesidades. Tales problemas se iran resolviendo a medida que los materiales y sus problemas de producción sean mejor conocidos y por tanto la demanda se acrecentará. Por necesidades sociales, es necesario entender aquellas que interesan a:

La salud pública
La contaminación
El control del medio ambiente
El transporte
La habitacion a precio bajo
El desarrollo urbano

Pueden ser citados numerosos ejemplos de problemas materiales en este dominio.

- YA SE IMPLANTAN MILLONES DE PIEZAS METÁLICAS Y NO-METALICAS EN CUERPOS HUMANOS; SIN EMBARGO, ESTE FACTOR TODAVÍA SIGUE EN PAÑALES.
- LOS PROGRESOS DEL TRANSPORTE POR FIERRO A GRAN VELOCIDAD HAN SIDO RETRASADOS POR PROBLEMAS DE DESGASTE DE SUPERFICIES, FRICCIONES Y APLICACION DE FRENOS.
- EL CONTROL DEL MEDIO AMBIENTE EXIGE MÉTODOS COMPLEJOS PARA TRATAR LOS MATERIALES UTILIZADOS; REDUCIR AL MÁXIMO LOS DESHECHOS Y AUN ESTOS, APROVECHARLOS.
- EN MATERIA DE DESARROLLO URBANO UN PROBLEMA IMPORTANTE SE TIENE EN LA CONSTRUCCION DE GALERÍAS ENORMES (COLECTORES) MUY RAPIDAMENTE; POR TANTO, SON NECESARIOS MATERIALES ADECUADOS PARA CONSTRUIR MÁQUINAS APROPIADAS PARA REALIZAR TALES TÚNELES.

ESTOS SON SOLO ALGUNOS DE LOS PROBLEMAS MÁS EVIDENTES EN LO QUE ATAÑE AL SECTOR SOCIAL.

3). LAS NECESIDADES EN MATERIALES PARA LA DEFENSA NACIONAL Y, EN ALGUNOS PAISES PARA LA CIENCIA Y LA TECNOLOGIA LIGADAS AL ESPACIO JUEGAN UN PAPEL IMPORTANTE QUE NO SERÁ VITAL PARA NOSOTROS. SIN EMBARGO, ES NECESARIO NOTAR LOS ÉXITOS QUE HAN PODIDO OBTENERSE BAJO LA PRESIÓN DE ESTOS ASPECTOS HAN LLEGADO A PROPORCIONES FANTÁSTICAS. PARA SEÑALAR UN EJEMPLO NO HAY MÁS QUE PENSAR EN LOS SEMICONDUCTORES Y EN TODA LA SERIE DE MATERIALES ELECTRÓNICOS Y MAGNÉTICOS; EN LOS MATERIALES DE GRAN RESISTENCIA UTILIZADOS A TEMPERATURAS QUE ALCANZAN MILES DE GRADOS; AL NACIMIENTO Y DESARROLLO EN POCO

MENOS DE 10 AÑOS DE UNA INDUSTRIA NUEVA PARA EL TITANIO; EL CONCEPTO AVANZADO DE MATERIALES A PARTIR DE COMPÓSITOS FIBROSOS QUE PERMITIRÁ SIN DUDA FABRICAR MATERIALES QUE RESPONDAN A NECESIDADES TAN COMPLEJAS QUE NO PODRÍAN SER SATISFECHAS POR NINGUN MATERIAL DE LOS LLAMADOS HOMOGÉNEOS.

4). EL PROBLEMA DE LOS RECURSOS NATURALES Y DE LAS FUENTES DE ENERGIA.

ESTE PROBLEMA HA EXISTIDO SIEMPRE, PERO HA LLAMADO FUERTEMENTE LA ATENCIÓN EN LOS ÚLTIMOS AÑOS, NO SOLAMENTE PORQUE AHORA EXISTE LA PREOCUPACIÓN DE ENCARAR A LAS NUEVAS NECESIDADES NACIDAS DEL PROGRESO TECNOLÓGICO Y DE LA EXPLOSIÓN DEMOGRÁFICA, SINO TAMBIÉN A CAUSA DE LA CORRELACIÓN QUE EXISTE ENTRE LA TRANSFORMACIÓN Y LA UTILIZACIÓN EFICIENTE DE LOS RECURSOS NATURALES, LA FORMACIÓN DE DESHECHOS Y LA CONTAMINACIÓN DEL MEDIO AMBIENTE RESULTANTE ASÍ COMO LA NECESIDAD Y LAS VENTAJAS DE RECUPERAR AL MÁXIMO ESTOS DESHECHOS Y LA ECONOMÍA DEL SISTEMA EN SU CONJUNTO. ESTAS CONSIDERACIONES CREAN PROBLEMAS NO SOLAMENTE EN EL CUADRO DE UN PAÍS DETERMINADO, SINO TAMBIÉN PROBLEMAS INTERNACIONALES; EN EFECTO, TODOS LOS PAÍSES TIENEN LA "NECESIDAD DE ALGO" Y DEPENDEN DE LAS IMPORTACIONES Y DE INTERCAMBIOS DE MERCANCIAS PARA ACABAR CON SUS NECESIDADES INTERNAS. LA INDUSTRIALIZACIÓN CRECIENTE DE TODOS LOS PAÍSES OTORGA AL PROBLEMA DE LOS MINERALES UNA DIMENSIÓN INTERNACIONAL DE TAL MAGNITUD QUE SE PUEDE PENSAR QUE EN UN MOMENTO DADO UN PAÍS DETERMINADO SE ENCUENTRE ANTE LA DESAGRADABLE NECESIDAD DE ESCOGER ENTRE UNA PENURIA DE MINERALES Y UNA PENURIA DE PRODUCTOS ALIMENTICIOS YA QUE UNOS PUEDEN SER INTERCAMBIADOS POR LOS OTROS. LAS NUEVAS FUENTES DE ENERGÍA, EN PARTICULAR LA ENERGÍA NUCLEAR HACEN NECESARIO UN NUEVO EXAMEN DEL EQUIPO INDUSTRIAL, ASÍ COMO EL ESTUDIO DE LA PLANIFICACIÓN

DE INTALACIONES INDUSTRIALES TANTO DE UN PUNTO DE VISTA ECONÓMICO COMO TÉCNICO. UN ESTUDIO JUICIOSO SOBRE ESTAS NUEVAS FUENTES DE ENERGÍA EN EL DOMINIO DE LOS MATERIALES ESTÁ POR REALIZARSE.

5). LA EXPLOTACION POR LA INDUSTRIA DE LAS POSIBILIDADES QUE OFRECEN LOS MATERIALES PRODUCIDOS POR LA INVESTIGACION CIENTIFICA Y TECNICA.

ESTE FACTOR CONSTITUYE OTRA DIMENSIÓN IMPORTANTE DE LA CIENCIA Y LA TECNOLOGÍA DE LOS MATERIALES QUE SON EXAMINADOS ACTUALMENTE POR TÉCNICAS Y MÉTODOS MAS SISTEMÁTICOS EN RAZÓN DE LAS VENTAJAS QUE PUEDEN SER SACADAS DE ESTOS. LOS EJEMPLOS INNOVADORES REVOLUCIONARIAS ABUNDAN.

- NUEVAS TÉCNICAS EN EL DOMINIO DE LA ACÚSTICA.
- NACIMIENTO DE LA INDUSTRIA DEL TITANIO.
- INDUSTRIA DEL PLÁSTICO.
- INDUSTRIA DE FIBRAS Y FILAMENTOS PARA MATERIALES COMPÓSITOS.
- EQUIPO CIENTÍFICO.

ETC.

EN ESTA EXPOSICIÓN DEL SR. PROMISEL DIRECTOR DEL MATERIALS ADVISORY BOARD, SEGUIDA POR M. SERVANT PONE EN EVIDENCIA CIERTOS FACTORES PERDIDOS DE VISTA POR LOS GEÓLOGOS PROSPECTORES Y DE ACUERDO CON M. SERVANT, ES IMPOSIBLE ESTUDIAR CONVENIENTEMENTE LOS PROBLEMAS Y LAS REPERCUSIONES EN LA SITUACIÓN SOCIAL Y ECONÓMICA DE ESE PAÍS Y LA AUSENCIA DE UN MECANISMO NACIONAL QUE PUEDA OFRECER UN CENTRO DE EXÁMEN Y DE DISCUSIÓN PARA EL ESTUDIO, LA PLANIFICACIÓN YLA PROGRAMACIÓN DE LA PRODUCCIÓN DE ESTOS MATERIALES QUE INTERESAN TANTO AL ESTADO COMO A LA INDUSTRIA Y A LA UNIVERSIDAD (CENTROS DE ESTUDIOS SUPERIORES)".

SOLO CON UN CENTRO DE PLANEACIÓN DE ESTE TIPO, LAS NECESIDADES DE LA INDUSTRIA EN CUANTO SE REFIERE A LAS MATERIAS PRIMAS SE PODRÁN TRATAR DE ELIMINAR CON PROSPECCIONES MINERAS ADECUADAS EN TODO EL ÁMBITO NACIONAL.

AHORA BIEN, AL TRATAR DE ANALIZAR LAS CLASIFICACIONES DE YACIMIENTOS MINERALES Y ACTUALIZAR NUESTROS CONOCIMIENTOS DE ELLAS, NO HEMOS DE PERDER DE VISTA LOS PUNTOS CITADOS ANTERIORMENTE.

POR OTRA PARTE, Y YA SITUADOS EN LOS YACIMIENTOS MINERALES PROPIAMENTE DICHOS, SE HA DE CITAR UNA ANTIGUA FRASE MENCIONADA POR H. PELISSONIER*

"PARA ENCONTRAR MINAS, ES NECESARIO MUCHO CORAZÓN Y LA DISPONIBILIDAD ILIMITADA DEL DINERO DE OTROS".

ES IMPORTANTE SEÑALAR QUE EL OBJETIVO FUNDAMENTAL QUE NOS HEMOS PROPUESTO EN EL ANÁLISIS SOBRE LAS CLASIFICACIONES DE YACIMIENTOS MINERALES ES EL DE FACILITAR LA "PROSPECCIÓN MINERA" Y QUE ESTA SÓLO PODRÁ REALIZARSE CON SUFICIENTES MEDIOS ECONÓMICOS PARA LLEVARLA A CABO. ES OBVIO QUE TANTO EL ESTADO PARA LA PLANEACIÓN DEL DESARROLLO NACIONAL COMO LA INDUSTRIA PARA SU PRODUCCIÓN PARTICULAR NECESITAN INCREMENTAR DÍA CON DÍA LA EXPLOTACIÓN DE LOS RECURSOS NATURALES DEL PAÍS. ESTA NECESIDAD NO PODRÁ LLEVARSE A CABO EVIDENTEMENTE SIN UNA TECNOLOGÍA ADECUADA PERO TAMPOCO SIN LOS MEDIOS ECONÓMICOS SUFICIENTES PARA REALIZARLA.

EN OTROS PAÍSES, CANADÁ POR EJEMPLO, LLEVAN A CABO PROSPECCIONES MASIVAS, SIN IMPORTAR LOS COSTOS, COMO CONSECUENCIA TIENEN ÉXITOS QUE PODRÍAN CONSIDERARSE COMO SORPRENDENTES SI NO SE TUVIERAN EN CUENTA LOS MEDIOS TANTO ECONÓMICOS COMO TÉCNICOS QUE HAN EMPLEADO. TAMBIÉN ES OBVIO, QUE UN PAÍS DE LOS LLAMADOS EN VÍA DE

DESARROLLO NO CUENTEN CON EL POTENCIAL ECONÓMICO QUE EMPLEAN LOS PAÍSES EN DESARROLLO; SIN EMBARGO, NO DEBE PERDERSE DE VISTA QUE PARA "ENCONTRAR" ES NECESARIO "INVERTIR" Y HASTA CIERTO PUNTO SACRIFICAR (APARENTEMENTE) CIERTOS MEDIOS QUE DESPUÉS SE VERÁN RECOMPENSADOS AMPLIAMENTE CON LOS DESCUBRIMIENTOS QUE INVARIABLEMENTE SERÁN REALIZADOS. MÉXICO YA HA PROBADO ALGO DE ESTOS ÉXITOS, BASTA NOMBRAR LOS GRANDES DESCUBRIMIENTOS REALIZADOS EN EL DOMINIO DEL COBRE CON LA CARIDAD Y EN DEL FÓSFORO CON BAJA CALIFORNIA SUR.

ANALIZAREMOS LAS NUEVAS CLASIFICACIONES DE YACIMIENTOS MINERALES PERO CON UN OBJETIVO FUNDAMENTAL, ESENCIAL PARA LA METALOGENIA QUE SERÁ EL CONOCIMIENTO DE LAS FORMAS, CONTENIDO Y VARIACIONES DE LOS YACIMIENTOS MINERALES EN SU CUADRO GEOLÓGICO COMPLETO. ES EVIDENTE QUE UN YACIMIENTO MINERAL NO SE FORMÓ AISLADAMENTE SINO DENTRO DEL DESARROLLO DE LA HISTORIA DE LA GEOLOGÍA DE LA REGIÓN DONDE SE ENCUENTRA.

LA REVISIÓN DE LAS CLASIFICACIONES DE YACIMIENTOS MINERALES CON PROPÓSITO DE ACTUALIZARLAS ES CADA VEZ MÁS URGENTE PUESTO QUE DÍA CON DÍA SE CONOCE MEJOR DESDE EL PUNTO DE VISTA GEOLÓGICO MINERO EL TERRITORIO NACIONAL AL MISMO TIEMPO QUE NUESTROS PROFESIONALES EN LA GEOLOGÍA HAN LOCALIZADO NUEVOS DEPÓSITOS MINERALES DE RENDIMIENTO ECONÓMICO.

SE HAN PODIDO ENCONTRAR UNA DIVERSIDAD ENORME DE TIPOS DE YACIMIENTOS MINERALES. ESTOS DESCUBRIMIENTOS, HAN MOSTRADO QUE LOS CRIADEROS MEXICANOS PUEDEN COLOCARSE DENTRO DE CIERTOS MODELOS MUY BIEN DEFINIDOS. ES DECIR, QUE CADA UNO DE ELLOS MUESTRAN METALOTECTONES TAN CONSTANTES QUE PUEDEN PERFECTAMENTE AGRUPARSE

DENTRO DE TIPOS MUY ESPECIALES Y CONSTANTES EN SU ASOCIACIÓN A LOS GRANDES FENÓMENOS GEOLÓGICOS QUE AFECTAN LA CORTEZA TERRESTRE MEXICANA.

PARA EJEMPLARIZAR ESTE HECHO, HEMOS DE CITAR AL VULCANISMO, CUYA IMPORTANCIA EN MÉXICO ES SOBRESALIENTE, EN LO QUE SE REFIERE TANTO A SU ENORME DISTRIBUCIÓN GEOGRÁFICA COMO A LA GRAN DIVERSIDAD DE SUS COMPOSICIONES Y ESTRUCTURAS QUE LO ENMARCAN.

COMO VAMOS A PUNTUALIZAR MÁS ADELANTE, UN GRAN NÚMERO DE DEPÓSITOS ESTÁN DIRECTAMENTE ASOCIADOS A ESTE VULCANISMO. EN ALGUNOS DE ELLOS, CÉLEBRES POR SU RIQUEZA, ESTA ASOCIACIÓN ES RECONOCIDA E INDUSCUTIBLE, NO SE PUEDEN OMITIR EN ESTE MOMENTO: PACHUCA, GUANAJUATO Y TAYOLTITA, COMO SOLO ALGUNOS DE LOS EJEMPLOS MÁS FAMOSOS. SIN EMBARGO, EN LA MAYORÍA, LA RELACIÓN CON LOS FENÓMENOS VOLCÁNICOS ES MUY CONTROVERTIDA Y EN ALGUNOS CASOS TAMBIÉN ENMASCARADA POR LO QUE PODRÍAN LLAMARSE ACCIDENTES GEOLÓGICOS, QUE POSTERIORMENTE A SU FORMACIÓN, VIENEN A ENCUBRIR SU REAL ASOCIACIÓN CON ESTE METALOTECTÓN. DE ESTA MANERA PODRÍAN ENNUMERARSE TODA UNA SERIE DE MODELOS EXISTENTES Y MUY CARACTERÍSTICOS DE NUESTRO PAÍS.

POR OTRA PARTE, VAMOS A INSISTIR EN EL CONCEPTO DE TIPO O MODELO DE YACIMIENTO MINERAL, ES DECIR, SERÁ NECESARIO TOMAR EL INDIVIDUO "YACIMIENTO MINERAL" COMO UN "ENTE" QUE HA SIDO FORMADO POR UNA SERIE MUY COMPLEJA DE METALOTECTONES LOS CUALES HAN CONCURRIDO A LA CREACIÓN DE ESE DEPÓSITO.

ADEMÁS, COMO SE HA DISCUTIDO CON VARIOS DE USTEDES EL UTILIZAR EXCLUSIVAMENTE ALGUNA DE LAS CLASIFICACIONES EXISTENTES SOBRE LOS YACIMIENTOS MINERALES TIENE MUCHOS RIESGOS:

1.- Las clasificaciones hasta la actualidad están basadas estrictamente en la génesis de los yacimientos y por tanto, es tomar exclusivamente un solo metalotectón y no el conjunto de ellos.

2.- Un mismo yacimiento puede incluirse en varios apartados de estas clasificaciones; por ejemplo, en el caso de los yacimientos relacionados con el granito. En una localidad minera definida pueden encontrarse pirometasomáticos e hidrotermales como es el caso de Fresnillo, Zac.

3.- En un momento dado, las clasificaciones de un yacimiento mineral puede ser una cuestión enteramente subjetiva. Un mismo depósito mineral puede ser clasificado de manera diferente de acuerdo a las concepciones teóricas del autor; o bien a la zona del depósito que la haya tocado investigar.

4.- Muy a menudo y para un gran número de yacimientos minerales el cuadro geológico que los enmarca es bastante mal conocido; por tanto, los procesos generadores de los depósitos, también serán desconocidos y la clasificación será bastante ficticia; por ejemplo pueden mencionarse en este caso la aparente ausencia de la "fuente" generadora de depósitos en el caso de la mayoría de las acumulaciones minerales en rocas volcánicas.

5.- En muchos depósitos minerales las relaciones cronológicas entre la formación de los depósitos minerales y las rocas encajonantes están sujetas a discusión y a menudo son desconocidas.

Aún con la elaboración de los análisis termométricos, con excelentes resultados en numerosas ocasiones, es probable llegar a conclusiones erróneas. Un mismo yacimiento puede formarse por una sucesión de eventos muy ampliamente distribuídos en el tiempo; este depósito estuvo sujeto necesariamente a una serie de eventos geológicos que en un momento dado pueden alterar la temperatura de su formación original. Un ejemplo se manifiesta por el sobrecalentamiento debido a derrames sucesivos en una región volcánica.

Por todo lo anterior, es muy arriesgado tomar la clasificación genética como única referencia para agrupar a los diferentes yacimientos minerales. De ahí la conveniencia de considerar a los depósitos minerales como modelos o tipos donde se deben considerar todos los metalotectones posibles.

DEFINICIONES ESENCIALES

En la revisión que he propuesto a ustedes, pienso que es muy necesario poner a su consideración la definción de algunos términos para las observaciones posteriores. En estas definiciones, se han notado a menudo; que tienen fuertes divergencias en sus acepciones.

A).- Paragénesis

Este término fué creado en 1849, por Breithaupt para definir "La asociación de minerales resultantes de un proceso geológico determinado". Por tanto, un depósito puede comportar varias paragénesis no contemporáneas yuxtapuestas.

B).- Sucesión

Define el orden según el cual se depositaron los minerales de una paragénesis durante el desarrollo de un proceso Geológico.

En sentido totalmente equivocado se utiliza la palabra paragénesis con el siguiente significado

"Lista de minerales con el orden de sucesión"

Por tanto, el concepto de paragénesis es un dato totalmente objetivo y susceptible de ser conocido en tanto se estudia la mineralogía de un depósito; mientras que la sucesión es una concepción de alguna manera hipotética y factible de ser reformada en cuanto se intensifique el conocimiento del depósito.

c).- Metalotecton

Este término es de gran importancia para tenerlo presente en la elaboración de los programas de prospección minera puesto que define "todo rasgo geológico" ligado a:

- Tectónica
- Magmatismo
- Metamorfismo
- Litología
- Paleoclimatología

que pueden favorecer la edificación de un yacimiento mineral y que por consecuencia es escogido para los trabajos de cartografía metalogénica.

Para Routhier (1977), un metalotectón es primeramente una hipótesis, que por observaciones sucesivas y directas puede convertirse en una certeza. Entonces se puede pensar en este metalotectón como una guía de prospección aplicable en amplias extensiones geográficas. En este punto se vuelve a poner evidente el ejemplo en México del vulcanismo como un metalotectón apropiado para considerarlo como excelente guía para la prospección minera en extensas áreas geográficas de nuestro país.

Es necesario igualmente definir dos conceptos en cuanto a sus relaciones espacio-temporales con las rocas encajonantes. Estos términos son: COGNADOS Y ALIENIGENOS:

Yacimientos Cognados

Son aquellos donde los minerales de mena tienen la misma fuente que la roca encajonante; como ejemplos se mencionan:

a) Un yacimiento de sulfuros de níquel y cobalto es cognado a las rocas ultramáficas encajonantes.

b) Igual consideración puede hacerse para los depósitos de plata y oro en las andesitas y dacitas del terciario de México.

Yacimientos Alienígenos.

Son las concentraciones minerales donde las menas son totalmente extrañas al origen de su roca encajonante, por ejemplo

a) Vetas y Chimeneas de Pb-Ag-Cu-Zn (Au)-Fe, provenientes de rocas graníticas emplazadas en calizas del Jurásico-Cretácico de la Sierra Madre Oriental de México.

Estos términos de COGNADOS-ALIENIGENOS no deben ser confundidos con los términos Singenético-Epigenético.

Un yacimiento Cognado, puede ser epigenético. Las vetas auro-argentíferas son epigenéticas en las dacitas-andesitas y sin embargo son cognados puesto que han tenido los mismos orígenes volcánicos que las rocas encajonantes.

b).- En lo que se refiere a los yacimientos hidrotermales es necesaria la siguiente aclaración. La división de este grupo de yacimientos se debe a W. Lindgren. Analizemos los diferentes términos:

Tele (griego): Preposición inseparable que significa transmisión de algo a lo lejos.

Epi (griego): Preposición inseparable que significa sobre.

Lepto (griego): Preposición inseparable que significa tenue, delgado, débil.

Meso (griego): Preposición inseparable que significa medio, mediano.

Hipo (griego): Preposición inseparable que significa inferioridad o dependencia.

Xeno (griego): Gas volátil

Termal, del griego termos que significa calor.

Por tanto, los vocablos utilizados en la clasificación de los yacimientos hidrotermales de Lindgren, aumentados por Bateman significan:

Teletermal: transmitido lejos del calor.
Epitermal: sobrecalentado, temperatura elevada.
Leptotermal: de calor o temperatura débil.
Mesotermal: de mediana temperatura o calor.
Hipotermal: de baja temperatura.
Xenotermal: Gas volátil caliente o con temperatura.

Independientemente de todas las explicaciones que se traten de dar para aclarar e interpretar lo que se quiere decir, es claro que excepto dos términos (tele y meso), los demás están muy lejos.

DE DESCRIBIR EXACTAMENTE LO QUE SE DESEA EXPRESAR. POR OTRA PARTE, ES CLARO QUE ESTA MULTIPLICACIÓN DE LA TERMINOLOGÍA VIENE A COMPLICAR Y AÚN A OSCURECER MUCHO LAS INTERPRETACIONES DEL ORIGEN DE NUMEROSOS YACIMIENTOS (LEPTOTERMAL, XENOTERMAL).

EN LA FIG. 2 (JENSEN Y BATEMAN) SE EXPRESA DE MANERA MUY CLARA EL CAMBIO DE MINERALIZACIONES A PARTIR DEL GRANITO DE ALTA TEMPERATURA QUE COINCIDE EXACTAMENTE CON EL "SISTEMA DE VETAS RECONSTRUÍDO DESDE LA SUPERFICIE HACIA ABAJO" PROPUESTO POR EMMONS EN LA PAG. 196 DE SU LIBRO "PRINCIPLES OF ECONOMIC GEOLOGY, 1940". AMBOS ESQUEMAS COINCIDEN AMPLIAMENTE AL PROPUESTO POR FERSMAN PARA EL ZONEAMIENTO PERIPLUTÓNICO (ROUTHIER, PAG. 471) A EXCEPCIÓN DE LA ZONA DE ORO Y PLATA REPETIDA ENTRE LA ZONA DE PLATA, PLOMO Y LA DE ANTIMONIO. SOBRE ESTO INSISTIREMOS MÁS ADELANTE. A CONTINUACIÓN SE PRESENTA EL ESQUEMA DE EMMONS.

"SISTEMA DE VETAS RECONSTRUÍDO DESDE LA SUPERFICIE HACIA ABAJO, EMMONS (1940)".

1.- ESTÉRIL: CALCEDONIA, CUARZO, BARITA, FLUORITA, ETC., ALGUNAS DE LAS VETAS CONTIENEN POCO MERCURIO, ANTIMONIO Y ARSÉNICO.

2.- MERCURIO: DEPÓSITOS DE CINABRIO COMUNMENTE CON CALCEDONIA, MARCASITA, ETC., Y VETAS DE BARITA-FLUORITA.

3.- ANTIMONIO: DEPÓSITOS DE ESTIBINITA CON FRECUENCIA PASAN HACIA ABAJO A GALENA, CON ANTIMONIATOS,ALGUNOS CON ORO ARRASTRADO.

4.- ORO-PLATA: DEPÓSITOS DE ORO DE BONANZA Y DEPÓSITOS DE ORO-PLATA ARGENTITA CON ARSÉNICO Y MINERALES DE ANTIMONIO COMÚNES. TELURUROS Y SELENIUROS IN SITU, ESTÁN PRESENTES RELATIVAMENTE PEQUEÑAS CANTIDADES DE GALENA, ESFALERITA Y CALCOPIRITA, LA GANGA INCLUYE CUARZO,

ADULARIA, ALUNITA CON CALCITA, RODOCROSITA Y OTROS CARBONATOS.

5.- ESTÉRIL: LOS MÁS CERCANOS A LA ZONA ESTÉRIL REPRESENTAN EL FONDO DE MUCHAS VETAS DE METALES PRECIOSOS TERCIARIOS; CUARZO, CARBONATOS, ETC., CON PEQUEÑAS CANTIDADES DE PIRITA, CALCOPIRITA, ESFALERITA Y GALENA.

6.- PLATA: VETAS DE ARGENTITA, COMPLEJOS MINERALES DE PLATA CON ANTIMONIO Y ARSÉNICO, ESTIBINITA ALGO DE ARSENOPIRITA, ETC., GANGA DE CUARZO IN SITU CON SIDERITA.

7.- PLOMO: VETAS DE GALENA, GENERALMENTE CON PLATA, ESPALERITA GENERALMENTE PRESENTE, INCREMENTADA CON LA PROFUNDIDAD, ALGO DE CALCOPIRITA, GANGA DE CUARZO CON CARBONATOS.

8.- ZINC: DEPÓSITOS DE ESFALERITA, GALENA Y ALGO DE CALCOPIRITA GENERALMENTE PRESENTE, LA GANGA ES CUARZO Y EN ALGUNOS DEPÓSITOS, CARBONATOS DE CALCIO, HIERRO Y MANGANESO.

9.- COBRE: TETRAEDRITA, COMUNMENTE ARGENTÍFERA, CALCOPIRITA, ALGUNOS PASAN HACIA ABAJO DENTRO DE CALCOPIRITA, VETAS DE ENARGITA GENERALMENTE CON TETRAEDRITA.

10.- COBRE: VETAS DE CALCOPIRITA LA MAYORÍA CON PIRITA, MUCHAS CON PIRROTITA LA GANGA ES CUARZO Y EN ALGUNOS LUGARES CARBONATOS Y FELDESPATOS, LA ORTOCLASA Y PLAGIOCLASA SÓDICAS NO SON RARAS, PERO LAS PLAGIOCLASAS CON BASTANTE CONTENIDO DE CALCIO SON MUY RARAS. GENERALMENTE ARRASTRA METALES PRECIOSOS.

11.- ORO: DEPÓSITOS CON PIRITA (COMUNMENTE ARSENOPIRITA), CUARZO Y CARBONATOS Y ALGUNOS FELDESPATOS DE GANGA. ALGUNOS CON TURMALINA, LOS TELURUROS COMÚNES E IN SITU ABUNDANTES. IN SITU, ZONAS 10 Y 11 SON REVERSIBLES.

12.- Arsénico: Arsenopirita con calcopirita, etc.

13.- Bismuto: Depósitos de bismutinita, bismuto nativo, cuarzo, pirita, etc.

14.- Tungsteno: vetas con minerales de tungsteno, arsenopirita, pirrotita, pirita y calcopirita. El tungsteno ocurre en las zonas más altas en cantidades acomodadas a lo largo, pero éste es el principal horizonte.

15.- Estaño: vetas de casiterita con cuarzo, turmalina, topacio y feldespatos.

16.- Estéril: cuarzo, feldespatos, pirita, carbonatos y pequeñas cantidades de otros minerales.

A.- YACIMIENTOS ENDOGENOS

- I.- YACIMIENTOS MAGMÁTICOS PROPIAMENTE DICHOS
  - 1.- YACIMIENTOS ORTOMAGMÁTICOS
  - 2.- YACIMIENTOS RECIENTES (TARDEMARGAMATICOS)
  - 3.- YACIMIENTOS DE LICUACIÓN
- II.- PEGMATITAS
- III.- POST-MAGMATICOS
  - 1.- PNEUMATOLÍTICOS
    - A) POR EXHALASIÓN
    - B) DE SKARNS
  - 2.- YACIMIENTOS HIDROTERMALES
    - A) DE PROFUNDIDADES MEDIANAS Y GRANDES, DE TEMPERATURAS ELEVADAS, MEDIANAS Y BAJAS.
    - B) DE POCAS PROFUNDIDADES Y VECINOS DE LA SUPERFICIE.

B.- YACIMIENTOS EXOGENOS

- I.- DE ALTERACIÓN
  - 1.- DE CONCENTRACIÓN - ELUVIALES Y DILUVIALES
  - 2.- RESIDUALES
    - A) ARCILLAS - CAOLINES Y LATERITAS
    - B) TIPO SOMBRERO DE FE
  - 3.- DE INFILTRACIÓN
- II.- SEDIMENTARIOS
  - 1.- DEPÓSITOS MECÁNICOS
    - A) MINERALES DE ALUVIÓN Y CONGLOMERÁTICOS
    - B) DEPÓSITOS REACOMODADOS DE PRODUCTOS DE EROSIÓN DISPERSOS.

2.- DEPÓSITOS QUÍMICOS

- A) PROVENIENTES DE VERDADERAS SOLUCIONES.
- B) PROVENIENTES DE SOLUCIONES COLOIDALES.
- C) BIOQUÍMICOS

C.- YACIMIENTOS METAMORFOGENOS

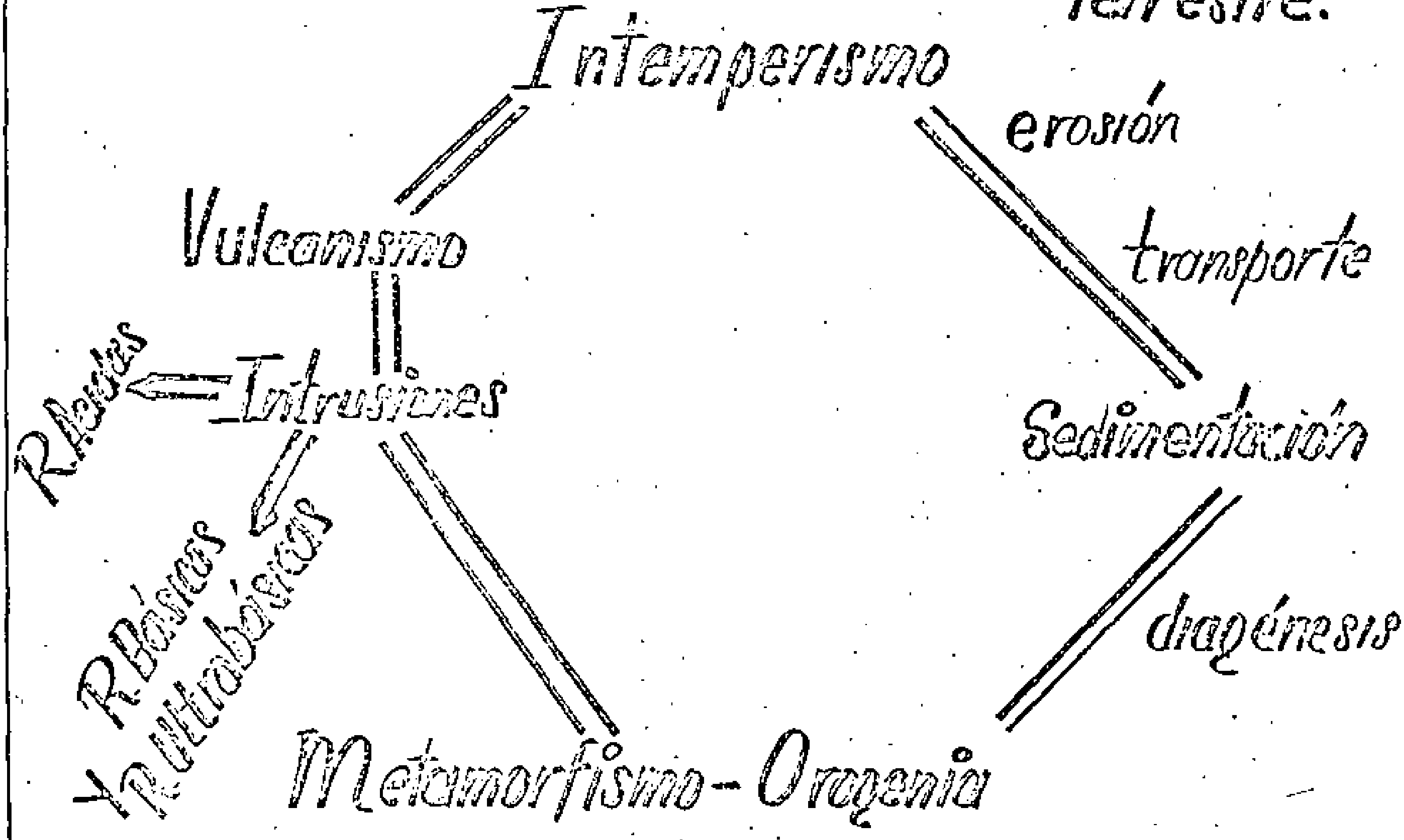
1.- METAMORFOSEADOS

2.- METAMÓRFICOS

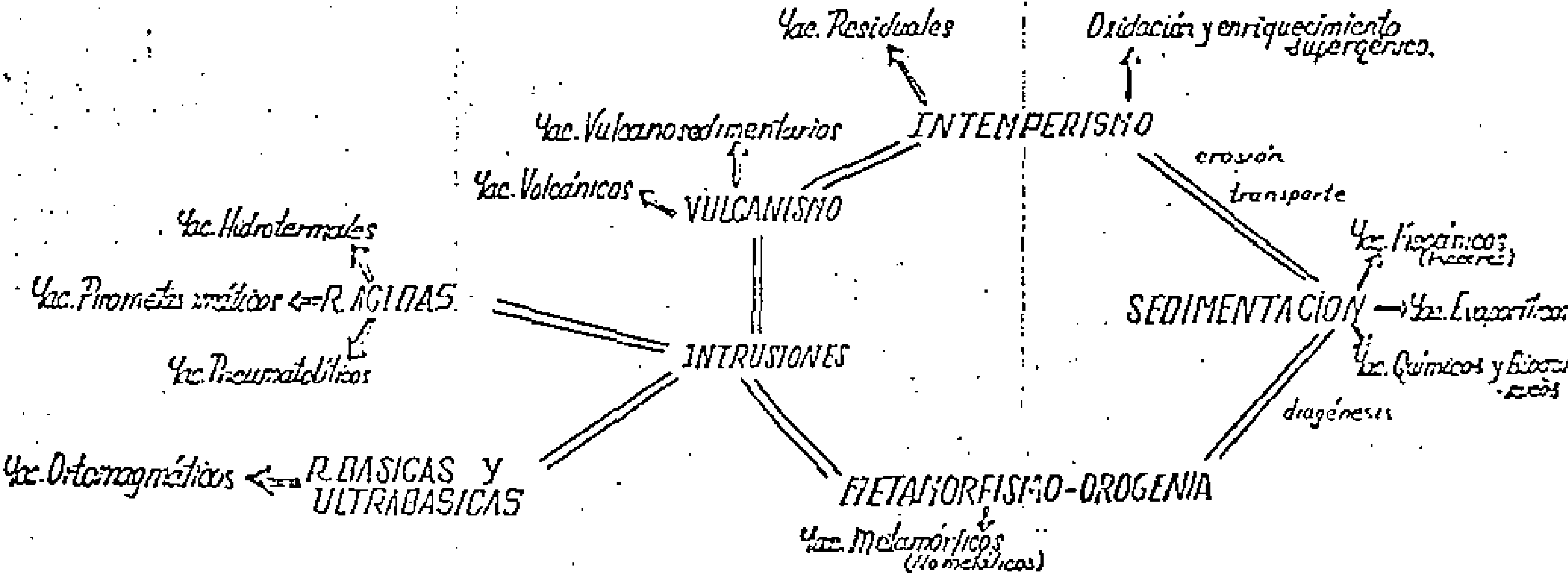
Clasificación propuesta por BATEMAN - JENSEN

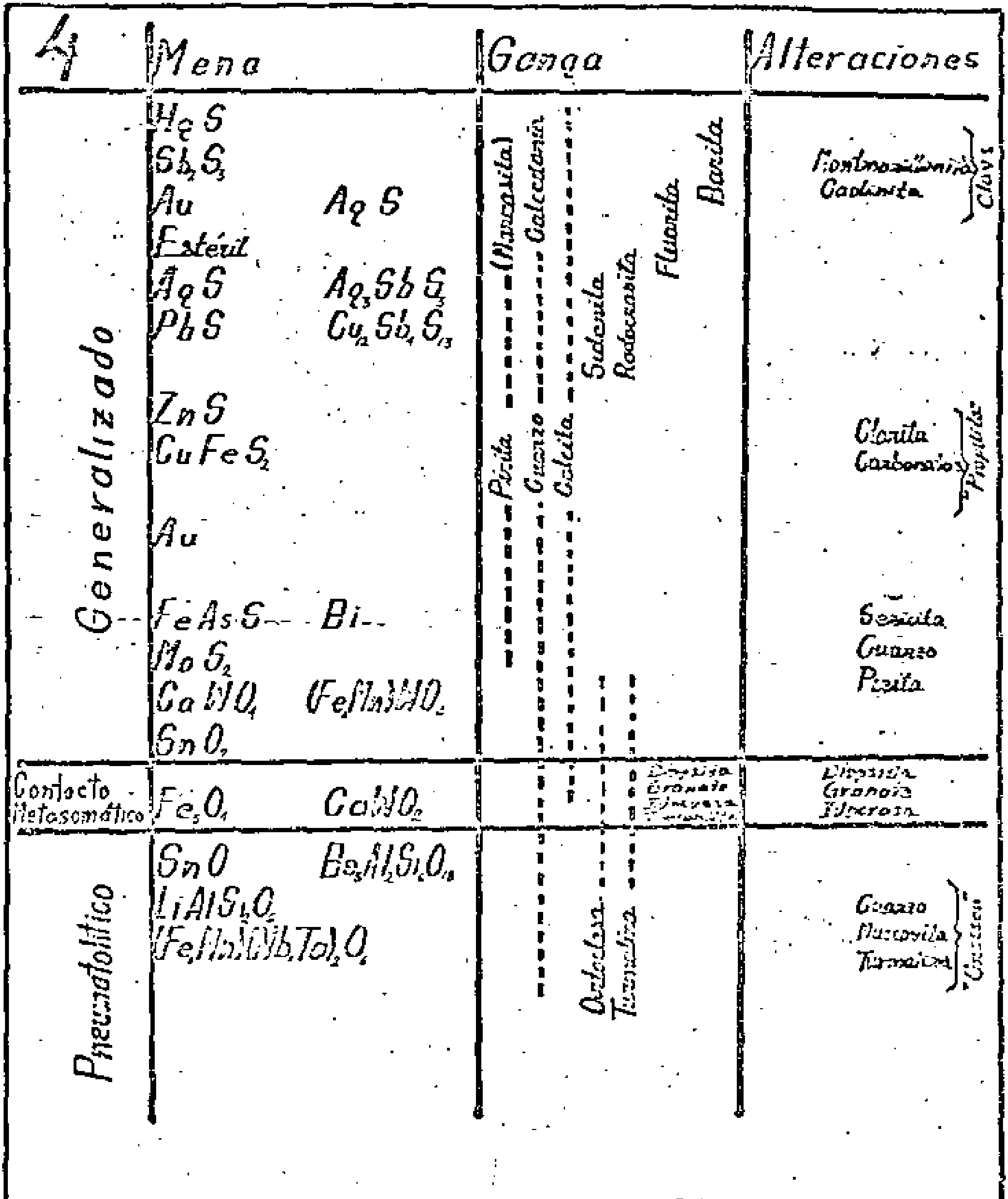
Procesos	Depósitos.	Ejemplos
1.- Concentración magmática altas T y P	I. MAGMATISMO TEMPRANO	Diamond pipes.
	A. Cristalización diseminada	Chromite [illegible]
	B. Segregación	Kiruna Magnetita
	C. Inyección	
	II. MAGMATISMO TARDÍO	
	A. Segregación de líquidos residuales	Taberg magnetita
	B. Inyección de líquidos residuales	Adirondack
	C. Segregación de líquidos inmiscibles	Insizwa Sulfides
	D. Inyección de líquidos inmiscibles	Vlakfontein, S.A.
2.- Sublimación baja T y P	Sublimados	Sulfuros
3. Metamorfismo de contacto, int. baja y alta T y P	Contacto-metamórfico Fe, Cu, Ag etc.	Cornwall magnetita Morenci (Az.) Iron Springs Utah.
4. Hidrotermales		
A. Condiciones de bajas a altas T y P		
1.- Teletermal		
2. Epitermal }	6.- Xenotermal	
3. Leptotermal }		
4. Mesotermal		
5. Hipotermal		
(1) Cavidades rellenas.	Cavidades rellenas	
	A.- Vetas de fisuras	Pachuca Hgo.
	B. Depósitos en zonas de cizallamiento	Otago N.Z.
	C. Stockwork	Quartz Hill.
	D. Veta escalonada.	Morning Star Aus.
	E. Filón en silla	Bendigo Aus.
	F. Fracturas de tensión rellenas	Mississippi
	G. Brechas rellenas.	
	a1. volcánica.	Bassick pipe Col.
	b1. Tectónicas	Mascot Tennessee.
	c1. Colapso	Bisbee Arizona.
	H. Cavidades de disolución rellenas	
	a1. cuevas y canales	Wisconsin Illinois
	b1. filón irregular	Upper Mississippi
	I. Relleno de espacios porosos	
	J. Relleno vesicular.	
(2) Reemplazamiento baja a alta T y P	Reemplazamiento	
	A1. Masivo	Bisbee Copper
	B1. Fisura-filoniana	Kirkland Lake Gold.
	C1. Diseminados	Porphyry Coppers
5. Sedimentación (excluye evaporación) baja T y P	Sedimentarios Fe. Mn.	Clinton Iron Ores.
6. Bacteriogénicos	Productos bacteriales o reducción	Azufre y domos salinos. Gulf-Coa
7. Vulcanismo Exhalativo submarino baja a alta T y P	Vulcanismo Submarino	Manganese nodules Kuroko deposits
8.- Evaporación baja T y P	Evaporitas	
	A. Marina	Yeso, sal, potasa
	B. Lacustres	Naco, Borato
	C. Agua subterránea.	Chile Nitratos
9.- Concentración mecánica y residual baja T y P		
A1. Conc. residual	Depósitos residuales Fe. Mn. Bauxita	Lake Superior Iron Ores. Gold Coast - Manganese.
B1. Conc. Mecánica	Placeres	
	A1. Fluvial	Calif. Placeres.
	B1. Playa	Nome. Alaska Gold.
	C1. Eluvial	Dutch East Indies
	D1. Eólico	Australian Gold.
10. Enriquecimiento supergénico y oxidación superficial baja T y P	Oxidación. Sulfuros supergénicos.	Chuquicamata Chile Ray Arizona Copper
11. Metamorfismo int. a alta T y P	A1. Depósitos metamorfoseados	Broken Hill Gore
	B1. Depósitos metamórficos	Grafito, asbesto, talco, Soapstone, Sillimanite group, Granate

Fenómenos Geológicos que se presentan en la corteza terrestre.



Los Yacimientos minerales y su relación con los grandes fenómenos geológicos





Zonecmiento segun BATEMAN (1979) modificada

ASOCIACIONES DE ELEMENTOS QUIMICOS CON LAS ROCAS DE LA CORTEZA TERRESTRE

P.M. Tatarinov.

1_ROCAS ULTRA-BASICAS. (Peridotitas-Dunitas)

a)_Cr. Fe. Mg (Cromita, Serpentina)
b)_Cr. Fe, Pt y metales de su Grupo
c). Asbesto talco. magnesita (Mg. Si. H. O. C)

2.-ROCAS BASICAS (Gabro, Noritas, Diabasas)

a)_Fe. Ti. V (Magnetita e Ilmenita en gabros)
b)_Fe. Cu. Ni. Co. Pt, Pd. S. O (Pirrotita, calcopirita, pentlandita, magnetita en las noritas y diabasas de olivino.

3 ROCAS ALCALINAS (Sienitas y sienitas nefelínicas)

P. Fe. F. algunas veces Zr. Ti, Nb., T.R.
(apatita. Magnetita. minerales de tierras raras)

4.-ROCAS ACIDAS (Granitos, Granodioritas, Dioritas cuarcíferas)

a) W. Mo. Sn. F. Li. B. algunas veces Be. Bi. Nb. Ta. en las pegmatitas graníticas
b)_Fe. W. Mo. Cu. Sn. en formaciones de contacto

5.-FORMACIONES HIDROTERMALES LIGADAS GENETICA- A ROCAS INTRUSIVAS ACIDAS

a)_Au. Fe. S. As. (Yacimientos auríferos arsenicales)
b)_Zn. Pb. Ag. y a veces Cu. Ba Cd. Sn, Ga, (yacimientos Polimetálicos
c)_Ag Co. Ni. Bi. U. a veces Cu. Fe As. (Yac. de Uranio)
d)_Au. Ag. Te. Se. (Yac de Teluros de oro y plata)
e)_Hg, Sb. S. F a veces As (Yac. de Antimonio con Fluorita)

6.-YACIMIENTOS RESIDUALES.

a) Fe. Mn. a veces Ni. Co. Mg. Cr
b) Al. Fe.

7.-FORMACIONES MARINAS SEDIMENTARIAS.

a)- Fe. Mn.
b)- Al. Fe (Bauxitas)
c)- P. F. Ca (Fosforitas)
d)- V. U. Cu.

8.-FORMACIONES SEDIMENTARIAS

a) Na. Ca. Mg. K. Cl. S. C. H. O. b)- B. Na. Ca. Mg

CARACTERISTICAS-PERTENECIENTES AL YACIMIENTO

I Paragénesis Hipogénica y eventualmente sucesión

II Alteración superficial y minerales supergénicos resultantes

III Composición Química y Leyes del mineral

IV Tonelaje del mineral o mejor tonelaje extraído mas reservas o cualquier dato susceptible de dar una idea de la importancia económica del tipo

CARACTERISTICAS-PERTENECIENTES A LA ROCA ENCAJONANTE

V Naturaleza litológica y petrográfica de las rocas encajonantes

VI Forma de los yacimientos en relación con la estructura de las rocas encajonantes

VII Rocas Plutónicas y/o volcánicas próximas

VIII Edad del Yacimiento y recapitulación de la Historia Geológica del lugar o región

IX Ejemplos similares y de ser posible la edad de los yacimientos

X Hipótesis genéticas relativas, sea al tipo, sea a un yacimiento particular del tipo

FICHA DE YACIMIENTOS MINERALES

(P. Routhier, 1963)

DIVISION DE EDUCACION CONTINUA
FACULTAD DE INGENIERIA U.N.A.M.

CLASIFICACION ACTUALIZADA DE YACIMIENTOS MINERALES

CLASIFICACION GENETICA DE DEPOSITOS MINERALES

ING, GERMAN ARRIAGA GARCIA

ABRIL, 1981

3.3. CLASIFICACION GENETICA DE DEPOSITOS MINERALES

SEGUN V: I: SMIRNOV

SERIE	GRUPO	CLASE	SUBCLASE
Endógeno	Magmático	Segregación	
		Magmático Temprano	
		Magmático Tardío	
	Pegmatítico	Magmático	
		Pegmatitas recristalizadas	
		Pegmatitas con reemplazamiento metasomático	
	Carbonatitas	Magmáticas	
		Metasomático	
		Combinado	
	Skarn	Skarn en calizas	
		Skarn magnesiano	
		Skarn silicatado	
	Greisen-albítico	Albítita	
		Greisen	
	Hidrotermal	Plutogénico	
		Vulcanogénico	
		Teletermal	
	Pirítico	Metasomático	
		Volcanogénico - sedimentario	
		Combinado	

4. LOS FENOMENOS GEOLOGICOS Y LOS YACIMIENTOS MINERALES ASOCIADOS

El observar a los yacimientos constantemente en su relación con los grandes fenómenos geológicos que afectan la corteza terrestre será uno de los propósitos mas apropiados que son originados al realizar la prospección minera. Es natural que la asociación:

Fenómeno
Geológico

Yacimiento
Mineral

La correspondencia entre ambos acontecimientos es evidente. Un fenómeno geológico determinado puede ser el origen de un yacimiento mineral bien definido. Asimismo, la asociación de los diferentes elementos químicos en relación con rocas de composición y textura definidas es constante.

Por tanto, un yacimiento mineral queda enmarcado dentro de un cuadro geológico establecido con rocas encajonantes de una composición específica.

En la figura 3, presento a ustedes un cuadro con el ciclo geológico simplificado donde están expuestos los grandes fenómenos que ocurren en la corteza terrestre. Naturalmente, estos fenómenos constituyen el marco donde se crearán los metalotectones que construiran los depósitos explotables.

En la siguiente figura (4) se exponen las relaciones entre los emplazamientos de las mineralizaciones y sus conexiones con las deformaciones de la litosfera: Es decir, las concentraciones minerales se originan en momentos diversos del ciclo geológico y su esmente sino de relevante importancia para la prospección minera, conocida en este sentido como prospección aluvionar.

2.- La sedimentación por evaporación.

Aquí se tienen los depósitos salinos, bastante abundantes en el sureste del País con una amplia gama de minerales generados a partir de la precipitación de las aguas marinas debido a la evaporación.

Con respecto a los depósitos de Azufre, es necesario notar la curiosa clasificación reciente de Jensen y Bateman donde, en capítulo aparte menciona a los depósitos "bacteriogénicos" como una "renovación" en las hipótesis genéticas. Con esto se podrá completar insuperablemente las clasificaciones genéticas de los yacimientos minerales. Ahora, el origen del azufre de domos salinos es enmarcado explendidamente en dos apartados diferentes: "yacimientos evaporíticos" y "yacimientos bacteriogénicos".

3.- La sedimentación química .

En este capítulo es donde se suele aceptar la acción biogénica combinada con la química para las hipótesis genéticas sobre los yacimientos producidos por la alteración de los materiales de la corteza terrestre, su transporte y depósito.

Ejemplos: Yacimientos de Fe mas grandes del mundo,
Manganeso, etc.

4.4. Metamorfismo

En general, el metamorfismo puede afectar a las concentraciones previamente formadas por otros metalotectones; en ocasiones, La forma de asociación pude ser:

Diseminaciones

Segregaciones:

- Cuerpos irregulares
- Cuerpos estratiformes

Inyecciones en la vecindad inmediata

Estos diversos modelos de mineralizaciones se presentan persistentemente en tipos bien definidos:

Por ejemplo:

El cromo y el platino se asocian a rocas peridotíticas y dunitas.

El niquel - cobalto - cobre en sulfuros se asocian a noritas.

La ilmenita es frecuente en anortositas.

4.5.2. ROCAS GRANITICAS

En este grupo de rocas se inserta una amplia gana de yacimientos minerales. Por tanto, puede hablarse de una compleja metalogenia asociada al granito algunos autores (Tatarinov) la denominan yacimientos post-magmáticos.

Por granito, debe entenderse todas las clases de rocas ácidas: granito alcalino, granito calcoalcalino, cuarzomonzonita, granodiorita y cuarzodiorita.

Sin embargo, puede hablarse de asociaciones mas o menos constantes:

A. Granitos alcalinos y calcoalcalinos:

Pegmatitas

Pneumatolíticos

Por el contrario los granitos originados por metamorfismo son normalmente estériles; estas rocas se insertan en regiones de metamorfismo regional, sus afloramientos son muy extensos y sus bordes son difusos.

4.6. VULCANISMO

En la clasificación que hemos visto de Jensen y Bateman como en la generalidad de las clasificaciones genéticas, el papel del vulcanismo es generalmente menospreciado. Sin embargo, en nuestro país numerosos yacimientos se encuentran asociados a rocas volcánicas de tipos muy variados. Algunos ejemplos serán suficientes para ilustrar esta aseveración.

- Uranio diseminado y en vetas en rocas riolíticas: El nopal y Las Margaritas en Chihuahua.
- Estaño en forma botroidal de casiterita y cristalizada en rocas riolíticas; numerosos ejemplos en Durango y Zacatecas.
- Fierro: en forma de magnetita con abundante apatita en cuerpos irregulares asociado a rocas riolíticas como Cerro de Mercado o traquíticas como en La Perla.
- Oro y plata en vetas. A este modelo pertenecen los célebres depósitos auro-argentíferos mexicanos. Ya se mencionan al inicio de la plática Guanajuato, Pachuca y Tayoltita.
- Fluorita en cuerpos irregulares en la vecindad del contacto entre rocas riolíticas y rocas carbonatadas. Ejemplos: El Rialito, Guanajuato, Las Cuevas, S.L.P.

En ciertos casos la paternidad de los yacimientos es atribuída a granitos con argumentos de muy dudosa validez como está bien discutido en el trabajo de L. Cepeda a propósito del origen de la mineralización de Guanajuato atribuída antiguamente al granito de Arperos.

Es grande el número de yacimientos volcánicos y subvolcánicos cuya fuente de origen o es totalmente desconocida o es atribuiída a cuerpos plutónicos con bases muy discutibles como en el caso de Guanajuato.

Por el contrario, existe una serie de metalotectones que permanecen constantes en las mineralizaciones vinculadas a las rocas volcánicas o subvolcánicas. A continuación se mencionan algunos de los más sobresalientes.

a) Las paragénesis que se manifiestan en cada modelo de yacimiento mineral es constante; a composición determinada de roca volcánica corresponde una misma asociación mineralógica. P. Eg: la casiterita con especularita en rocas riolíticas; el oro y la plata para las andesitas y dacitas, etc.

b).- La potencialidad de las mineralizaciones se mantiene similar en la mayor parte de los distritos mineros. No se pretende decir que se tenga un tonelaje idéntico, sino que constituyen distritos mineros con un contenido mineral equivalente. La generalidad de los ejemplos que se han mencionado son válidos en esta aseveración.

c) La proporción relativa de los elementos presentes en estos depósitos es constante; por ejemplo, los yacimientos considerados

5. METALOGENIA REGIONAL

El problema de agrupar a los distintos yacimientos minerales metálicos en áreas o provincias metalogénicas con criterios definidos es una tarea indispensable y a menudo menospreciada sobre todo en nuestro país. Es indudable que el conocimiento de provincias coherentemente seleccionadas y fundamentadas en los distintos metalotectones de acuerdo con su distribución en el espacio y en el tiempo, podrá orientar adecuadamente la prospección; en este sentido la metalogenia regional se interesa tanto en las agrupaciones de yacimientos conocidos como en el conjunto de estos y los que están por descubrirse en la corteza terrestre.

En México el problema de la Metalogenia regional permanece aún en una etapa muy incipiente; apenas se cuenta con una carta de repartición de yacimientos minerales y queda aún mucho por hacer para realizar una carta metalogénica a escalas convenientes para ser utilizados en la prospección minera.

Ha existido varios grupos de ideas tendientes a establecer una metalogenia regional a las cuales P. Routhier le da el nombre de Escuelas las cuales serían agrupadas bajo el calificativo de "estructuralistas". Sin embargo, pueden definirse 3 tipos diferentes.

1.- Escuela Crono-estructura-faciológica.

Esta escuela fundada por Bilibine y seguida por Tatarinov indica:

Toda región de la corteza continental ha sido un fragmento de un cinturón móvil (zona tecto-orogénica). Todo cinturón móvil se desarrolló a partir de una subsidencia alargada o geosinclinal en diversas etapas siguiendo un sistema casi inmutable hasta lle-

En este caso se hace caso omiso de el significado tectónico y se tienen la constancia esencial de la repartición de los yacimientos minerales en redes o elementos lineares y en donde en numerosas ocasiones la intersección de dos rasgos estructurales constituye un "nudo" mineralizado.

Actualmente este tipo de estudios se lleva a cabo por las fotos de satélites. Por medio de trazos de los lineamientos existentes se llegan a interpolaciones o extrapolaciones eventualmente útiles en la prospección de yacimientos por descubrir.

Este método (lineamientos a partir de fotos de satélites) puede, teniendo en cuenta los conocimientos previos de la metalogenia, y la geología y la tectónica, de una región, marcar en cierta forma la existencia de un metalotectón de orden estructural importante para determinado metal.

3.- Escuela de la Tectónica Global o Subduccionista.

Esta se establece sobre esquemas de la tectónica global y sobre las relaciones espaciales con las márgenes activas de los continentes y los planos de subducción.

Esto se ha establecido esencialmente por Sillit oc (1972) en la periferia del Océano Pacífico, de manera especial para los pórfidos cupríferos.

4.- Escuela Metálica.

Esta propuesta por Routhier pone de manifiesto el "olvido" de discontinuidades y heterogeneidades del emplazamiento y diversidades de los yacimientos minerales. El autor plantea un método analítico de la metalogenia regional fundamentada sobre una base de áreas metálicas en forma de cinturones con un contenido de

5.2.1. Recursos Marinos

Los recursos de minerales marinos son de lejos, enormes tal como lo han demostrado los estudios relativamente recientes que han efectuado en particular los científicos amercianos.

Ahora bien, hasta que punto es posible la explotación masiva de estos recursos sin romper el equilibrio ecológico existente en las aguas marinas.

Es indudable que los factores ciencia, tecnología aunados a la explosión demográfica como se señaló en la introducción, marcan una importante necesidad de materias minerales cada vez un mayor volúmen. Por tanto, en caso de ser el agua del mar una fuente para los recursos y dada su facilidad en una posible explotación económica con teconologías modernas ¿Hasta donde podrá el hombre extraer las sustancias minerales que necesita antes de que las condiciones favorables al desarrollo de la vida dejen de existir?

Tal vez esta pregunta pueda no ser contestada aún; sin embargo, es un hecho que se podrán ser explotados los recursos marinos hasta un límite razonable que siempre será bastante grande y que proveerá de recursos a la humanidad durante un buen numero de años.

5.2. La Corteza Terrestre y la Tectónica Regional

Ahora bien, en lo que se refiere a los recursos existentes en las Áreas continentales: ¿Hasta donde existen las reservas? De acuerdo con P. Routhier (Diciembre de 1977). Una hipótesis plausible sería el considerar que la explotación actual de los yacimientos minerales llegará a una media del orden de 300 metros. Por otra parte, se supone que solo la mitad (2) de los yacimientos que existen

DIVISION DE EDUCACION CONTINUA
FACULTAD DE INGENIERIA U.N.A.M.

CLASIFICACION ACTUALIZADA DE YACIMIENTOS MINERALES.

Syngenetic Massive Sulfide Deposits

Dr. Samnuel B Romberger

Abril, 1981

SYNGENETIC MASSIVE SULFIDE DEPOSITS

Syngenetic massive sulfide deposits belong to a distinct group of deposits having a set of characteristics which set them apart from other metalliferous hydrothermal deposits. The deposits essentually consist of chemical sediments where the metals are transported and deposited by hot aqueous solutions in a submarine hot spring environment. Deposition occurs typically at or near the ocean floor-seawater interface around a vent. Stockwork mineralization often occupies the feeder system below the massive sulfide body.

The source of the metals in these deposits is probably the enclosing, or footwall, volcanic rocks or sediments. Stable isotope studies on Tertiary massive sulfide deposits suggest the sulfur may be derived from seawater (Ohmoto and Rye, 1974). These same studies also suggest the solutions responsible for mineralization are heated deep circulating sea water. The heat responsible for driving the convecting hydrothermal system may be derived from local centers of cooling volcanic units or from a deeper magmatic source. However, some of these deposits occur in geologic environments lacking any evidence of magmatism which can be genetically related to the base metal mineralization.

Many massive sulfide deposits have experienced one or more periods of deformation and metamorphism where the sulfides have benn remobilized significantly. Replacement textures in the ores are common, however these can be interpreted as a result of recrystallization during metamorphism. These textures, along with cross-cutting relationships, resulted in the interpretation of these deposits as products of epigenetic replacement processes. The syngenetic origin for these deposits has become popular in recent years only after much geologic work on these and less disturbed occurrences. Detailed studies involving the interpretation of the geologic histories of mineralized areas have resulted in a better understanding of the regional and local environment of mineral deposition. As a result more and more sulfide deposits originally considered as epigenetic now are being reinterpreted as having syngenetic origins (Anderson and Nash, 1972).

Syngentic massive sulfide deposits occur in two major groups: those associated with volcanic rocks with which they are related genetically; and those which are not related to volcanism. The major difference between the two groups is the presence of volcanic rocks. There are also differences in the mineralogy of the ores which will be discussed later.

Volcanogenic Massive Sulfide Deposits

The volcanogenic deposits are the most numerous of the two types and are easiest to interpret. They occur in many volcanic terranes which can be interpreted as submarine in origin. The largest number of volcanogenic massive sulfide deposits have been found in the Precambrian shield of Canada where they occur in thick piles of metamorphosed submarine basaltic to rhyolitic volcanic rocks referred to as grenstone belts. Similar deposits are known in Precambrian rocks of South Africa and western Australia. Younger deposits occur in volcanic island arc sequences along the orogenic zones of the Appalachian chain in eastern North America and the western Cordillera of North and South America. These deposits range in age from early Paleozoic to early Mesozoic. Deposits of this tectonic setting and age also occur in eastern Australia. Still younger deposits occur in island arcs in western and southwestern Pacific regions, for example the mid-Tertiary Kuroko deposits of Japan. Finally, base metal sulfides are being deposited in present day submarine hot spring environments, primarily along the East Pacific Rise and mid-Atlantic Ridge (Francheteau, and others, 1979).

There appears to be a relationship between the composition, grade, age, and tectonic setting of the massive sulfide deposits. Hutchinson (1973) classified these deposits according to their base and precious metal content (Table 1). The most impressive of the types shown are the zinc-copper-pyrite deposits of Archean age. These probably represent the greatest concentration of base metals of any type of metalliferous deposits. The same type of deposits reappear during younger geologic periods, but is nowhere near the same scale as during the Archean. These deposits are best preserved on the stable Archean shields, particularly the Canadian shield. However, similar deposits occur in younger terranes in many parts of the World, but deformation, metamorphism, and remobilization have obscured their original syngenetic character. Such deposits occur in California, Arizona, Wyoming, and Colorado.

The lead-zinc-copper-pyrite type of deposit did not appear until Proterozoic time but even these do not have the size and

Table 1

COMPARATIVE CHART
SOME GEOLOGIC CHARACTERISTICS OF DIFFERENT VOLCANOGENIC SULPHIDE DEPOSITS

BASE METAL TYPE	PRECIOUS METAL ASSOCIATION	ASSOCIATED VOLCANIC ROCK TYPES	TYPE OF VOLCANISM	TYPE OF SEDIMENTATION	TECTONISM	AGE	EXAMPLES (age)
① Zn-Cu-pyrite	both Au (with high Cu) and Ag (with high Zn)	- fully differentiated suites of intermediate bulk composition(?); - basalt-andesite-dacite-rhyolite, etc.	initial deep subaqueous mafic platform; with differentiation toward felsic volcanism, building domical centres	- chemical; cherts, iron formations - clastic; immature, first cycle, volcanogenic greywackes	- early eugeosynclinal-orogenic stage; major subsidence	Archean	Timmins, Ont Noranda, Que United Verde, Ariz.
(3B) Zn-Cu-pyrite	ditto	ditto	ditto	ditto	ditto; early subduction	Phanerozoic	W Shasta, Calif. (Dev)
② Pb-Zn-Cu-pyrite	mainly Ag	- intermediate to felsic (calc-alkaline) volcanic suites; - andesite-dacite-rhyolite-porphyry-crystal tuff, etc.	- felsic centres of explosive, pyroclastic and ignimbritic activity, subaqueous to subaerial	- clastic predominates; immature volcanogenic greywackes, manganiferous shales, graphitic shales and argillites - chemical minor, cherts, iron formations	- later eugeosynclinal-orogenic stage; infilling with uplift balances subsidence(?)	- Proterozoic, early Paleozoic (?)	Mt Isa, Queensland Cons. Sudbury Basin, Ont
(3C) Pb-Zn-Cu pyrite	ditto	ditto	ditto	ditto	ditto; later subduction	Phanerozoic	Bathurst, New Brunswick (Ord) E Shasta, Calif. (Jurassic) Kuroko, Japan (Tertiary)
(3A) Cu-pyrite	mainly Au	- poorly differentiated mafic-ultramafic (ophiolitic) suites, - basaltic pillow lavas, serpentinite, etc.	- deep subaqueous quiescent fissure eruptions	- chemical predominates, cherts, ironstones, manganstones - clastic insignificant	- early stage of continental plate rifting; tension, separation, graben	Phanerozoic	Cyprus (Jurassic ?) W Newfoundland (Ord ?) Island Mountain, California (Jurassic ?)

grade as the zinc-copper-pyrite deposits of Archean age. This type occurs in Proterozoic to recent orogenic belts around the world.

The copper-pyrite type of massive sulfide deposit did not appear in the geologic record until Phanerozoic time. These deposits commonly occur along spreading centers characterized by basaltic volcanism. The various tectonic, petrologic, and geochemical characteristics of the various types of massive sulfide deposits are summarized in Table 1 from Hutchinson (1973). Because of their relatively well preserved nature and significance as metal producers, the Archean Deposits will be considered first.

Precambrian Volcanogenic Massive Sulfide Deposits

Rocks of Archean age are recognized on many continents around the World in stable cratonic shields or uplifted erosional windows in younger geologic terranes. Notable examples of the former are the Canadian, South African, and western Australia shields. Examples of the latter occur in Wyoming, Montana, and Arizona.

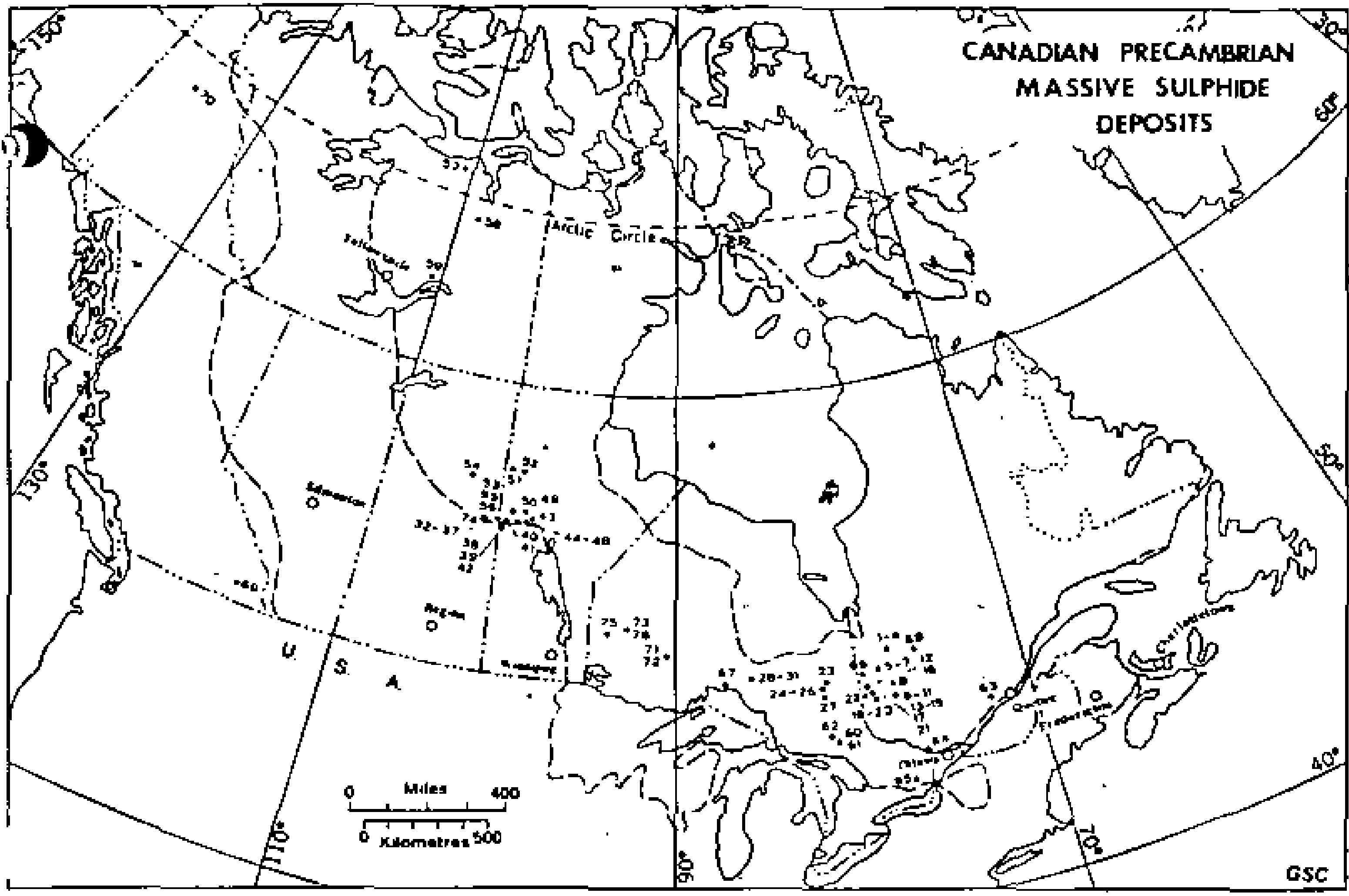
Archean time was a period of extensive volcanism and deposition of great thicknesses of sediments, mostly greywackes with minor iron formations. Volcanism occurred around specific centers or along belts where up to 60,000 feet of volcanic rocks are found. In many places volcanism appears to be contemporaneous with, and conformable to sedimentation. The volcanic units range in composition from ultramafic through basalt to rhyolite, where often basaltic rocks grade upward to more felsic volcanic units. However, reversals in this trend occur, and cyclicity in the volcanism is apparent. Locally, ultramafic intrusive and extrusive rocks are abundant and may be important hosts for nickel sulfide deposits. The entire sequence of volcanic and sedimentary rocks is metamorphosed to at least the greenschist facies, and in some cases to upper amphibolite facies. Some areas show multiple metamorphic events. The periods of volcanism and sedimentation are culminated by a major invasion of granitic plutons which are themselves often metamorphosed. This results in areas of volcanic and sedimentary rocks, called greenstone belts, separated by large areas of gneissic granite terrane. The most significant massive sulfide deposits occur in the volcanic complexes of these greenstone belts.

The greenstone belts of the three shield areas consist of ultramafic extrusive and intrusive rocks, mafic to volcanic rocks, and sedimentary rocks composed mostly of greywackes and iron formations. Even though the rock types of the three shield areas are similar, their relative proportions may vary. The Canadian shield appears to have been most favorable for the formation of massive sulfide deposits as this is where most of the known deposits occur. Syngenetic copper-zinc-pyrite deposits are associated with felsic volcanic rocks in thick piles of extrusive units ranging from basalt to rhyolite. Therefore these sulfide deposits would be most abundant in terranes containing a high proportion of felsic units.

A comparison of the relative abundance of the various rock in the Abitibi greenstone belt of the Canadian shield and the Barberton greenstone belt of South Africa reveals the following proportions: Abitibi belt: ultramafic rocks, 4.8%; basalt, 57%; andesite, 28%; felsite, 9.7%; Barberton belt: ultramafic rocks, 24%; basalt and andesite, 72%; and felsite, 3.7%. The greenstone belts of the Yilgarn and Pilbara blocks of western Australia appear to be similar to those of South Africa. Therefore, if the abundance of felsic volcanic units can be used as an indicator, the belts of the Canadian shield should contain more massive sulfide deposits than those of South Africa and Australia.

Massive sulfide deposits may not have formed in larger numbers on the Canadian shield. The latter may be exhibiting a higher stratigraphic level of preservation and the other shields may be more deeply eroded thus removing the horizons favorable for massive sulfides. Alternatively, the South African and Australian shields may be exhibiting a more primitive stage in the geochemical evolution of the crust and upper mantle as evidenced by the abundance of primitive ultramafic rocks. The rocks of the Canadian shield are as much as one billion years younger than those of the other two shields.

Figure 1 shows the distribution of massive sulfide deposits of the Canadian shield. The clustering of deposits into belts or areas is apparent. Basaltic volcanics and greywackes are the predominant lithologies in any one greenstone belts. Minor komatiitic, or high magnesium, ultramafic and basaltic units occur. Locally the basalts grade upward into andesite and rhyolite and more than one cycle may occur. The differentiation



1. Matt. Lake
2. New Hosco
3. Radiore
4. Orchan
5. Joutel
6. Mines de Poirier
7. North. Exp.
8. Barrute
9. Man.-Barvue
10. Louvem
11. East Sullivan
12. Vauze
13. W. MacDonald
14. Waite
15. Amulet
16. Lake Dufault
17. Millenbach
18. Quemont
19. Horne
20. Delbridge
21. Mobrun
22. Aldermac
23. Texas Gulf Sulphur (Kidd Creek)
24. Jameland
25. Kam-Kotia
26. Cndn. Jamieson
27. Genex
28. Geco
29. Willecho
30. Willroy
31. Nama Creek
32. Flexar
33. Coronation
34. Flin Flon
35. Schist Lake
36. Mandy
37. Birch Lake
38. White Lake
39. Cuprus
40. North Star
41. Don Juan
42. Centennial
43. Osborne Lake
44. Stall Lake
45. Rod
46. Anderson Lake
47. Ghost Lake
48. Chisel Lake
49. Dickstone
50. Wim
51. Fox Lake
52. Ruttan Lake
53. Sherridon
54. Brabant
55. Bob Lake
56. Jungle
57. High Lake
58. Hackett River
59. Big Indian Mtn.
60. Errington
61. Vermillion
62. Geneva Lake
63. Tetrault
64. New Calumet
65. Syngenore
66. Normetal
67. Zenmac
68. Coniagas
69. Sullivan
70. Hart River
71. Mattabi
72. Sturgeon Lake-Mattabi
73. South Bay (Uchi Lake)
74. Western Nuclear
75. Trout Bay (Red Lake)
76. Copper-Man

Figure 1 (Sangster, 1972)

of the rock units appears to follow a normal calc-alkaline trend. Most of the volcanism appears to be deep marine and is characterized by pillowed flows, bedded tuffaceous units, ash beds, agglomerates and volcanic breccias. The latter occurrences typify the more felsic lithologies. Dikes and sills of mafic rocks are associated with the basalts, and shallow felsic intrusions may occur with the andesites and rhyolites. Iron formation and chert beds are common and represent chemical precipitates deposited by submarine hot springs. These deposits locally grade laterally into massive sulfide accumulations. The latter are usually associated with rhyolitic domes and breccias and mark the close of a basalt or andesite to rhyolite volcanic cycle. Many massive sulfide deposits can be related to a stratigraphic horizon which represents the sea floor during a period of quiescence where chemical sedimentation predominated over volcanism.

The largest greenstone belt of the Canadian shield, and perhaps in the World, is the Abitibi greenstone belt of eastern Ontario and northwestern Quebec (Fig. 2). The belt is 125 miles long and 47 miles wide and is bounded on the west by the Kapuskasing subprovince and on the east by the Grenville structural province (Fig. 3). The general geology of the belt is shown in Figure 4. Even within the belt, the volcanic rocks are concentrated in centers separated by areas of granite gneiss and metamorphosed sediments. The volcanic centers consist of thick sequences of volcanic rocks and associated sediments. Figure 5 outlines the volcanic centers and the distribution of felsic volcanic rocks within the centers. The felsic rocks constitute

Figure 2 Distribution of greenstone belts on the Canadian Shield

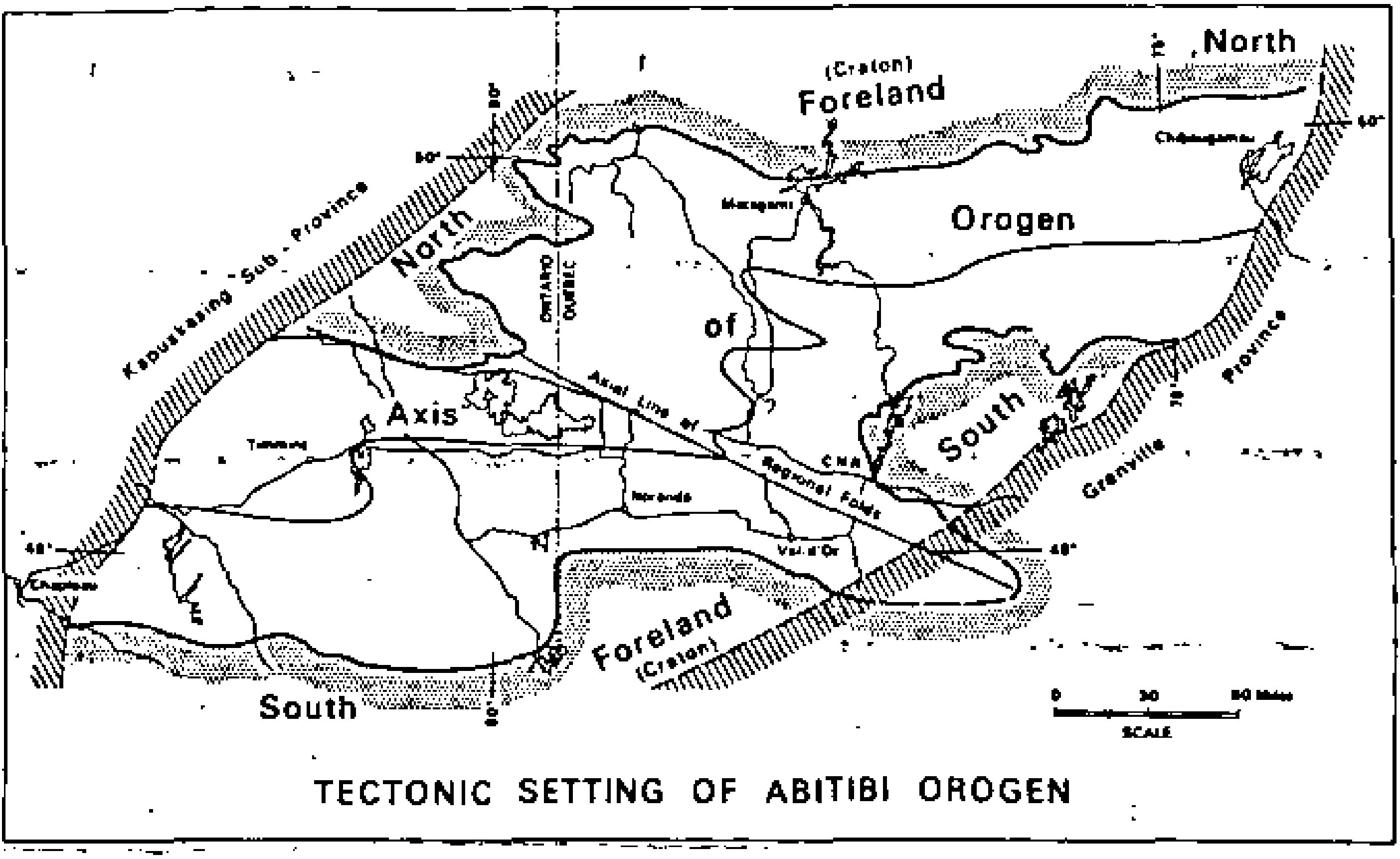


Figure 3 (Goodwin and Ridler, 1970)

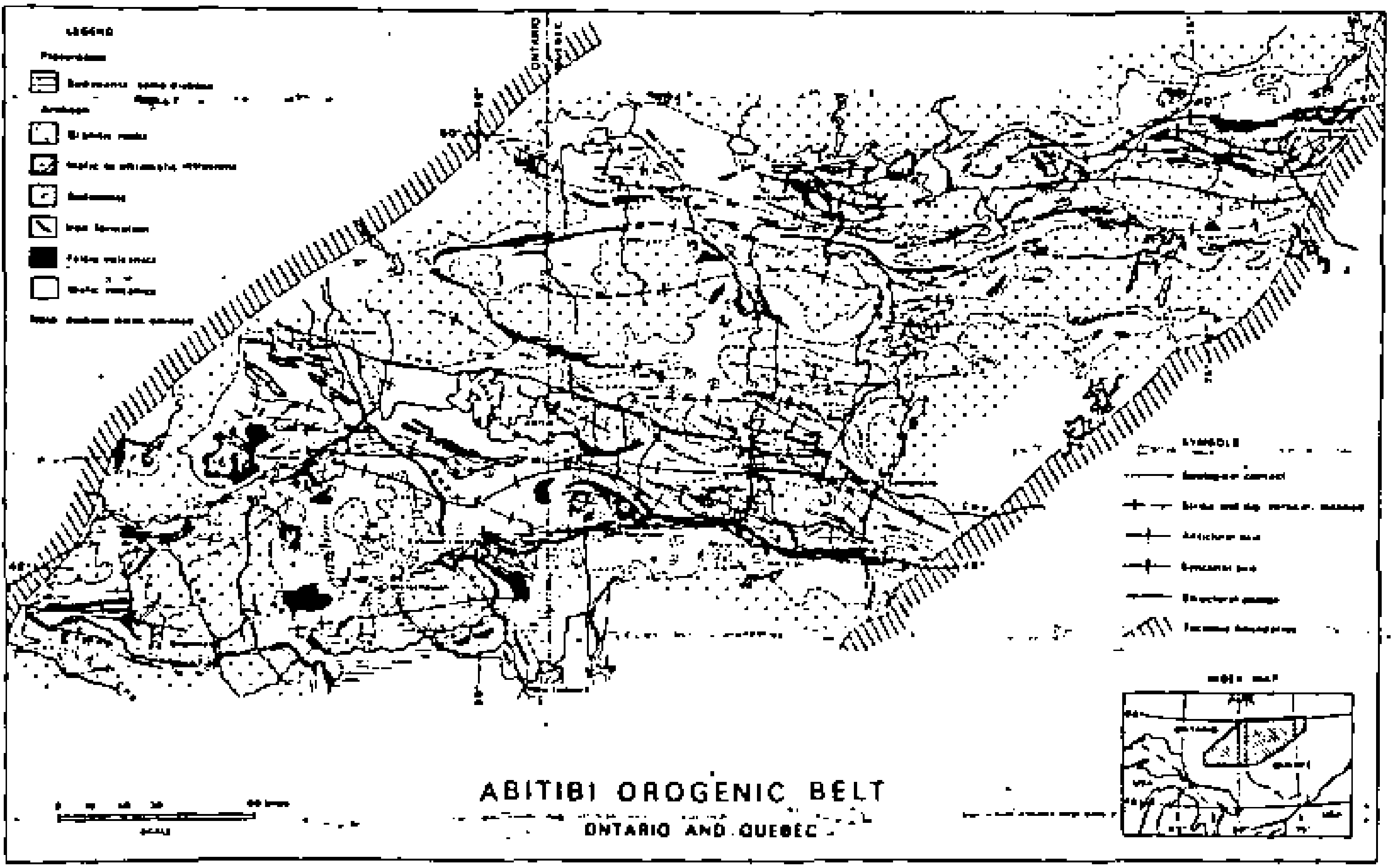


Figure 4 (Goodwin and Ridler, 1970)

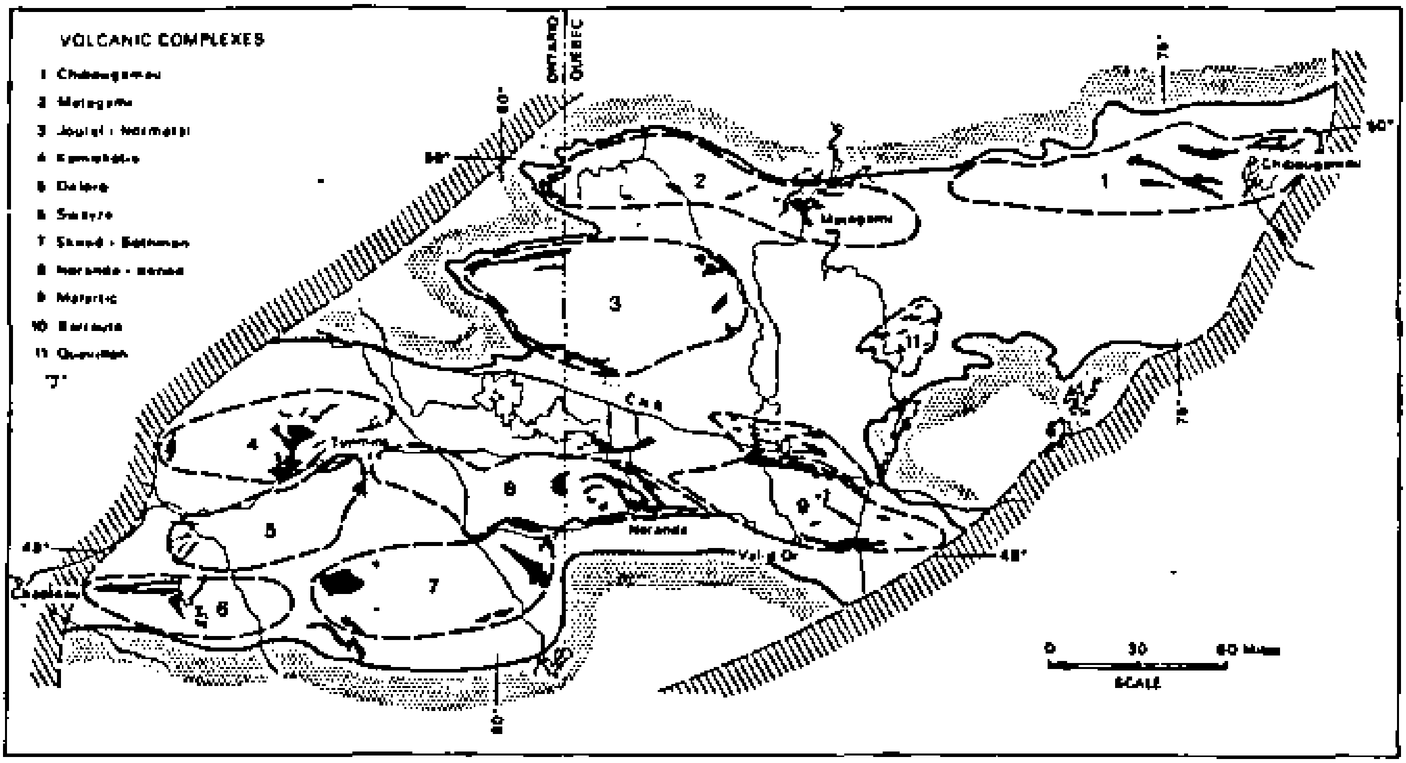


Figure 5 Distribution of Volcanic Complexes in the Abitibi Greenstone Belt (Goodwin and Ridler, 1970)

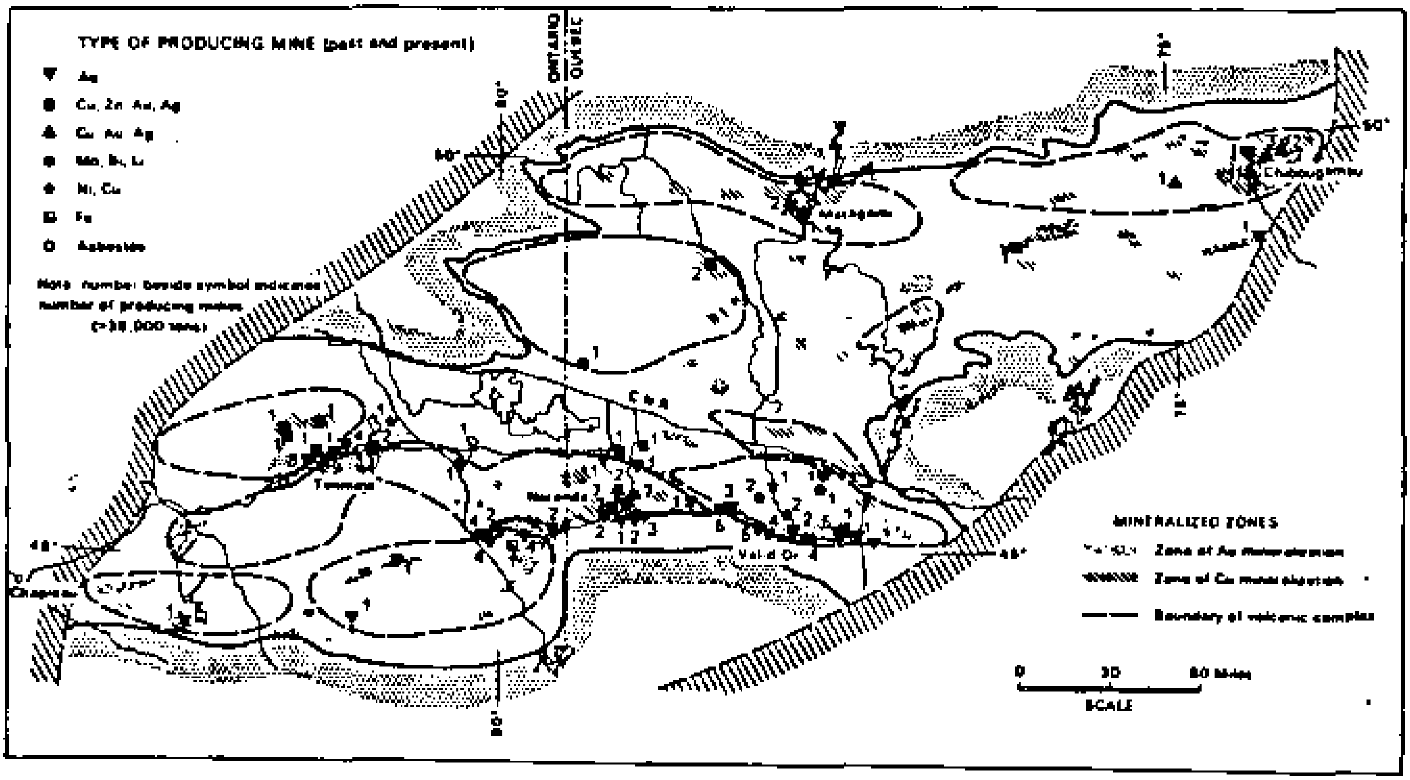


Figure 6 Distribution of Mineral Deposits in the Abitibi Greenstone Belt and Their Relation to Volcanic Complexes (Goodwin and Ridler, 1970)

only a very small proportion of the total volume of volcanic units. However, these felsic units are very important as the massive sulfide deposits show a close spatial relationship to them. The association of the mineral deposits with the volcanic centers is shown in Figure 6. Of approximately 150 past and present producing deposits, all but 3 occur in or near one of the 11 volcanic complexes. This is true for all mineral deposits and not just the massive sulfide deposits.

The structure of the Abitibi greenstone belt is dominated by east-west trending doubly plunging anticlines which are actually elongated domes centered about the thick volcanic sequences (Fig. 7). The intervening areas consist of granitic complexes of composite plutons ranging in composition from granite to diorite. It is thought that the elongated volcanic complexes were originally roughly circular and deformed into their present shape by later orogenic activity. Figure 8 is a hypothetical reconstruction of Abitibi orogenic belt at the time of volcanic activity. It consisted of an area of crustal thinning between 2 cratonic land masses where the volcanic complexes occur along the margins as a result of erosion of both the cratons and the volcanic islands (Goodwin and Ridler, 1970). Iron formations were widely deposited in the basin as shown in Figure 9. These are important because of their suggested relationship to gold mineralization in the area (Ridler,1970).

There are differences between the various volcanic complexes in terms of the relative proportions of volcanic rocks, clastic sediments, ultramafic rocks, and iron formation. There are

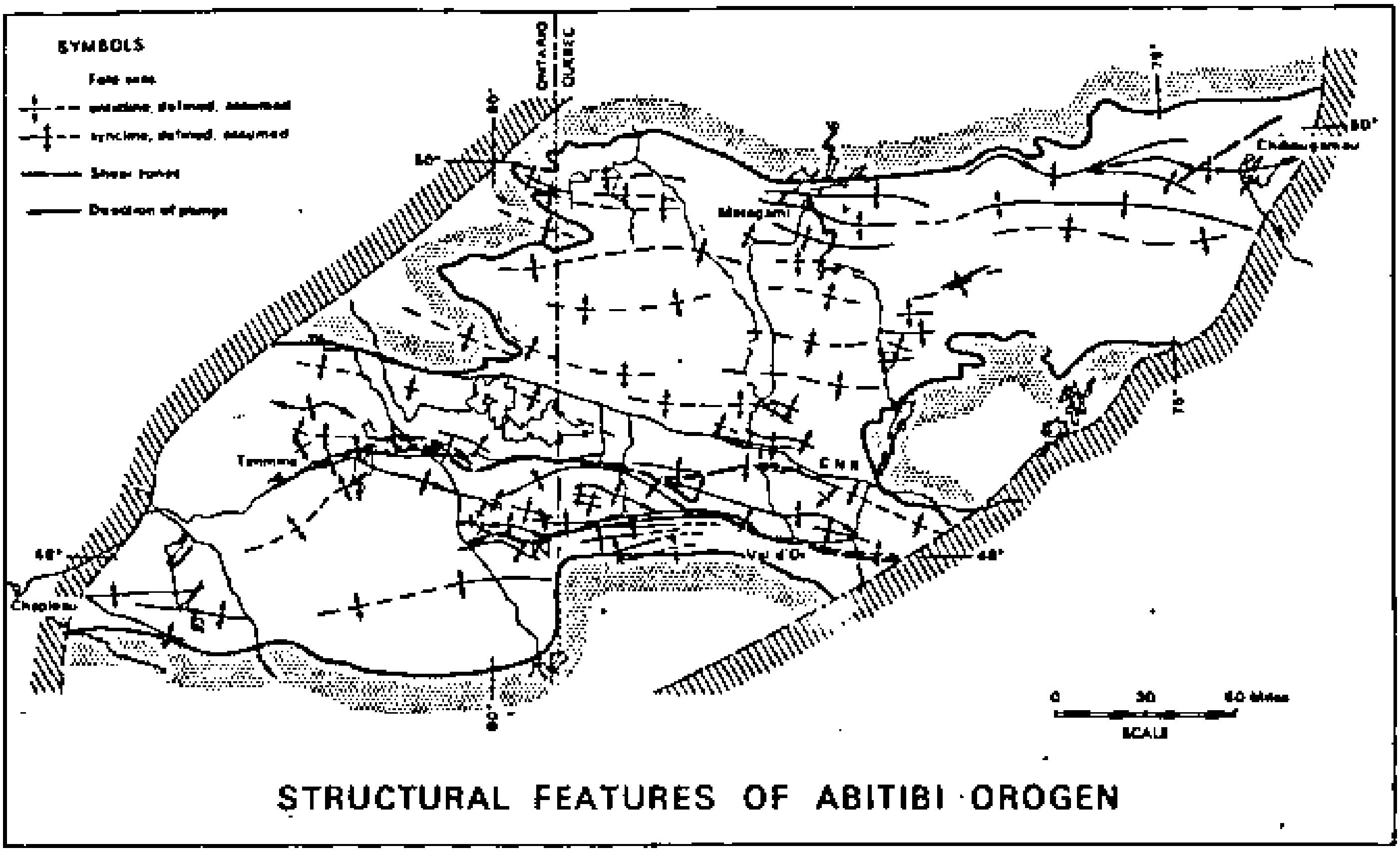


Figure 7 (Goodwin and Ridler, 1970)

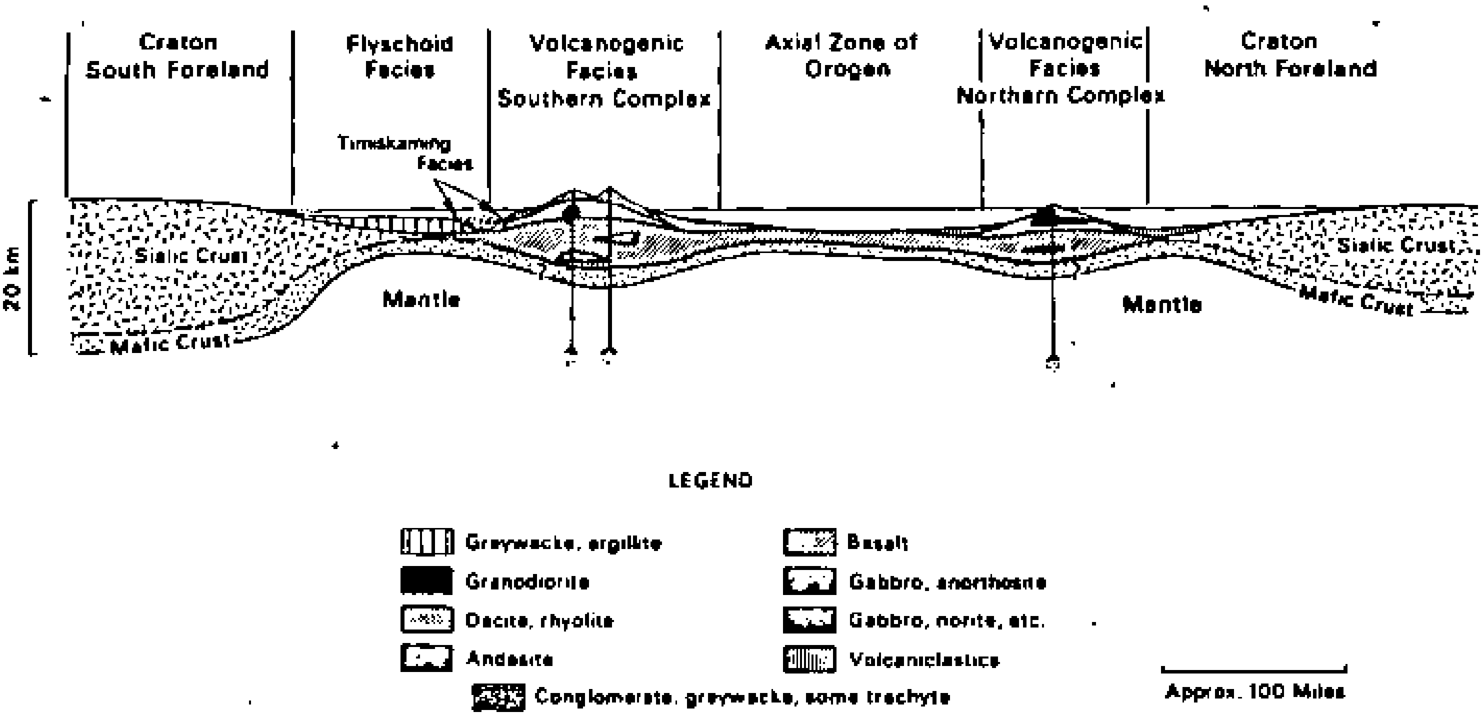
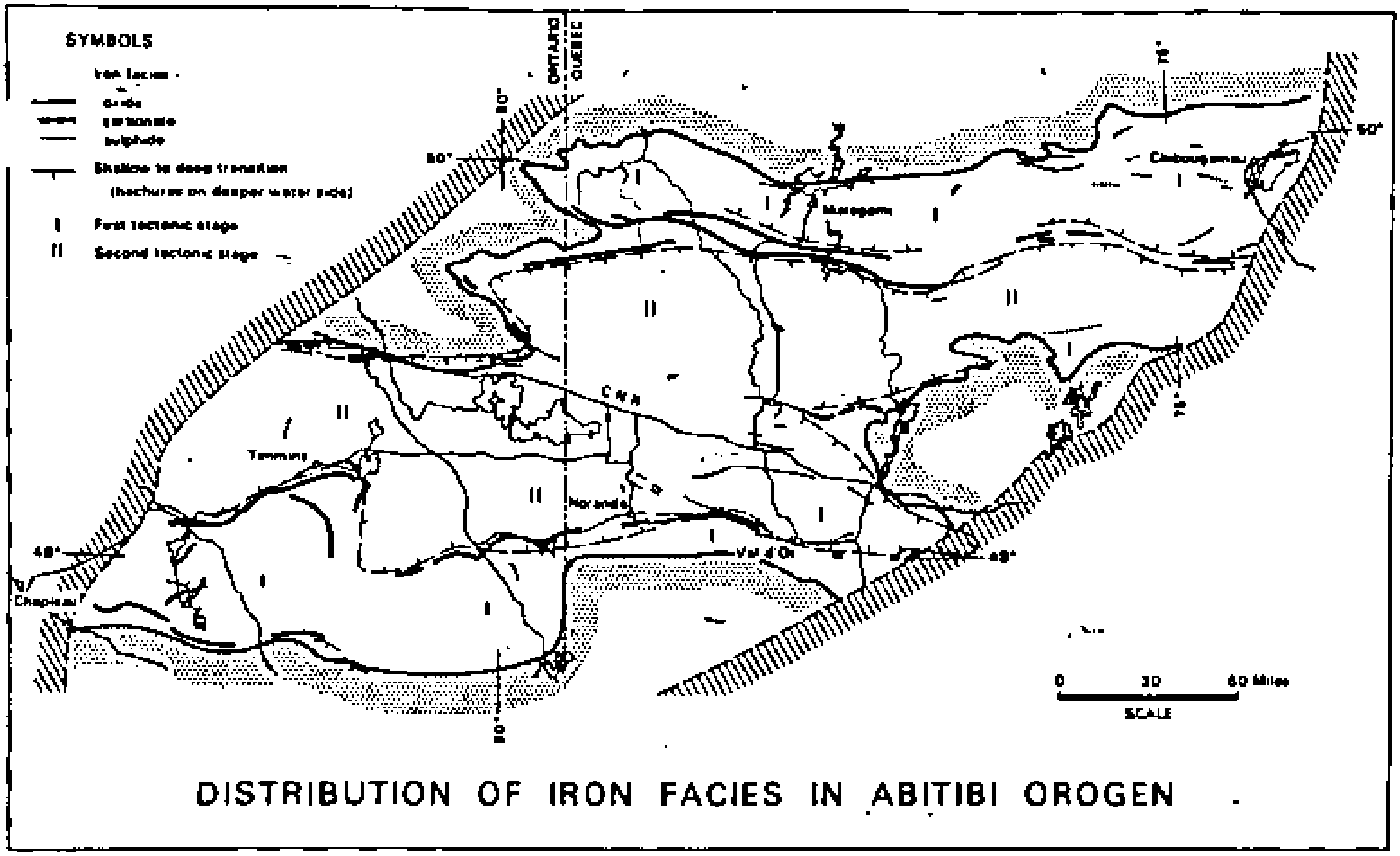


Figure 8 Hypothetical Reconstruction of the Abitibi Orogen (Goodwin and Ridler, 1970)



DISTRIBUTION OF IRON FACIES IN ABITIBI OROGEN

Figure 9 (Goodwin and Ridler, 1970)

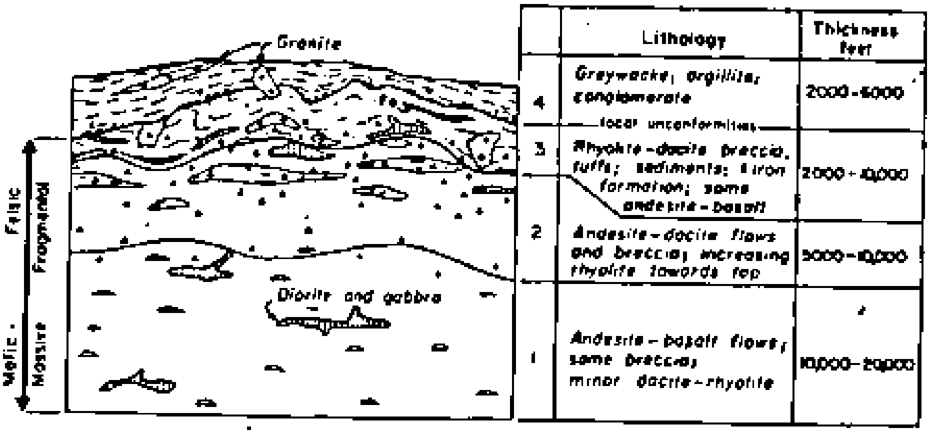


Figure 10 Diagrammatic Lithologic Section of an Archean Volcanic Complex in the Porcupine-Kirkland Lake-Noranda Region (Goodwin, 1965)

differences in the nature of the mineral deposits found in the various complexes also. This is particularly well illustrated in the Noranda-Kirkland Lake-Timmins areas which represent typical domed volcanic complexes (Goodwin, 1965; Fig. 10). Kirkland Lake and Timmins (Porcupine) have been important gold-producing districts where the gold occurs mostly in quartz veins along major east-west structural zones. These areas contain significant amounts of clastic sediments and iron formations. The Kidd Creek deposit is the only major massive sulfide deposit known in the Timmins area, and none is known in the Kirkland Lake area. Ultramafic intrusive and extrusive units are known in these areas and some contain significant nickel sulfide deposits.

The Noranda area is dominated by volcanic rocks and associated intrusions. Sediments are essentually absent in this area. The Horne and Quemont mines are the only significant gold producers in the Noranda area. These lie astride the eastern extension of the Kirkland Lake-Larder Lake break, a major structural feature containing important gold deposits to the west. The Noranda volcanic complex contains more known massive sulfide deposits than any other complex in the Abitibi belt (Fig. 6). These deposits are closely associated with felsic volcanic units which appear to be particularly abundant in this area.

Massive Sulfide Deposits of the Noranda District

Figure 11 illustrates the general geology of the Noranda area. The area is dominated by mafic to felsic volcanic rocks and associated intrusions. Spence and de Rosen-Spence (1975)

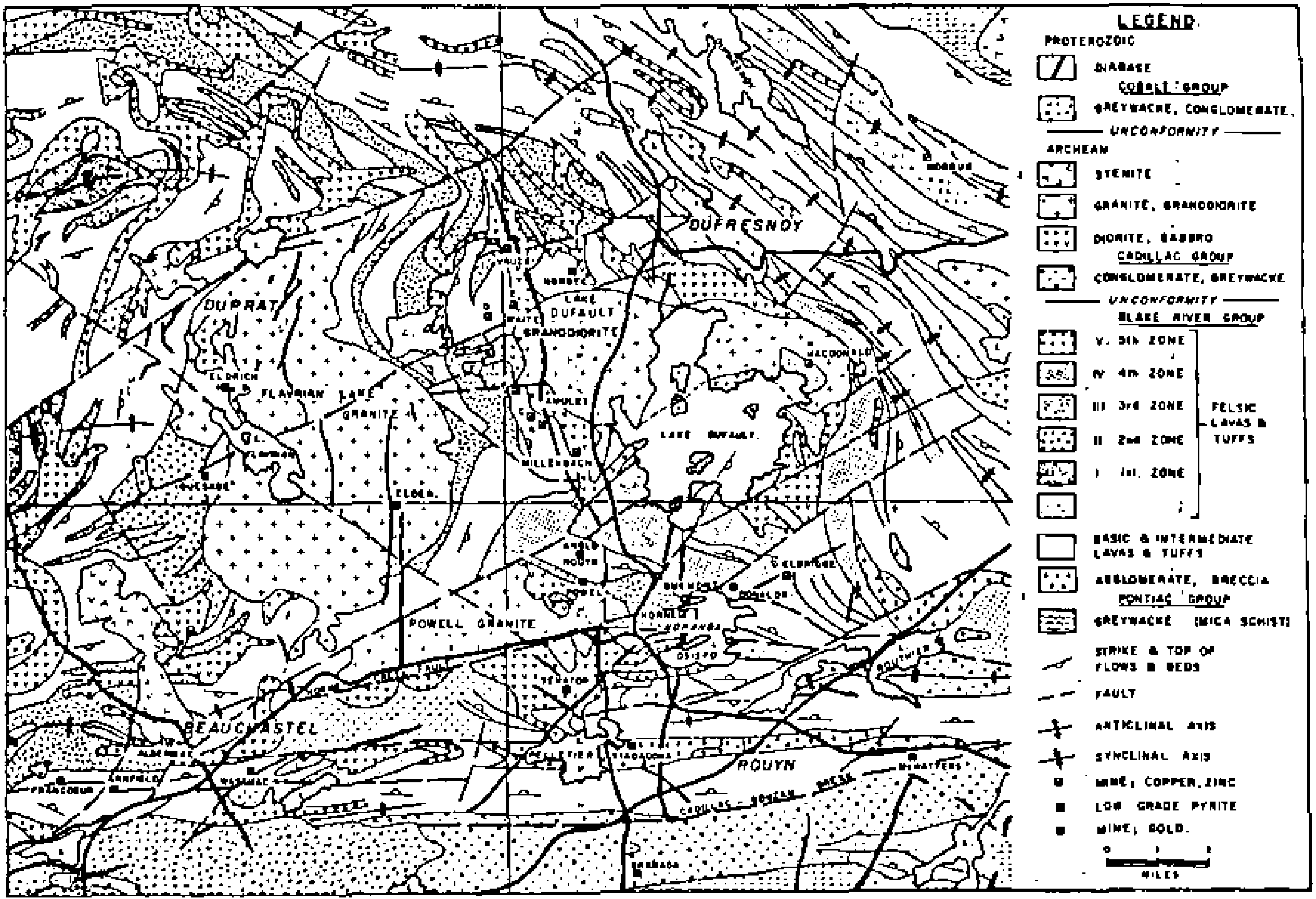


Figure 11 Geology of the Central Part of the Noranda Area (Spence and de Rosen-Spence, 1975)

recognized 5 cycles of volcanism beginning with andesitic extrusive activity at the beginning of each cycle changing to rhyolitic volcanism towards the end. An apparent break in volcanic activity occurred at the end of each cycle. The Flavrian Lake and Lake Dufault granite and granodiorite shown on Figure 11 are two large hypabyssal intrusions of the same composition as the felsic volcanic rocks and are interpreted as being related to volcanism. They appear to be unrelated to the development of the massive sulfide deposits, however.

Until recently, no deposits have been found associated with the two lowermost volcanic cycles. Most of the known deposits are found at the top of cycle 3 where the mineralizing events occurred at or very close to a single horizon overlying the uppermost rhyolites of cycle 3. This horizon appears to have been the seafloor for a significant but unknown length of time at the end of cycle 3 volcanism. Most of these deposits occur in a belt trending northwest between the two large felsic intrusions (Fig. 11). Minor mineralization also occurs associated with cycles 4 and 5 volcanism. Figure 12 schematically summarized the occurrences of massive sulfide deposits with the various horizons and units within the volcanic sequence in the Noranda area. The large number of deposits along the top of cycle 3 volcanic rocks is quite evident. This horizon can be traced throughout the district and in unmineralized areas amounts to a few inches of fine grained siliceous material often containing small amounts of pyrite and other sulfides. In all areas except to the south the hanging wall of this horizon is

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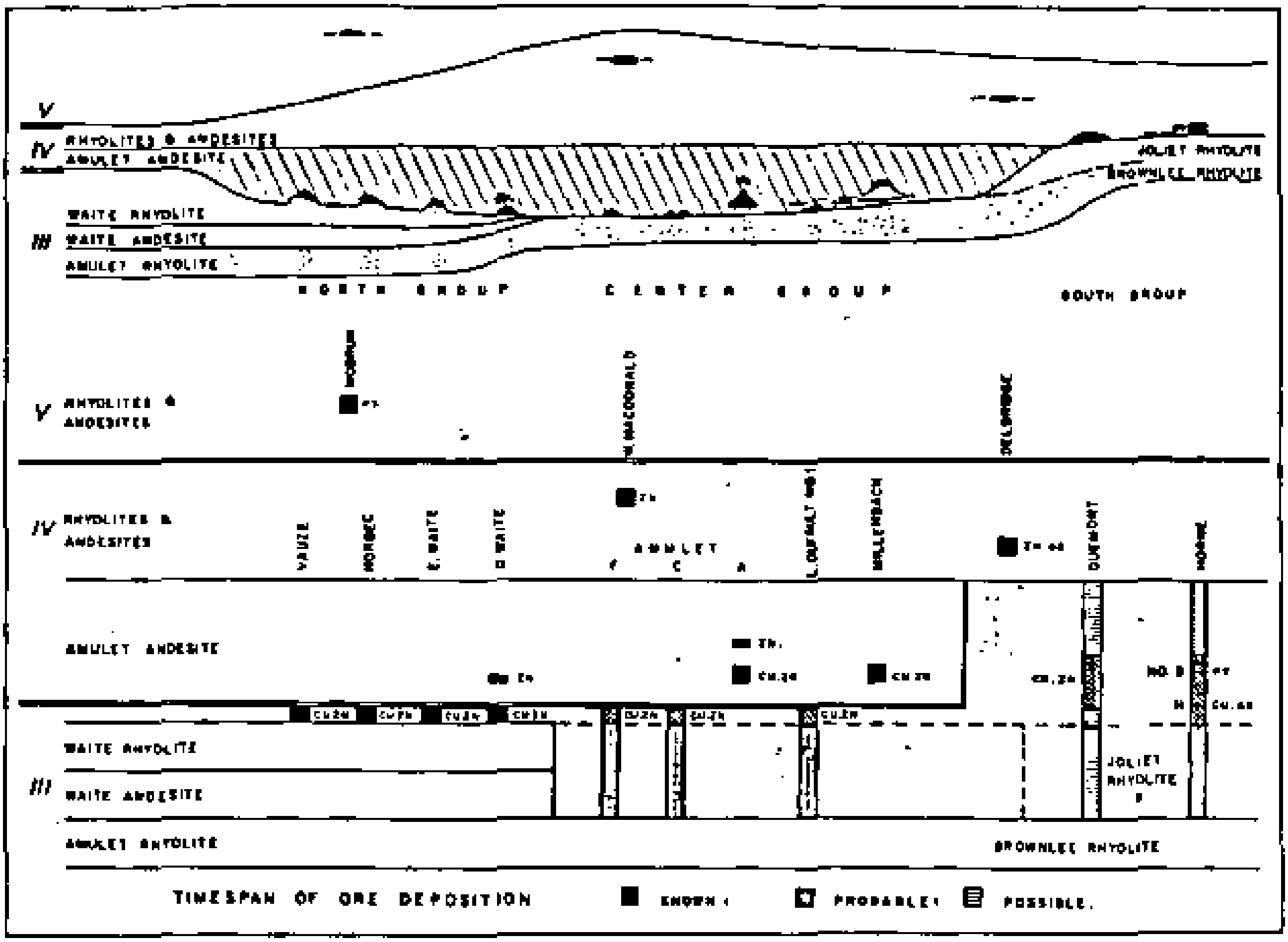


Figure 12 Diagrammatic Section Showing Stratigraphic Position of Ore Deposits in the Noranda Area (Spence and de Rosen-Spence, 1975)

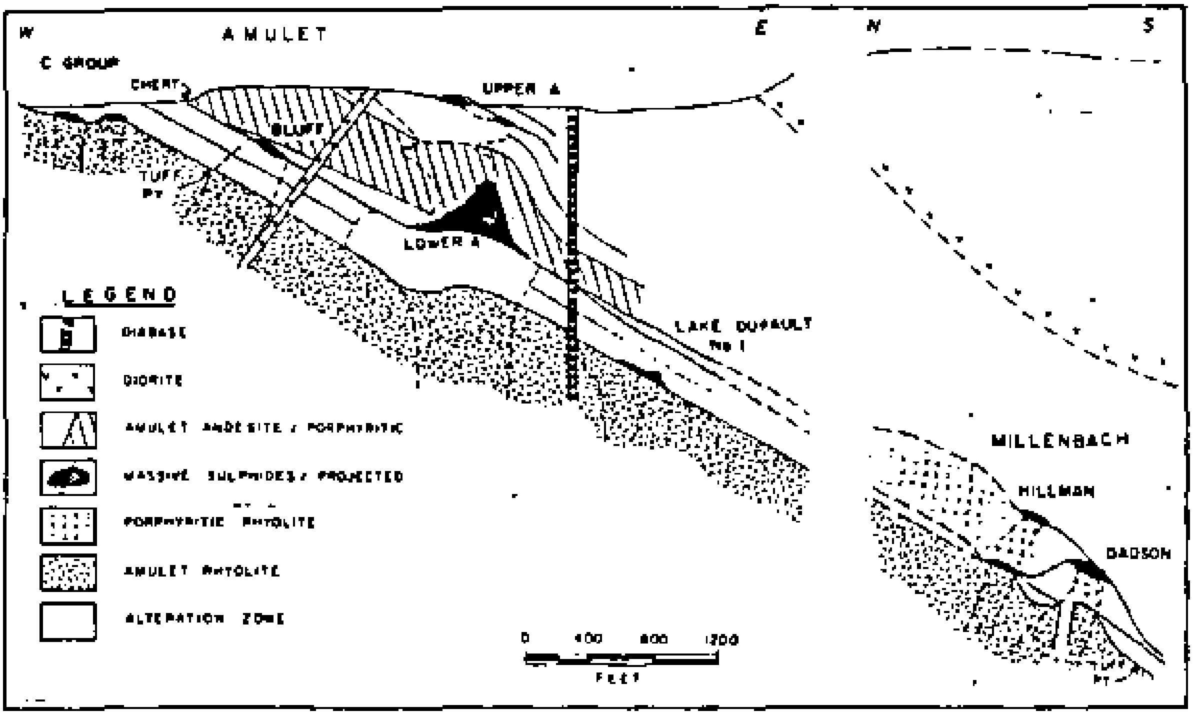


Figure 12a Detailed Central Portion of Above Section (Spence and de Rosen-Spence, 1975)

the Amulet Andesite, the lowermost unit of cycle 4. Some mineralization occurs slightly above the horizon within the andesite, indicating the hot spring activity continued after andesite volcanism began.

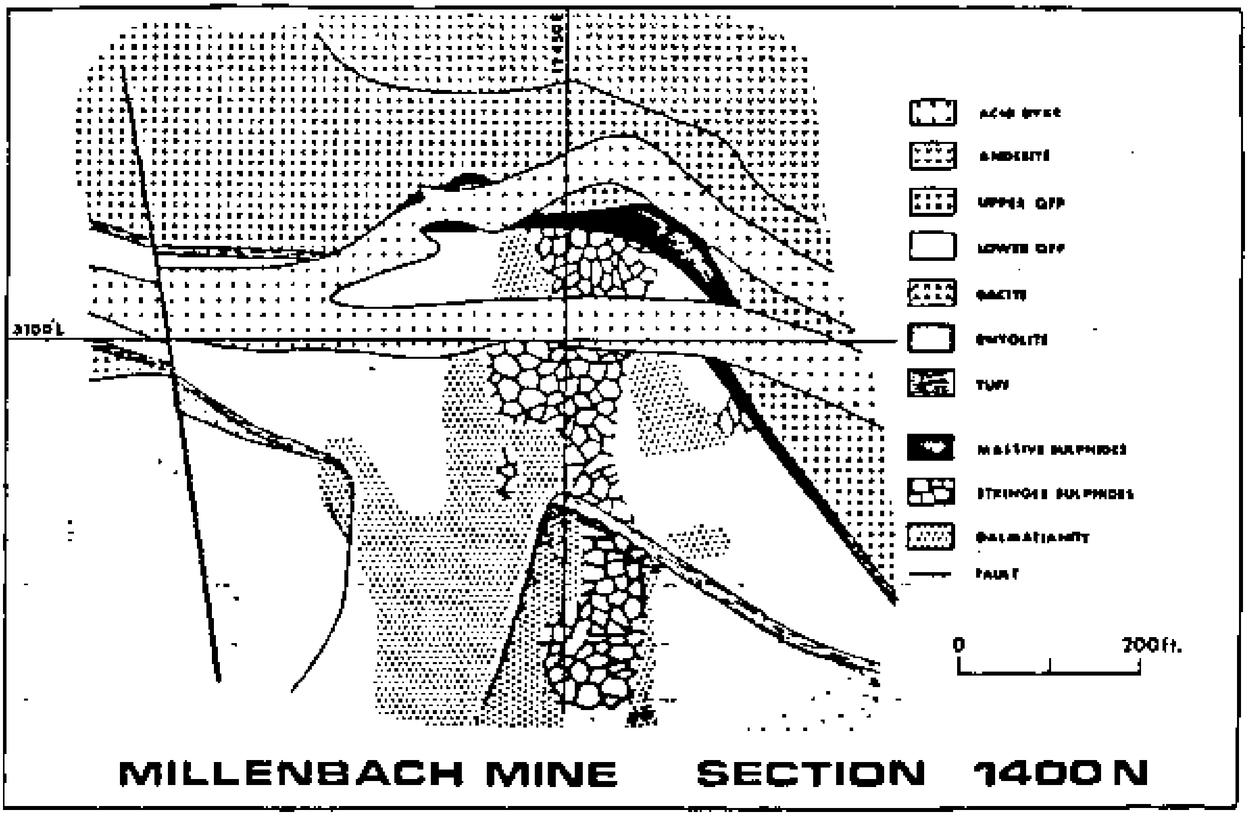
Locally, the massive sulfide deposits are associated with rhyolite extrusion domes emplaced along this horizon. Emplacement of these domes appears to be most favorable along fractures or zones of weakness asindicated by the linear arrangement of deposits in some areas. Even on a very local scale within a single deposits the sulfides appear to be distributed along linear zones. The individual sulfide masses occur on and in the rhyolitic domes along with rhyolite tuffs and breccias.

The Millenbach deposit (Fig. 11) is one of the recent producers in the Noranda district, and while it is not one of the larger deposits, it exhibits in a relatively well preserved state the characteristics typical of these massive sulfide deposits. The deposit occurs about 3000 feet below the surface and was discovered in 1966 during a drilling program with the objective of testing favorable structural sites along the horizon discussed above. Production began in 1971, and in 1973 reserves amounted to over 2.5 million tons at 3.5% copper, 5% zinc, 3 to 4 oz. silver and 0.004 oz. gold per ton. Since that time additional ore bodies have been found by subsurface exploration.

Most of the sulfides occur as lenses and pods at the crest and flanks of a large rhyolite porphyry dome referred to as the lower QFP, or quartz feldspar porphyry. The dome appears to be elongate in a southwest direction and sulfide lenses are arranged along a linear zone parallel to this direction. Each lense appears to be a separate hot spring center. The largest concentration of sulfides occurs at the intersection between this southwest linear zone and a more regional northwest structural zone. The massive lenses are often underlain by vein and stringer ore in a circular to ellyptical pipe-like body. The latter may represent the feeder pipe for the syngenetic hot spring deposits precipitated on the seafloor. Figure 13 is a geologic section throught the largest ore body in the mine. The upper QFP is a second rhyolite porphyry which overlies the massive sulfide body and probably represents the distal portion of another dome extruded from another center. This latter dome appears to be genetically unrelated to the Millenbach ores.

Between the upper and lower quartz feldspar porphryies lies a thin tuffaceous bed consisting of chemically precipitated chert, volcanic fragments, and disseminated sulfides. This material grades laterally into massive sulfide in the ore zones, and converges at the margins of the extrusion dome with another tuffaceous unit lying between the lower QFP and underlying Amulet rhyolite (Fig. 13). The resultant tuff unit is widespread throughout the district and marks the end of cycle 3 volcanic activity. If followed far enough this unit can be traced to other massive sulfide deposits (Fig. 12).

Associated with the domes are breccias consisting predominantly of rhyolite and tuff fragments in a cherty matrix. These breccias are rare or absent away from mineralized areas, which led many prospectors to the realization that they served



DADSON ZONE, EAST.WEST VERTICAL SECTION LOOKING NORTH

Figure 13 (Simmons, 1973)

as good ore guides. Locally fragments of sulfide ore occur in the breccias, and sulfide material may serve as a matrix to volcanic fragments. In some deposits fragments of sulfide occur in a matrix of finer grained sulfide often of a different composition. The breccias appear to have formed from explosive activity resulting from the interaction between hot solid material and cooler seawater.

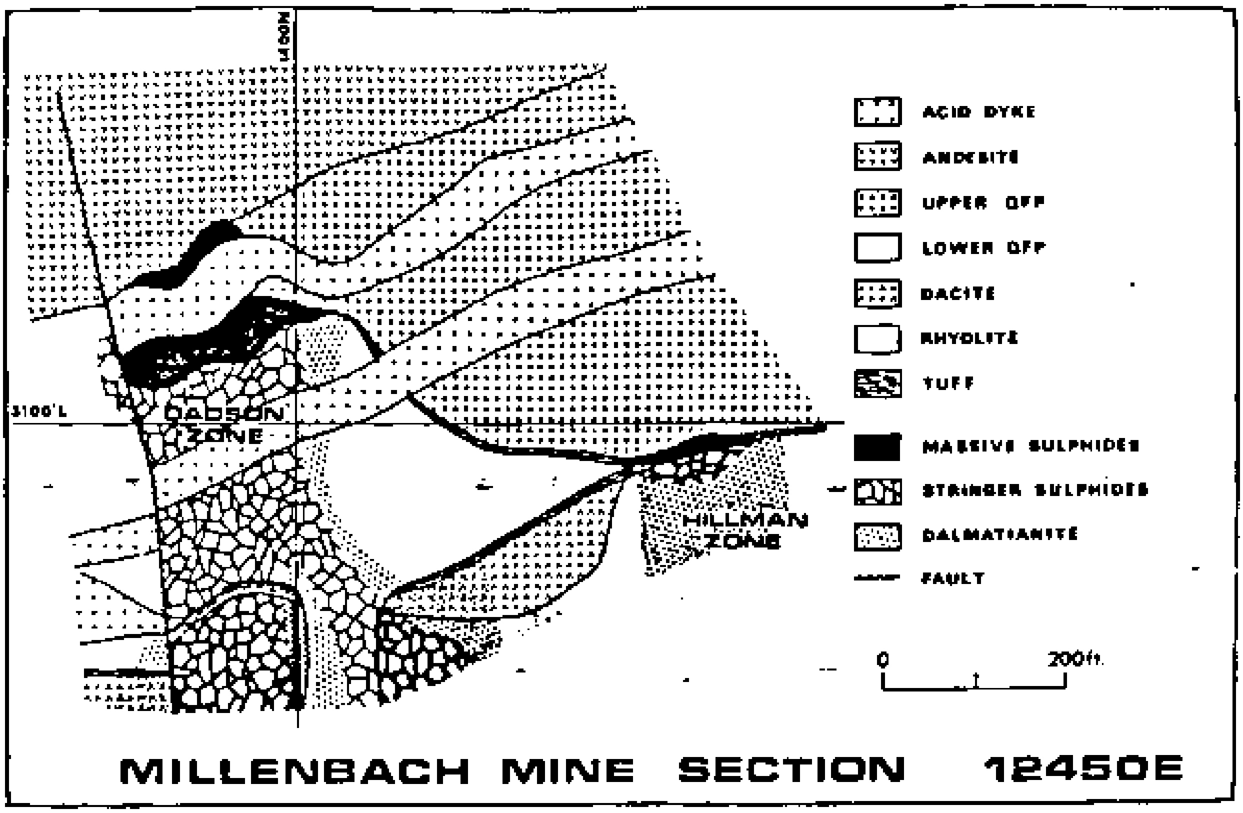
The sulfide deposits are zoned both texturally and compositionally. In the footwall below the massive sulfide lenses occurs a pipe of stringer ore where chalcopyrite and pyrrhotite with minor pyrite and sphalerite occur in a stockwork of interconnecting veins 1 to 12 inches wide. This pipe is surrounded by a 10 to 20 foot envelope of anomalous zinc where sphalerite occurs in small veinlets and as fine intergranular material.

The stringer zone grades upward into the massive sulfide of the main ore lenses. The lower zones of the massive ore bodies may be brecciated where fragments of chalcopyrite occur in a matrix of pyrite and pyrrhotite. The upper portions of the massive zone grade upward into banded material where sphalerite bands alternate with bands of pyrrhotite and pyrite. From the massive to the banded sulfide there is a general decrease in chalcopyrite and increase in sphalerite. From the bottom to the top of the banded zone there is a decrease in sphalerite content. At the top of the banded zone sulfide layers may alternate with layers of chert. The upper contact between the sulfide lense and upper quartz feldspar porphyry is sharp and may show a scalloped surface. Sulfide fragments have been found in the hanging wall in the upper QFP. Also present in the massive sulfide deposits of the Millenbach mine are minor magnetite and rare arsenopyrite, galena, and silver minerals.

Alteration at the Millenbach deposit consists of a halo of spotted rock, or dalmatianite, around the pipe of stringer ore and in the immediate footwall of the massive sulfide lenses. The altered rock consists of small fine grained aggregates of chlorite, sericite, or anthophyllite in otherwise relatively fresh rhyolite. Locally rhyolite has been intensely altered to chlorite and biotite. Individual sulfide veins within the stringer ore have selvages of chlorite, sericite, epidote, and carbonate. Alteration in the hanging wall of the massive sulfide lenses is either weak or absent.

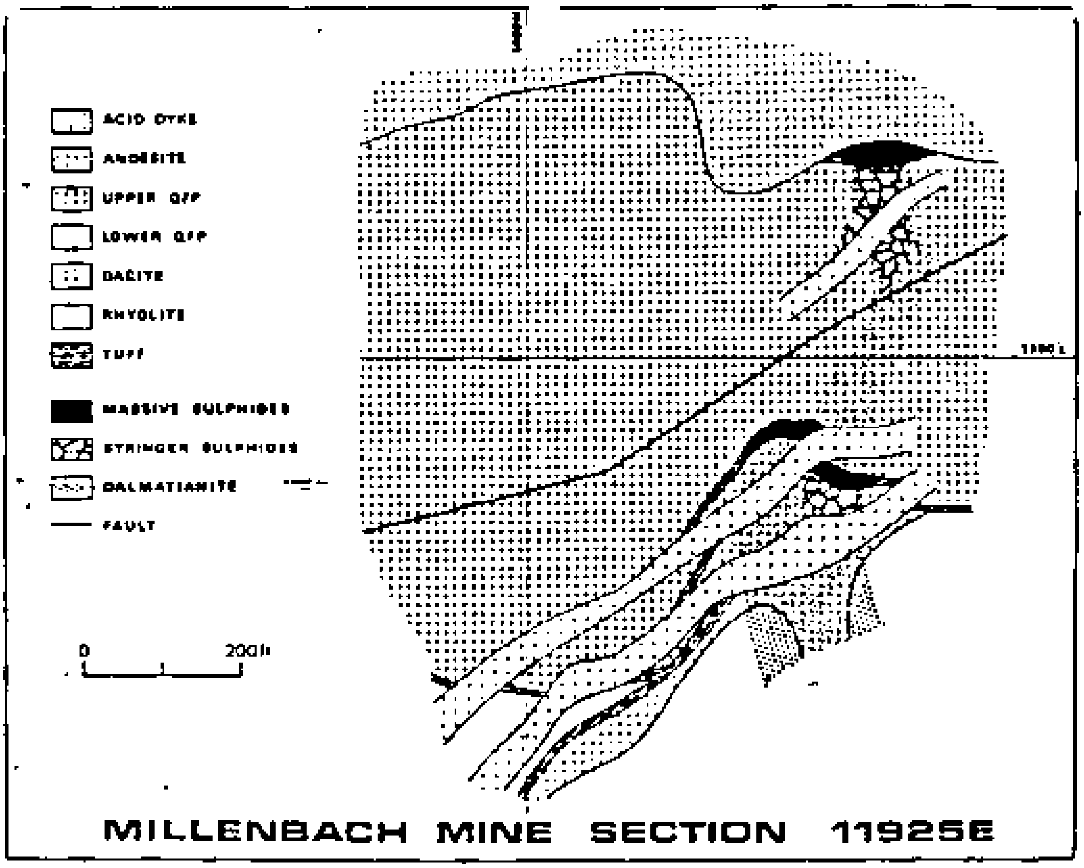
Figure 14 is a geologic cross section through another part of the Millenbach deposite showing a satellite fumarolic center on the flank of the rhyolite dome. Figure 15 shows an additional ore zone at the contact between the upper QFP and the overlying Amulet andesite. This sulfide body represents a continuation of hot spring activity after the emplacement of the upper QFP. A continuous pipe of alteration extends from the lower massive zone to this upper body.

The Horne mine was the largest in the Noranda area, producing over 1.2 million tons of copper and 8.6 million ounces of gold from in excess of 56 million tons of ore. The rocks along the southern margin of the Noranda volcanic complex containing the Horne and Quemont mines have been fractured and deformed (Fig.



DADSON AND HILLMAN ZONES
NORTH-SOUTH VERTICAL SECTION LOOKING WEST

Figure 14 (Simmons, 1973)



HILLMAN ZONE, NORTH-SOUTH VERTICAL SECTION LOOKING WEST

Figure 15 (Simmons, 1973)

11). The volcanic units strike roughly east-west, dips 85 to 90 degrees to the north, and have tops to the north. The Horne mine is unusual in the Noranda district because of its high gold content. There are 2 main ore zones in the deposit, the upper zone and the lower H. These bodies are roughly circular in plan and approximately 500 feet in diameter. The ore bodies are conformable to the foliation where developed and plunge down dip of the enclosing volcanics for several thousand feet. The most abundant sulfides are pyrite, pyrrhotite and chalcopyrite. The gold occurs in the native state, as tellurides and in solid solution in pyrite.

The No. 5 zone is a subeconomic body of massive and disseminated mineralization stratigraphically above the lower H ore body (Sinclair, 1971). This lense extends down dip from a depth of 1900 feet to 8900 feet, has a strike length of 3000 feet, and a thickness ranging from 100 to 450 feet. This roughly conformable mass consists of tuffs, rhyolite tuff breccias, and rhyolite breccias as complex interfingering units which were deposited by pyroclastic activity and subsequent collapse off a topographic high on the seafloor. The sulfides, mostly pyrite, occur as irregularly distributed conformable lenses within the volcanic units. Sulfide fragments are commonly enclosed in the tuff breccias. These fragments are chemically and mineralogically similar to the massive sulfides of the lower H ore body stratigraphically below. The more massive sulfide lenses in the No. 5 zone appear to have been formed by post-depositional slumping and flow of sulfide mud accompanied by explosive volcanic activity to produce the fragmentation.

In the vicinity of the Horne mine the volcanic units are intruded by structurally controlled syenite porphyry dikes. These intrusions are genetically unrelated to the volcanic units and appear to be related to igneous activity along the major east-west fracture system extending to the west. Similar intrusions occur in the Larder Lake and Kirkland Lake gold districts. These porphyries are post deformation and faulting and therefore are post massive sulfide deposition. The gold in the Horne deposit may be related to this intrusive activity.

Kidd Creek Massive Sulfide Deposit, Timmins, Ontario

The Kidd Creek massive sulfide deposits is the only known major deposit of its type in the Kamiskotia volcanic complex containing the Timmins district (Fig. 5). Figure 16 shows the location of the deposit within the Abitibi greenstone belt. The geology of the Timmins area is shown in Figure 17. The area is dominated by ultramafic and mafic intrusive and extrusive units and clastic sedimentary rocks. Felsic volcanic rocks occur locally as in the vicinity of the Kidd Creek deposit. The structure of the area is very complex. Locally the rocks have been highly deformed and faulted and in places are overturned. A major fracture zone striking slightly north of east passes through the Timmins area. Most of the gold deposits are associated with subsidiary faults and folds associated with this structure. Some of the ultramafic units contain magmatic nickel sulfide deposits, however these are generally small and uneconomical.

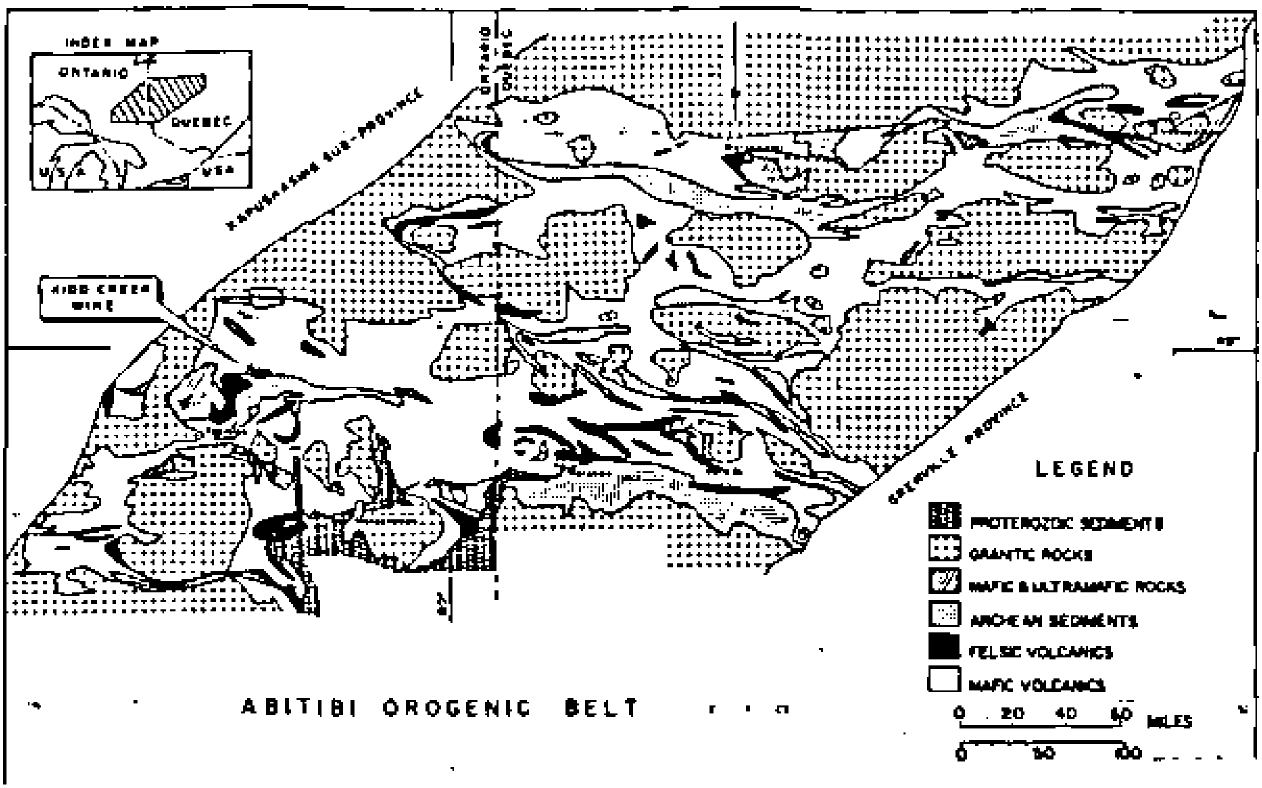


Figure 16 Location of the Kidd Creek Mine in the Abitibi Greenstone Belt (Walker and others, 1975)

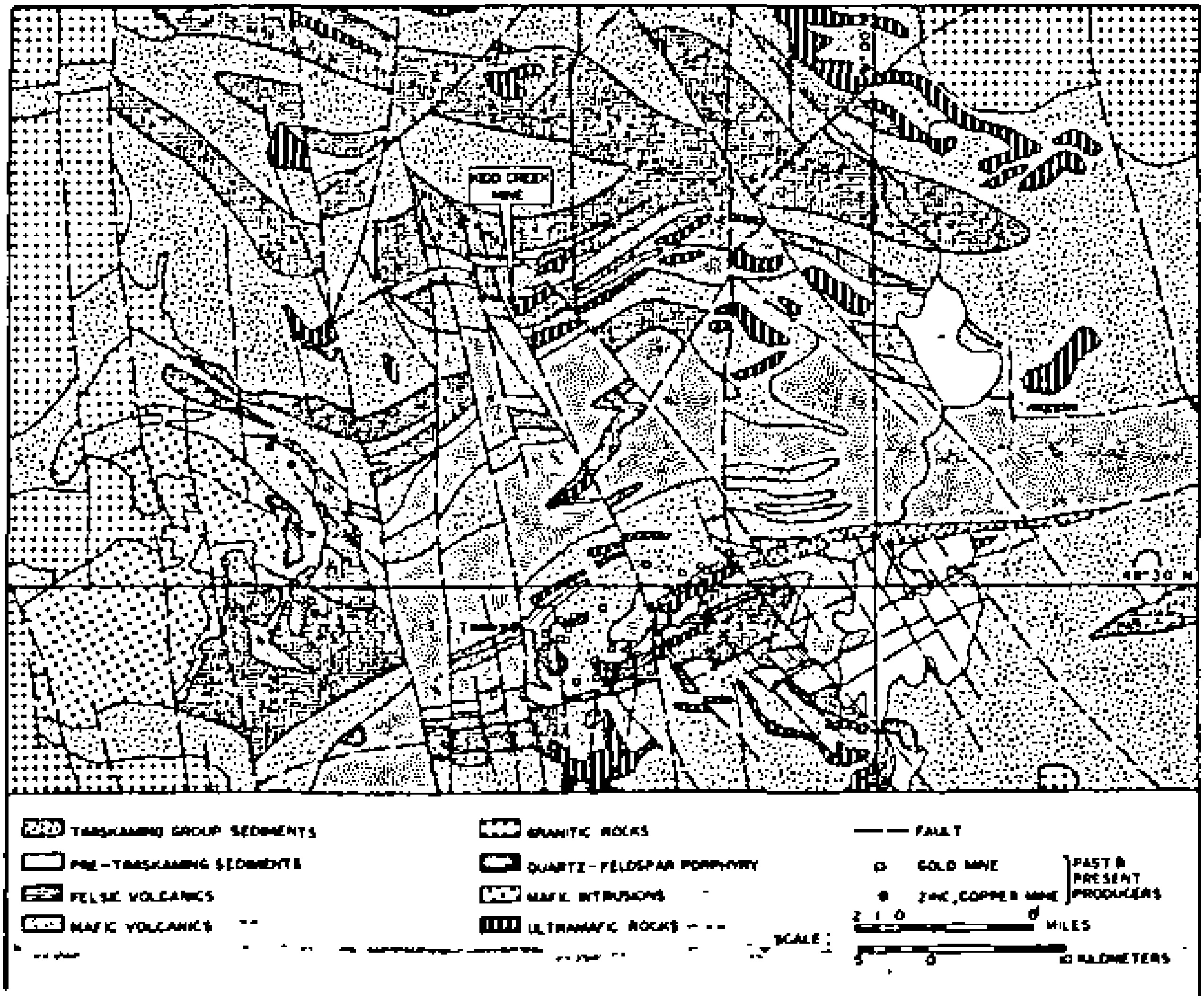


Figure 17 Geology of the Timmins, Ontario Area (Walker and others, 1975)

The Kidd Creek deposit is located 17 miles north of the town of Timmins. The deposit was discovered in the early 1960's and production began in the late 1960's by open pit mining. In excess of 100 million tons of ore were proved to a depth of approximately 2800 feet. The grade of ore is approximately 8% zinc, 1.8% copper, 0.5% lead and 5 ounces silver per ton. Tin is locally present in amounts as high as 3%. This deposit is considered to be the largest zinc-silver-cadmium deposit in the world.

The Kidd Creek deposit is located in an isolated patch of felsic volcanic rocks within an area dominated by mafic and ultramafic units. The massive sulfide deposits occur in a pile of rhyolites, fragmental rhyolites, tuff breccias, and andesites overturned to the west. The local strike is north although the regional structural trend is east-west conforming to the domal nature of the volcanic complex. Figures 18 and 19 show a geologic plan and cross section respectively of the mine area. The massive sulfide bodies are associated with, and conformable to, local concentrations of fragmental rhyolite and rhyolite tuff breccia which may represent a rhyolite dome which has been strung out by later deformation. Intense shearing has complicated the original geologic relationships, however there are sufficient recognizable features to place this deposit in the volcanogenic syngenetic massive sulfide type.

As shown on the cross section in Figure 19, the ore zone dips steeply to the east, however the deposit is overturned as are the enclosing volcanic units. Additional evidence for the overturned nature of the deposit is the apparent inverse zoning

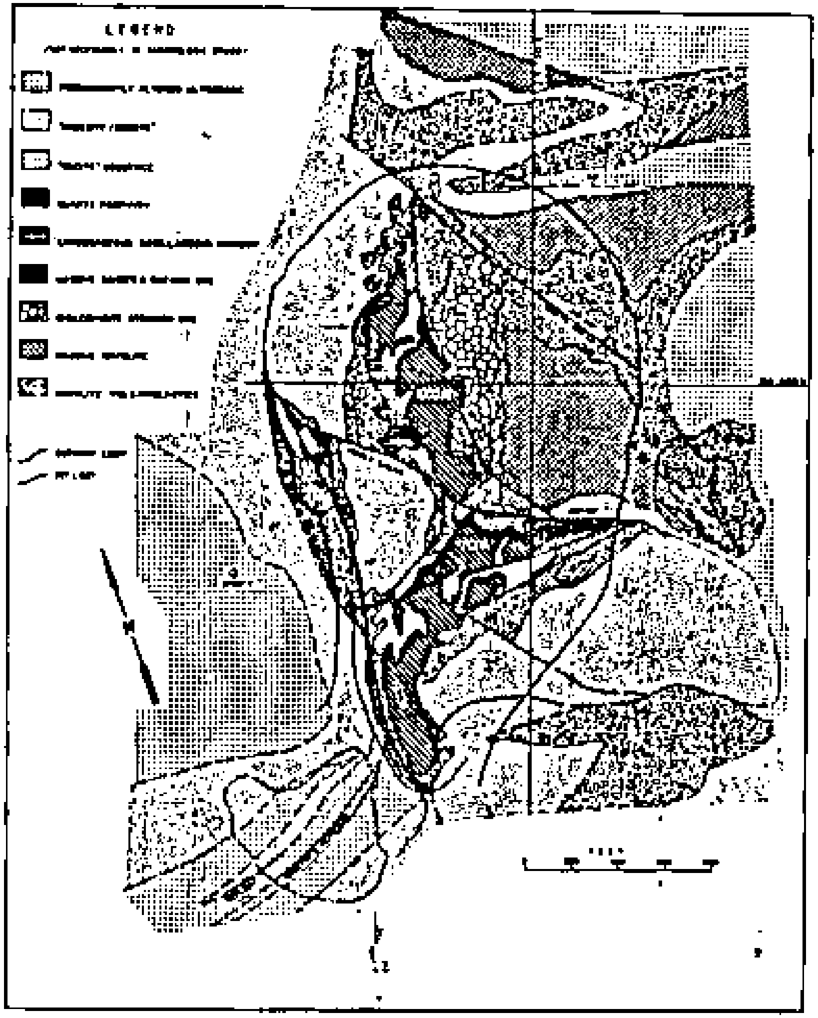


Figure 18 Surface Geology Plan of Kidd Creek Mine.

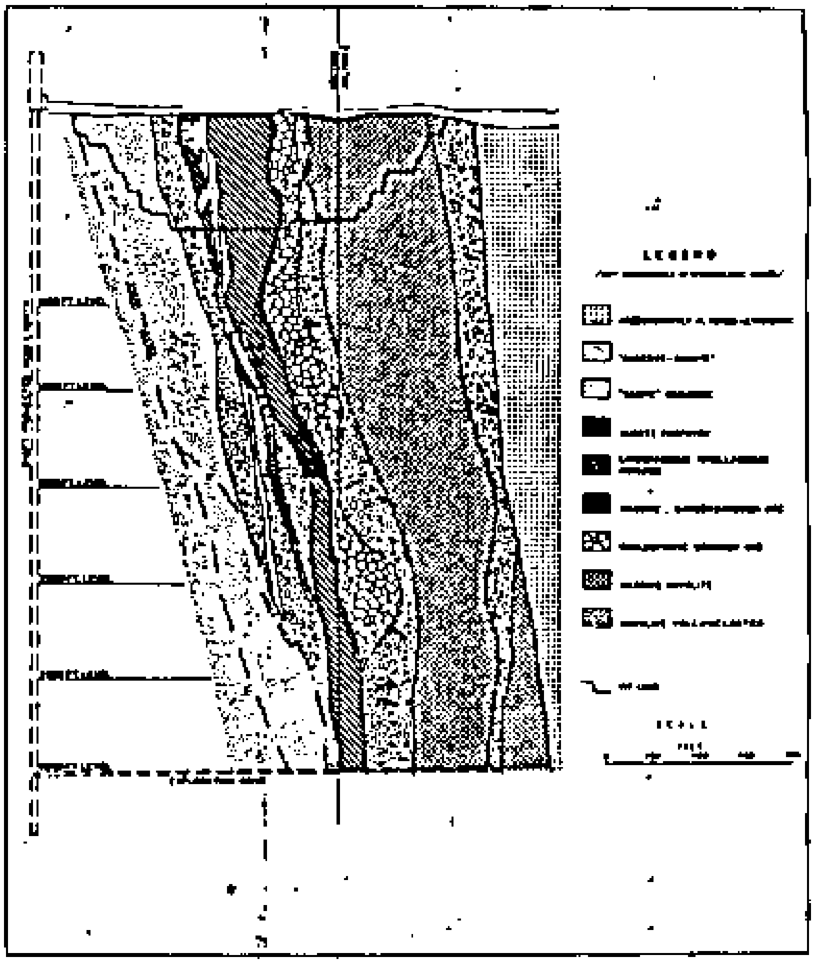


Figure 19 East-West Geologic Section of the Kidd Creek Mine.

(Walker and others, 1975)

in the volcanic rocks and sulfide units. The rhyolite which normally lies in the stratigraphic footwall of massive sulfide deposits occurs in the structural hanging wall. Conversely, the andesite occupies the structural footwall. In addition, chalcopyrite stringer ore occurs in the hanging wall and massive sphalerite and sphalerite-pyrite banded ore occur in the structural footwall. Intense alteration occurs in the hanging wall rhyolite whereas there is little alteration in the footwall andesite.

The volcanoclastic rocks associated with the deposit consist of both fragmental volcanic rocks and sulfide breccias. The deposit averages 25 to 30% pyrite, 15% sphalerite, 5% chalcopyrite, 0.5% galena, 1% pyrrhotite and lesser amounts of silver, acanthite, tetrahedrite, tennantite, stromeyerite, stephanite, pyrargyrite, pearceite, bornite, and cassiterite. The ores show most of the textures and structures observed in the well preserved Millenbach deposit, including the banding, stringer zone, and overall mineral zoning. Also present are siliceous zones resembling quartz veins which cross cut the ore. There is a high copper zone near the core of the deposit whic is characterized by high bornite content and unusual silver minerals. Both the siliceous zones and bornite zone appear to represent remobilized material which cross cut the syngenetic massive sulfides.

The geologic relationships suggest the presence of two separate ore bodies plunging steeply down dip, the north and south ore bodies separated by the middle shear (Fig. 18). The ore bodies have a rough cross section measuring 500 by 1500 feet. The ore bodies converge at depth, and are known to go to a depth exceeding 4100 feet. It is unclear if the north and south ore bodies were separated by later movement along the middle shear, or if they represent two separate depositional units.

Alteration in the wallrocks consists mostly of silicification, chloritization, and sericitization of rhyolite around the stringer ore pipe. Contacts between sericitized and unaltered rhyolite can be quite sharp. The andesite of the structural foot wall (stratigraphic hanging wall) is essentually unaltered.

An unusual carbonaceous unit occurs in the mine area which is conformable to the enclosing volcanic rocks. There appears to be a spatial if not genetic relationship between this carbonaceous unit and the massive sulfide bodies. It consists of carbonaceous argillite, slate and chert containing disseminated pyrite, pyrrhotite, chalcopyrite, and sphalerite.

Massive Sulfide Deposits at Manitouwadge, Ontario

The Manitouwadge massive sulfide deposits are located in western Ontario northeast of Marathon on the north shore of Lake Superior. These deposits are of interest because they lie in a high grade metamorphic terrane. The massive sulfide bodies occur in a synclinal roof pendant of Archean metavolcanic and metasedimentary rocks completely surrounded by granitic gneisses. Preservation of this small remnant of greenstone occurred by down-folding of the syncline into the gneiss during intense deformation and metamorphism. The volcanic rocks have been so intensely metamorphosed that it is impossible to determine the nature of the protolith. The wallrocks of the massive sulfide deposits are described as muscovite schist, however other lithologies present are biotite-amphibole-garnet schist, iron formation, and metabasalts. The sulfide bodies occur as lenses conformable to the enclosing rocks, however they are enveloped by a halo of disseminated mineralization.

Three mines have operated in the district, the Geco, Willroy, and Willecho. The Geco is the largest and highest grade, having 2.1% copper, 5.1% zinc, and 2.2 ounces silver per ton. The massive ores consist of 25% pyrite, 20% pyrrhotite, 14% sphalerite, 6% chalcopyrite, and less than 1% galena. The silver appears to be associated with the chalcopyrite. Gahnite, $ZnAl_2O_4$ is found, however this phase is considered to be a result of high grade metamorphism of sphalerite-bearing rocks. The origin of this deposit is interpreted as being typically syngenetic, with post depositional metamorphism and remobilization.

Syngenetic Massive Sulfide Deposits of Paleozoic Age

The lead-zinc-copper-pyrite type of syngenetic massive sulfide deposit did not appear until Proterozoic or later time (Table 1). The appearance of lead in these deposits is attributed to a more advance stage of differentiation within the crust and upper mantle. Ultramafic rocks were becoming less abundant in the rock record of these later periods and more felsic volcanic units and their intrusive equivalents were becoming more abundant. There are no important deposits of this type of Proterozoic age although a number of examples occur in Paleozoic and younger rocks. Massive sulfide deposits of early Paleozoic age occur at the northern end of the Appalachian orogen in eastern North America, particularly in New Brunswick and Newfoundland of eastern Canada.

The Buchans deposit of Newfoundland lies in a belt of Silurian and Ordovician sedimentary and volcanic rocks intruded by later Devonian plutons and batholiths of various compositions. The local geology of this area is shown in Figure 20. All rocks have been regionally metamorphosed to lower greenschist facies and deformed during the Acadian orogeny. The folding during this event was locally intense and open to isoclinal folds within the bedded units are common.

The Ordovician rocks consist of mafic pyroclastic units and some pillow lavas intercalated with marine greywacke, siltstone, argillite and chert. Felsic volcanic units occur locally. The overlying Silurian rocks consist of a thick sequence of shallow water conglomerate and greywacke overlain by mafic agglomerate, felsic pyroclastic units; and ignimbrites which are overlain in turn by fluvial red micaceous sandstone.

The Buchans group of volcanic rocks lies in the middle of the Ordovician sequence and appears to represent 4 cycles of of volcanism with andesite at the base of each cycle and dacite at the top. The andesites contain local interflow arkose and siltstone. The local area of the deposits appears to contain a local concentration of felsic volcanic rocks, however the terrane is isolated from the regional stratigraphic setting by the Devonian intrusions (Fig. 20).

Figure 21 shows the distribution of rock units and metal

BUCHANS POLYMETALLIC SULFIDE DEPOSITS

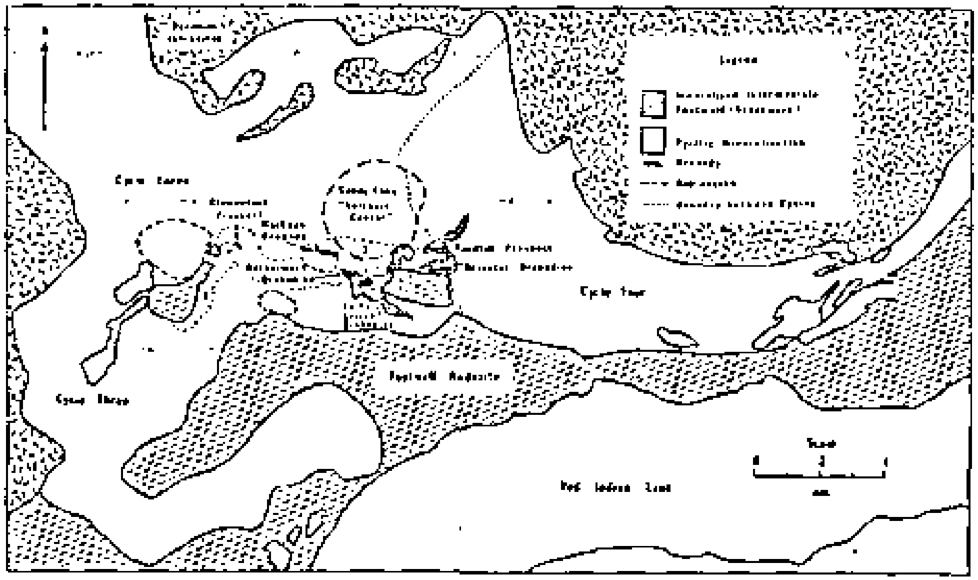


Figure 20. Geology of the Buchans Area, Newfoundland (Thurlow and others, 1975)

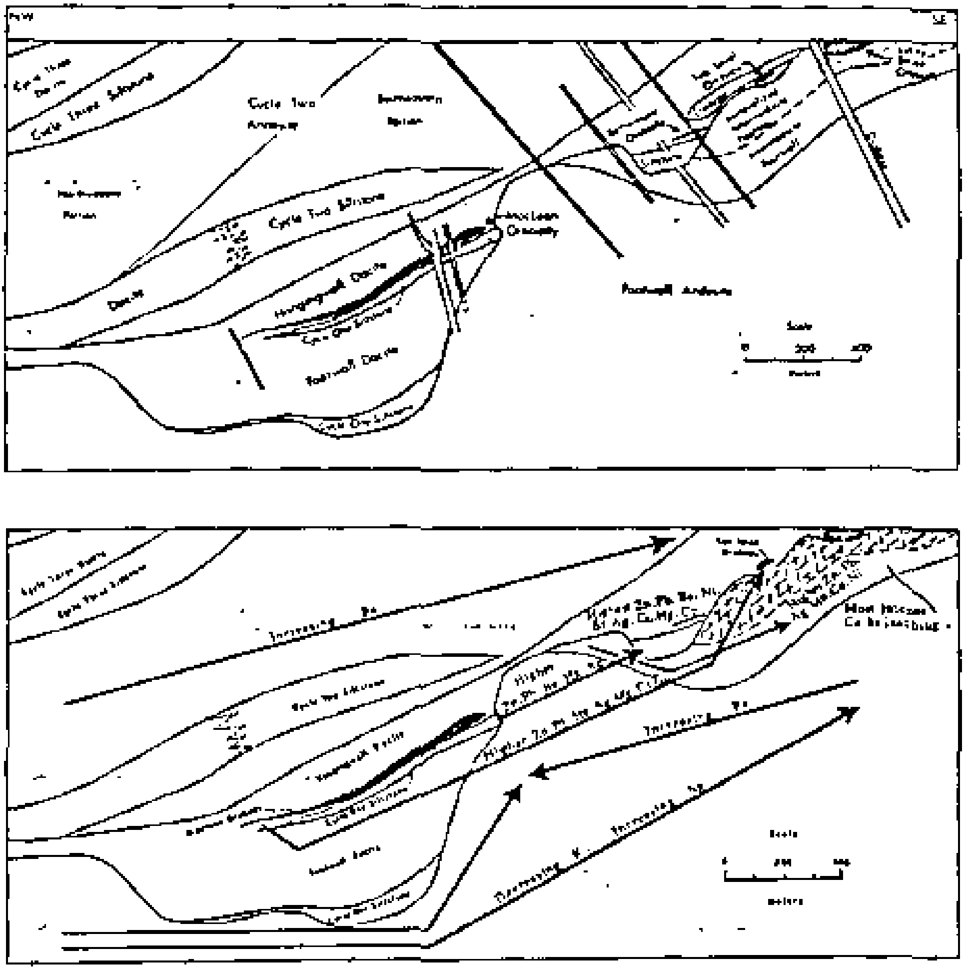


Figure 21 Diagrammatic Geologic Sections of the Buchans Deposits Showing stratigraphic and Geochemical Relationships (Thurlow and others, 1975)

zoning in cross section. The sulfide bodies occur as conformable lenses within the dacites of cycles 1 and 2 which appear to occupy topographic depressions in the footwall andesite. The largest depression is about 3 km in diameter. The distribution of the volcanic rocks appears to be structurally controlled where a distinct pile of volcanic units have developed over the depression. The overall geologic environment suggests the depressions represent collapse calderas over volcanic vents.

The dacite units were emplaced rapidly as ash flows, welded tuffs and agglomerates. Following dacite deposition, siltstone was deposited in a subaqueous environment along with bedded coarse-grained crystal-rich tuff of dacite composition. The massive sulfide deposits occur in a stratigraphic horizon above the siltstones and tuffs and are associated with a distinct breccia zone. The siltstone is crossbedded and exhibits soft sediment deformation features. It contains disseminated pyrite, often in distinct beds in a crossbed set. Detrital sphalerite is also found in the siltstone as individual grains and in mineralized volcanic fragments. The breccias containing the sulfide lenses consist of a mixture of sedimentary and volcanic rock fragments in a fine detrital matrix. Fragments of massive sulfide and barite occur near ore bodies.

Massive sulfide deposits occur in horizons at the top, within, or at the base of the breccias and appear to be roughly contemporaneous with the breccias. The breccias are concentrated along troughs and could represent laharic breccias released by dislodging unconsolidated material on the flanks of a dome by

explosive activity. The contacts between massive sulfide lenses and surrounding units are generally sharp except where breccia occurs as the footwall, in which case footwall contacts are gradational. The ore lenses are overlain by andesite and dacite of the next volcanic cycle.

The ore consists of a fine grained mixture of sphalerite, galena, and chalcopyrite with small amounts of pyrite and tetrahedrite. Trace amounts of bornite and covellite occur throughout the ores, and enargite, native silver, argentite, and ruby silver have been reported also. The most abundant gangue mineral is barite which may constitute up to 25% of the ore. Quartz, calcite, sericite and chlorite are also present.

There are 3 ore types recognized: massive ore, barite ore, and breccia ore. The massive ore is essentually structureless, but locally contains conformable bands and streaking. Slump structures occur where massive ore grades into breccia ore. The massive sulfide ores occupy channels in the footwall. Barite ore consists of a mixture of fine to coarse grained barite and sulfide minerals concentrated towards the top of the ore bodies. Breccia ore consists of fragments of wall rock suspended in sulfide. Fragments of sulfide in a matrix of sulfide also occurs locally in the massive ore.

A stockwork of mineralization occurs in the footwall of the massive sulfide lenses, and in places grades upward into massive ore. This stringer ore has the same sulfide minerals as the massive ore except for a large proportion of pyrite. This zone has an alteration halo of intense silicification and chloritization.

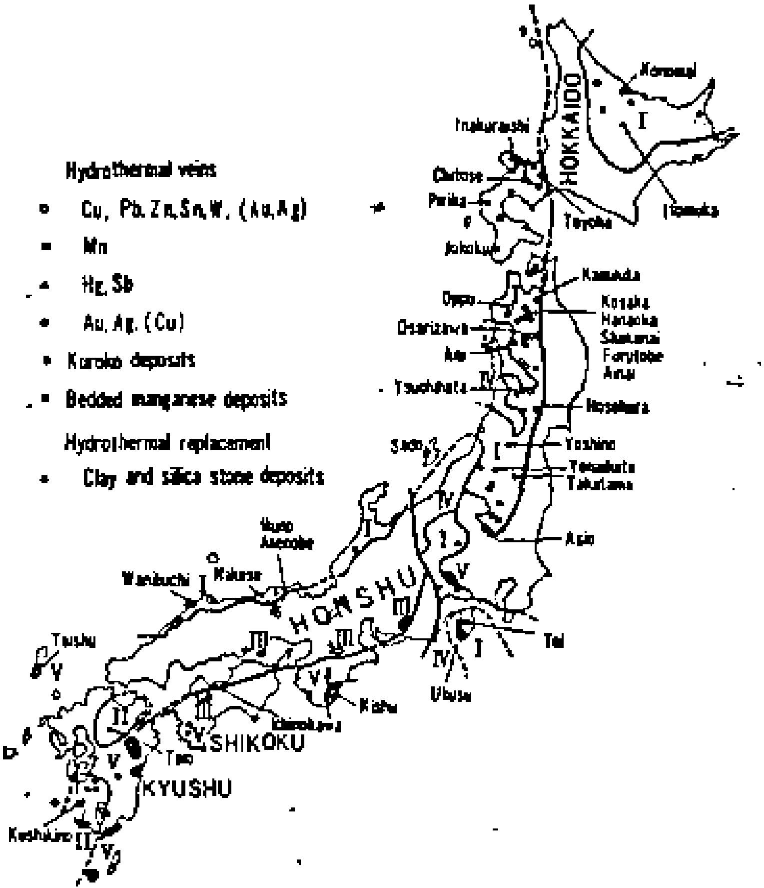
The Buchans area has produced approximately 20 million tons of ore since 1928 with an average grade of approximately 15% zinc, 7.7% lead, 1.4% copper and 3.7 ounces of silver and 0.046 ounces of gold per ton.

Massive Sulfide Deposits of Tertiary Age

Massive sulfide deposits of the lead-zinc-copper-pyrite type also occur in Tertiary age rocks (Table 1). The Kuroko deposits of Japan represent the best example of this class of deposits. Much geologic and geochemical work has been carried out in recent years and theresults of these studies have contributed much to the interpretation of all massive sulfide deposits. The term Kuroko is an old Japanese mining term meaning black ore because of the fine grained nature of the sphalerite-galena mixture which constitutes the ore. The individual deposits are not large in comparison to their Precambrian equivalents. The total tonnage of ore discoverd in the last 25 years is approximately 80 million tons containing important amounts of zinc, lead, copper, silver, gold, and other minerals.

Figure 22 shows the various tectonic provinces of Japan and the distribution of mineral deposits associated with volcanic rocks. The Kuroko deposits occur in the green tuff region of northern Honshu, a narrow belt characterized by extensive submarine volcanism during Miocene time. The massive sulfide deposits were formed during a relatively short time period during Middle Miocene as shown in Table 2 and Figure 23. The deposits occur along a relatively narrow time-stratigraphic horizon.

The massive sulfide deposits are spatially associated with



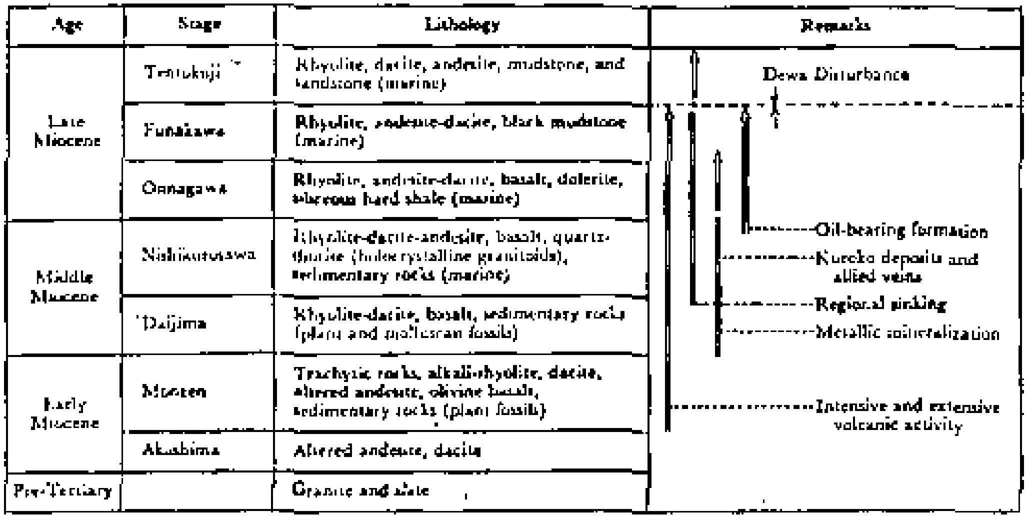
Tectonic provinces and distribution of mineral deposits of volcanic affinity of the Neogene in Japan.

I Zone of Early Miocene volcanism, so-called "Green Tuff region". (Mainly submarine, associated with some acidic intrusives of Late Miocene.) (Zone 13-I in Fig. 2.)
II Zone of Miocene volcanism in the Ryukyu Arc. (Mainly subaerial.) (Zone 13-II in Fig. 2.)
III Zone of Neogene volcanism along the Median Tectonic Line. (Mainly subaerial.) (Zone 13-IV in Fig. 2.)
IV Zone of Late Neogene foldings, mainly in the Green Tuff region. (Zone 14 in Fig. 2.)
V Zone of Neogene intrusives and extrusives on the Shimanto terrain. (Zone 9-III in Fig. 2.)

Figure 22 (Tatsumi, and other, 1970)

Table 2 (Matsukuma and Horikoshi, 1970)

Schematic geologic succession of the Miocene formations in the Akita district, northeastern Japan (after Huzioka, 1963)



Age	Stage	Lithology	Remarks
Late Miocene	Tentokuji	Rhyolite, dacite, andesite, mudstone, and sandstone (marine)	Dewa Disturbance
	Funakawa	Rhyolite, andesite-dacite, black mudstone (marine)	
	Onnagawa	Rhyolite, andesite-dacite, basalt, dolerite, siliceous hard shale (marine)	
Middle Miocene	Nishikurosawa	Rhyolite-dacite-andesite, basalt, quartz-diorite (holocrystalline granitoids), sedimentary rocks (marine)	Oil-bearing formation Kuroko deposits and allied veins
	Daijima	Rhyolite-dacite, basalt, sedimentary rocks (plant and molluscan fossils)	Regional sinking Metallic mineralization
Early Miocene	Monzen	Trachytic rocks, alkali-rhyolite, dacite, altered andesite, olivine basalt, sedimentary rocks (plant fossils)	Intensive and extensive volcanic activity
	Akashima	Altered andesite, dacite	
Pre-Tertiary		Granite and slate	

felsic pyroclastic units and rhyolite to dacite dome extruded in a shallow submarine environment. Volcanic explosion breccia are common along with beds of tuff and tuff breccias originating by submarine slumping and turbidity currents. The sulfide deposit show evidence of being caught up in this slumping and brecciation. Many occurrences indicated the sulfide material has been transported into depressions in the sea floor by density or turbidity currents. However, the source of the sulfides can be traced to a fumarolic center on or near an extrusion dome (Fig. 28).

Ore bodies are tabular and lense-like and in most cases conformable to the enclosing volcanic units. The deposits are often accompanied by a stockworks of fissure fillings and replacement veins which served as the feeder system for the massive sulfides. The deposits are commonly underlain by altered rhyolite volcanic units which have been hydrothermally altered. This alteration consists mostly of silicification and sericitization. The hanging volcanic units also show a low intensity alteration (Fig. 24). The alteration of the hanging wall rocks may be a result of the rapid sequence of events where fumarolic activity continued through the period of emplacement of overlying units. Locally the massive sulfide deposits are overlain by altered submarine sediments. This relationship may have been a result of flow of metal-bearing brines along the interface between solid footwall rocks and overlying water-saturated unconsolidated sediments. Figures 25 and 26 show the relationship of the massive sulfide deposits with felsic extrusion domes.

The Kuroko deposits exhibit a mineral zoning which is

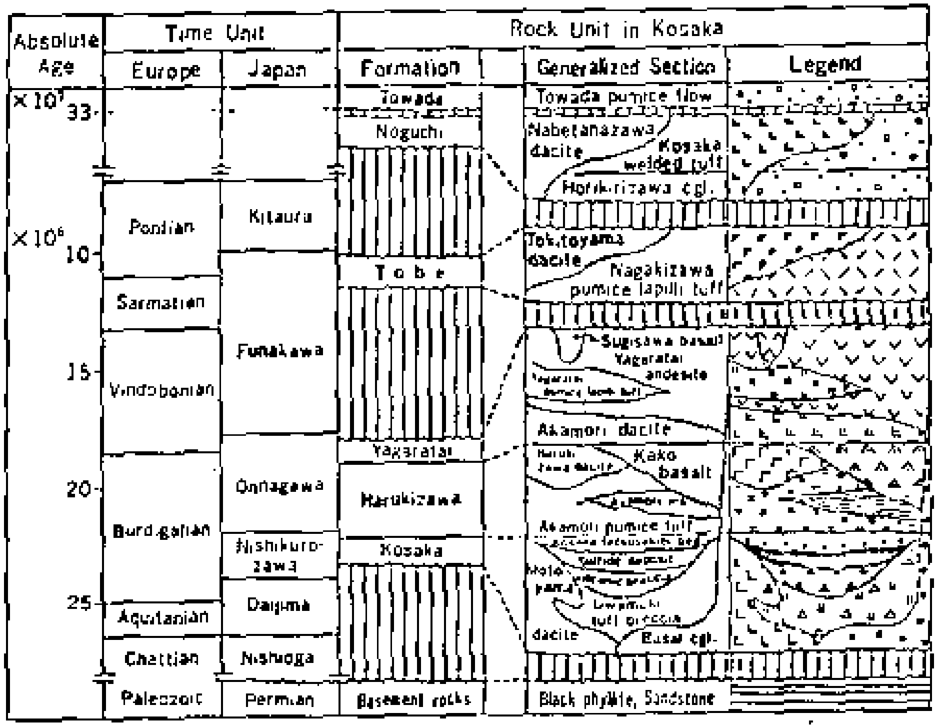


Figure 23 Stratigraphic Relationships of Kuroko Ores in the Kosaka District (Horikoshi and Sato, 1970)

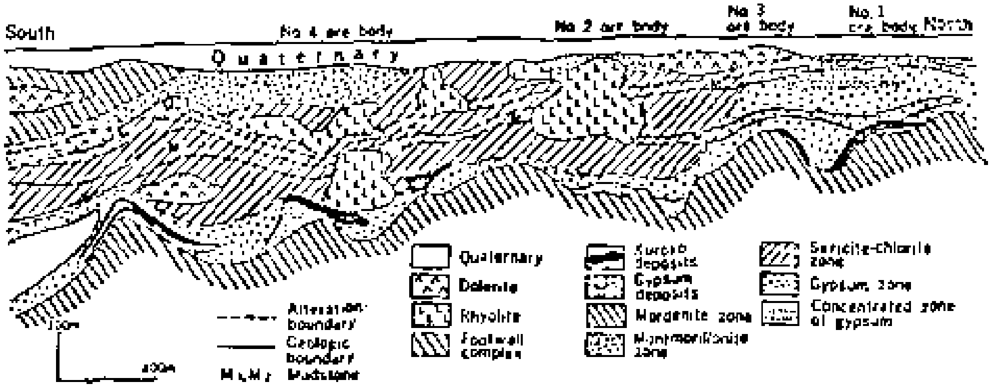


Figure 24 Geologic Section of the Shakanai Mine Showing Zonal Relationships of Alteration Types (Matsukuma and Horikoshi, 1970)

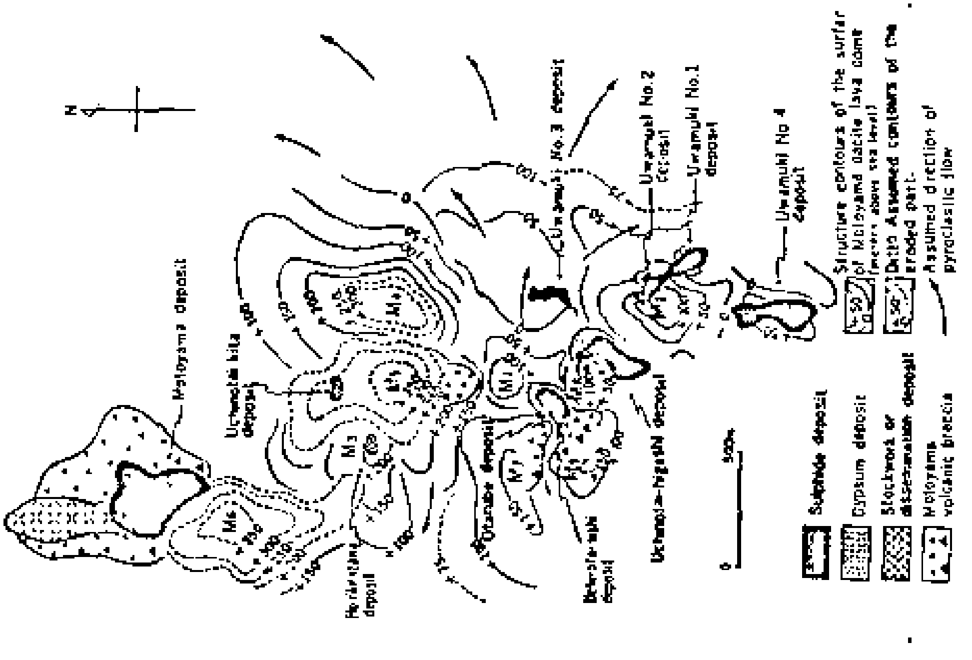


Figure 26 Distribution of Dacite Lava Domes and Associated Kuroko Deposits (Horikoshi and Sato, 1970)-

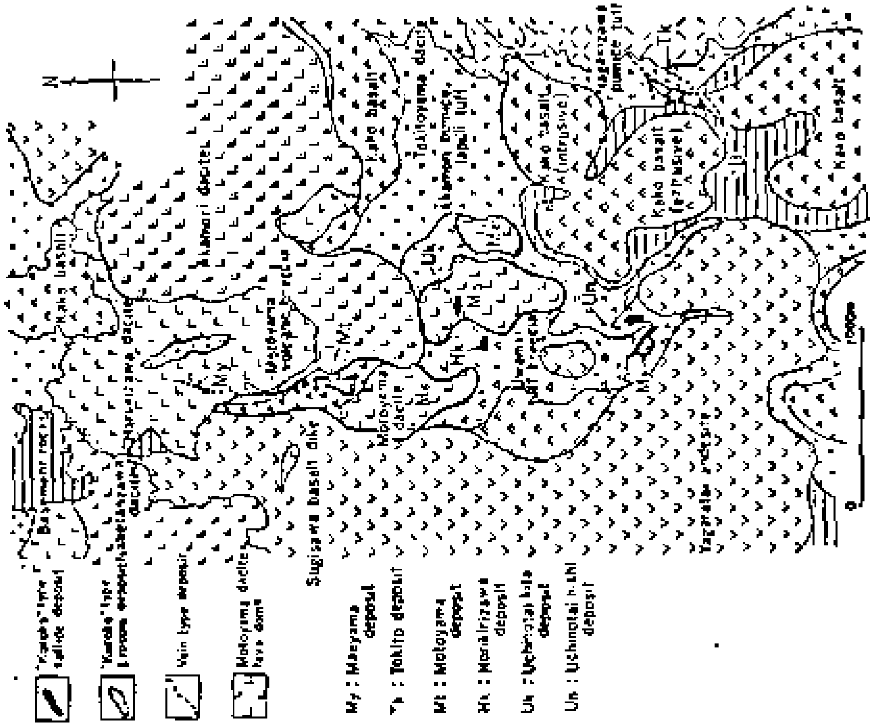


Figure 25 Geologic Map of the Kosaka District (Horikoshi and Sato, 1970)

similar to, but more complicated than, that observed in their Precambiran equivalents. Below is a summary of this zoning from top to bottom:

1. Hanging wall consisting of an upper volcanic or sedimentary unit which may or may not be altered;
2. Ferruginous quartz zone consisting of hematite, quartz, and some pyrite;
3. Barite zone usually consisting of monomineralic barite;
4. Kuroko zone, or black ore, consisting of fine grained barite, sphalerite, galena with minor copper and silver sulfides and sulfosalts;
5. Oko zone, or yellow ore, consisting of chalcopyrite and pyrite;
6. Keiko zone, or siliceous ore, which consists of chalcopyrite and pyrite with quartz gangue in a stockworks in silicified rhyolite;
7. Sekkoko zone, consisting of anhydrite, gypsum, and pyrite;
8. Footwall consisting of silicified rhyolite and pyroclastic rocks containing disseminated or vein sulfides.

A wide range of textures and structures are observed depending on the minerals being precipitated and the mode of precipitation. The ferruginous quartz zone may be equivalent to iron formation which is commonly associated with Archean massive sulfide deposits. Within the massive and stratified ore, many sedimentary features are present, including laminations, bedding, graded bedding and others. All these features are indicative of the syngenetic origin for the ores. Breccias are also common where fragments of sulfide may occur in fine grained sediment and tuffaceous material, or in a sulfide matrix of a different composition. The Kuroko and Oko zones are generally massive or banded whereas the Keiko ore occurs in a stockworks in the footwall. The mineralogy and textures are transitional between the various sulfide zones.

The Kuroko ore is the main base metal zone. It consists of sphalerite, galena, barite, chalcopyrite, pyrite, and tetrahedrite in order of abundance. Minor amounts of bornite, electrum, and native silver also occur. Tetrahedrite and silver increase towards the top of the zone and chalcopyrite increases towards the bottom. Silver occurs in the native state, and as tetrahedrite, argentite, jalpaite, stromeyerite, and polybasite. Less common minerals present are covellite, idaite, fukuchilite, and enargite.

The gypsum deposits usually underlie the massive sulfide lenses and also occur around the margins. The volume of sulfate material usually exceeds that of the sulfides. The gypsum is bedded and is a secondary alteration of anhydrite, the primary mineral deposited. Mirabilite, Na_2SO_4 $10H_2O$, is also found with the gypsum. Minor amounts of sulfide occur in the gypsum, including pyrite, base metal sulfides, and unusual copper sulfides. Figure 27 shows the metal and mineral zoning for the typical Kuroko deposit.

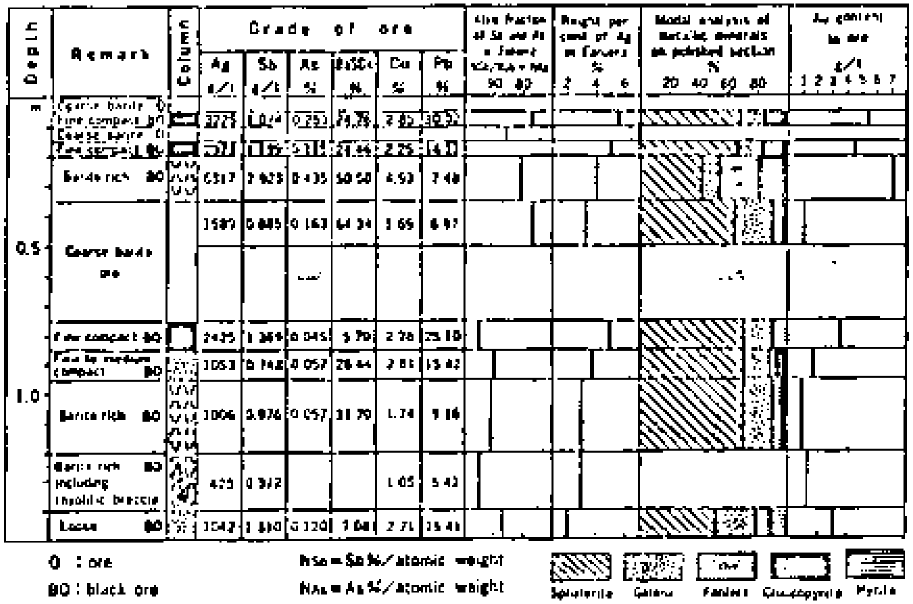


Figure 27 Columnar Section of Kuroko Ore Bodies Showing Mineralogical and Geochemical Zoning (Matsukuma and Horikoshi, 1970)

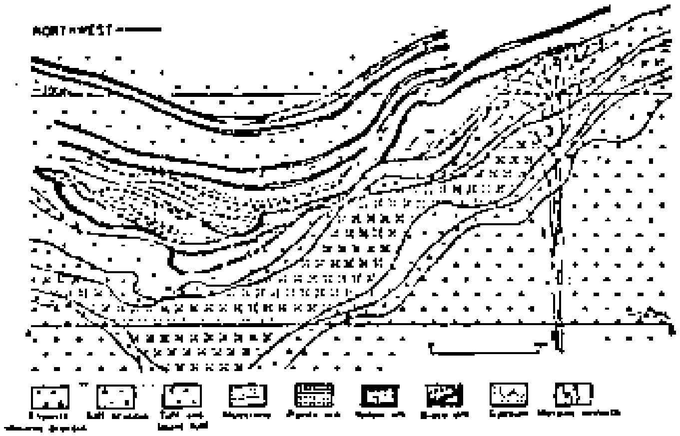


Figure 28 Geologic Section of No. 1 Ore Body, Shakanai District (Kajiwara, 1970)

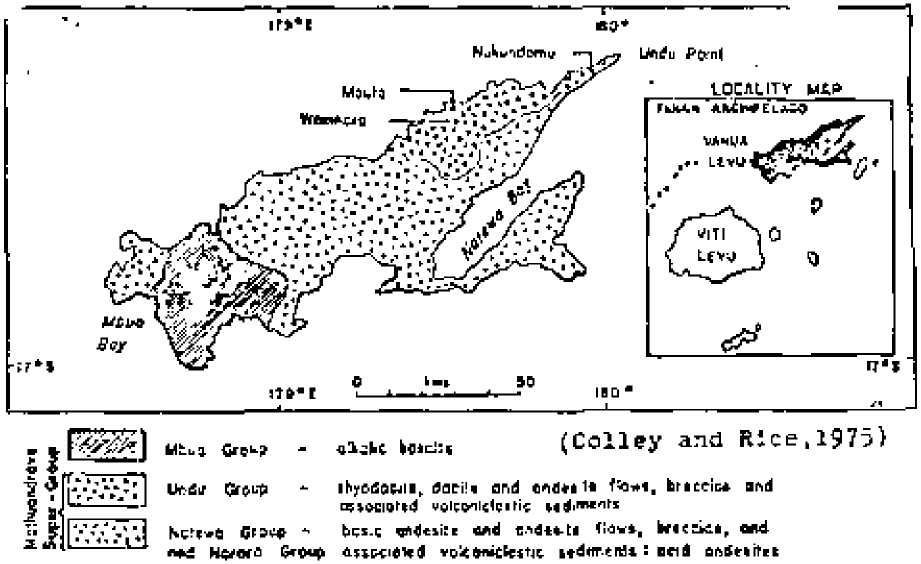
Four different episodes of alteration have occurred in the vicinity of the massive sulfide deposits. The first of the two main episodes consists of widespread regional metamorphism and is characterized by the conversion of the volcanic rocks to the assemblage epidote-chlorite-albite-sericite-quartz. The second most common alteration is that associated with mineralization and shows a zonal distribution around the deposits. From unaltered to altered rock the sequence observed is:

1. Montmorillonite-zeolite zone in the outer areas away from mineralization in contact with unaltered rock;
2. Sericite-chlorite-pyrite zone above the sulfide ore body;
3. Sericite-chlorite-quartz zone within the ord body where sericite and chlorite predominate;
4. Silicified zone with some sericite and chlorite in footwall and central part of ore body within stringer zone.

Some deposits are associated with the margins of basins which may be interpreted as calderas. Regional distribution of these calderas indicate they are controlled by prominent fracture zones. The extrusion domes appear to be structurally controlled as well. However, the small intrusions are not large enough to supply all the heat required to drive the mineralizing system. Temperatures of formation of the deposits from fluid inclusions and sulfur isotope geothermometry were 300°C for the stockwork ore and 250°C for the Kuroko ores. Therefore there had to be a large pluton beneath the caldera. The domes intruded along fracture systems which were formed with the development of the calderas.

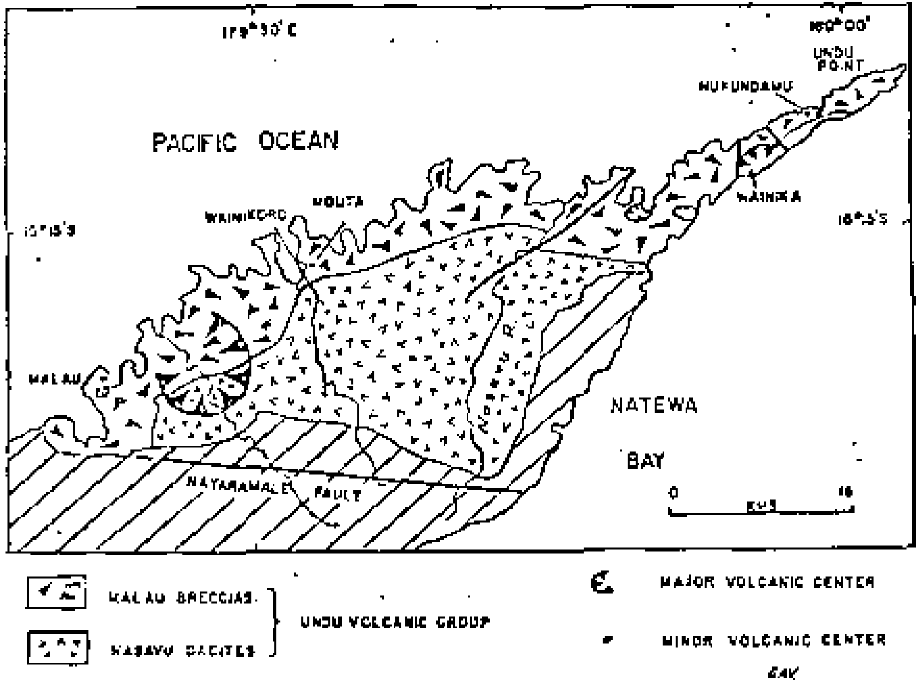
Using stable isotope data from sulfides and fluid inclusions Rye and Ohmoto (1974) developed a model for the origin of the Kuroko deposits. They established that the water and sulfur were derived from seawater. Heat, either from the intrusions or from a pluton at depth, set up a convection cell which pulled seawater into the mineralizing system. The metals were leached from the volcanic rocks and redeposited in fractures and on the sea floor as the solutions rose along the ascending limb of the convection system. Anhydrite may have precipitated directly from seawater as the latter was heated. The solubility of anhydrite decreases as temperature increases. The mechanism by which the sulfate was reduced to sulfide in unclear. It has been postulted to be a result of interaction with ferrous iron in the volcanic rocks.

Colley and Rice (1975) describe a Kuroko-type deposit on the island of Fiji. Figures 29 and 30 show the location of the deposits and the generalized geology of the northeast section of Vanua Levu Island in the vicinity of the deposits. The deposits are associated with a sequence of Miocene to Pliocene rhyodacites, andesites, and basalts with associated volcaniclastic sediments. Figure 31 shows the geology in the vicinity of the Undu mine. The deposits resulted from fumarolic activity on the sea floor at the end of the volcanic episode. The most common primary sulfides are pyrite, chalcopyrite, sphalerite, and galena, with



(Colley and Rice,1975)

Figure 29 Location and geologic map for Vanua Levu, Fiji.



Geologic map for the Undu region showing location of kuroko-style deposits, structural features, and important volcanic centers. Information on volcanic centers from Hindle (pers. commun., 1971).

Figure 30 (Colley and Rice, 1975)

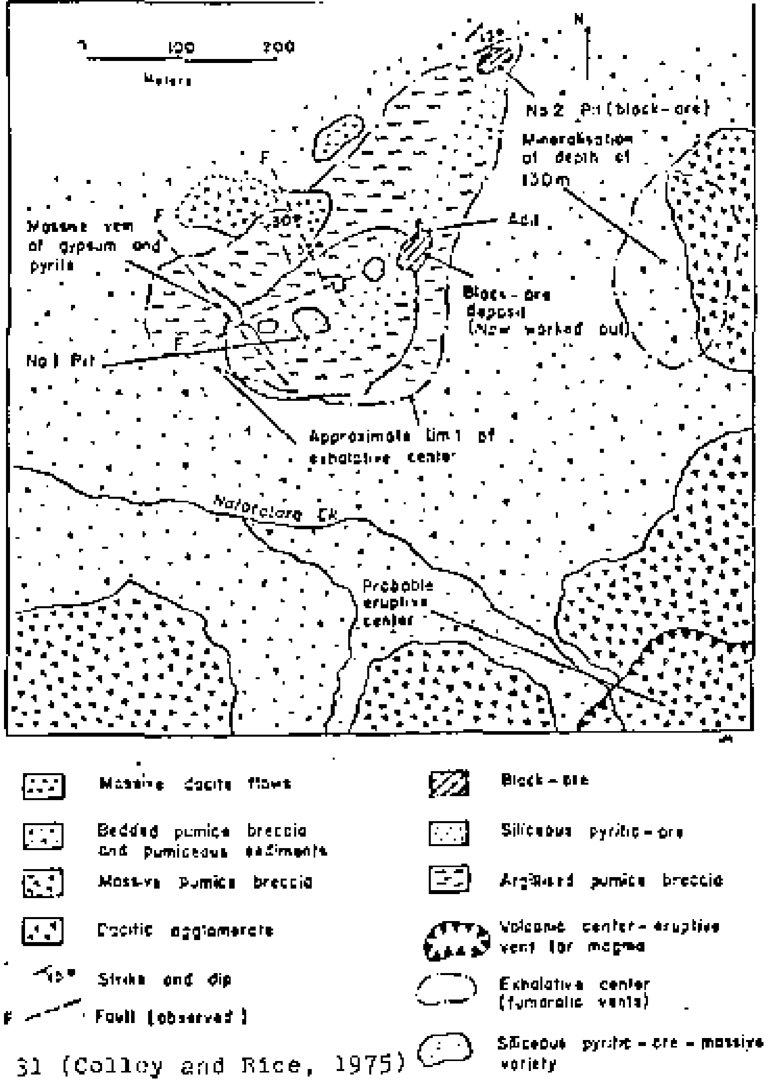
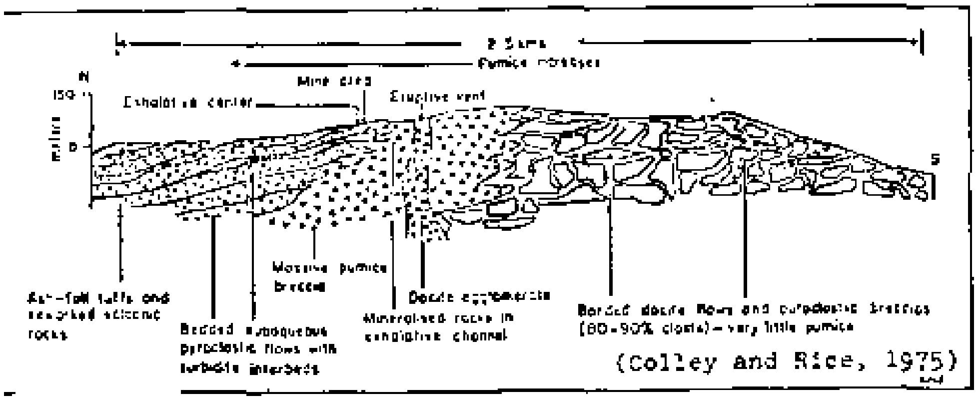


Figure 31 (Colley and Rice, 1975)

Geologic map for Undu mine based on traverse data of Colley and company map (Takahashi, 1965).



(Colley and Rice, 1975)

Figure 32 Cross section of the Undu peninsula in the region of Undu mine showing the relationship of the various members of the Undu Volcanic Group.

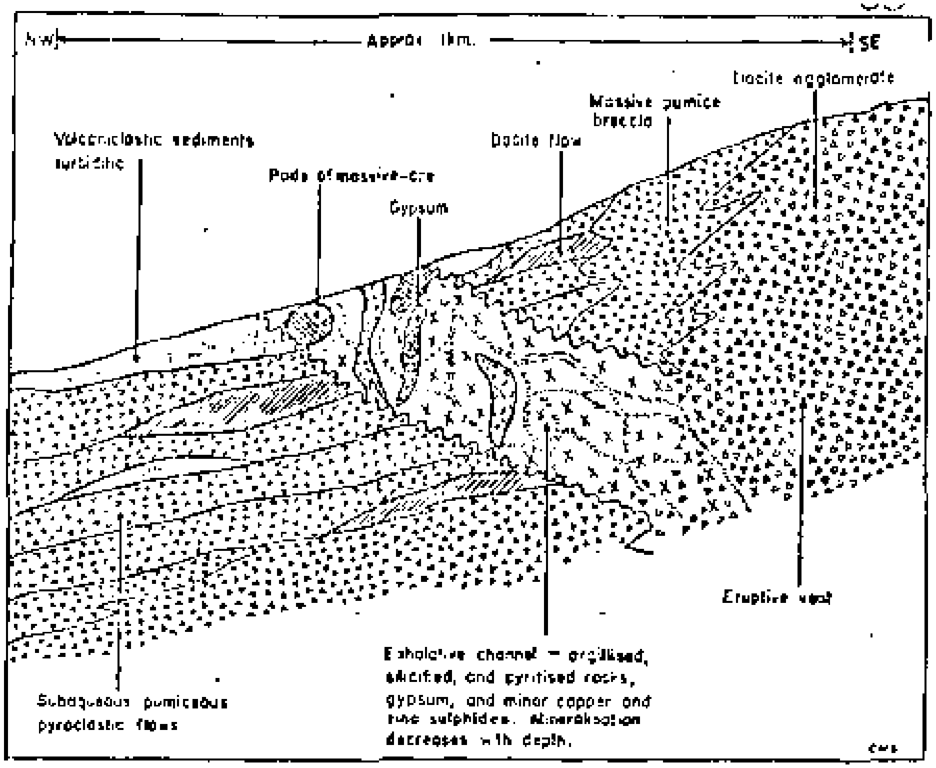
lesser amounts of enargite, tennantite, bornite, and idaite. The deposits are zoned vertically, with copper sulfides concentrated at the base and lead and zinc sulfides are concentrated at the top.

Ore deposition was accompanied by silicification and argillization of the enclosing wall rocks. Barite and anhydrite were also deposited with the sulfides. The footwall of the sulfide lenses consists of breccia, however, well developed extrusion domes are not found. Sulfide deposition occurred as open space filling in the breccias and syngenetic precipitation on the sea floor. Minor replacement of the volcanic rocks also was observed.

Figure 32 is a cross section of the area in the vicinity of the Undu mine showing the stratigraphic relationships of the various volcanic units. The association of the deposit with a volcanic center is apparent. Figure 33 schematically shows the local geological relationships of the mine area and the idealized representation of the fumarolic center. Figure 34 shows a reconstruction of the environemnt at the time of formation of the deposits.

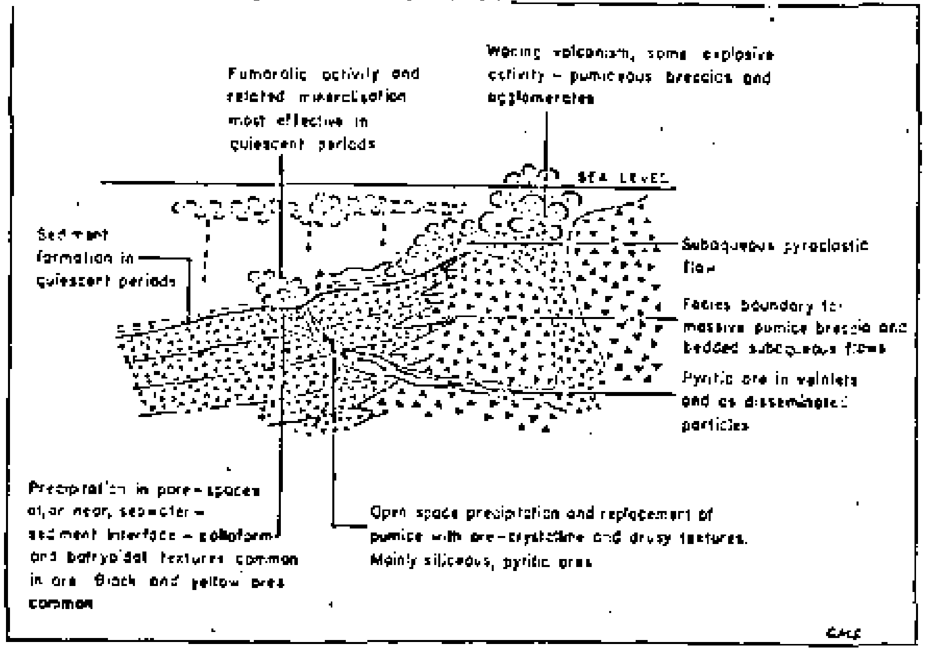
Copper-Pyrite Syngenetic Massive Sulfide Deposits

During Phanerozoic time massive sulfide deposits consisting mostly of copper sulfides and pyrite began to develop in association with mafic volcanic rocks. The environment of formation of these deposits is postulated to be oceanic spreading centers. The deposits on the island of Cyprus appear to be of this type. These deposits are associated with a large ultramafic complex, the Troodos complex, in the western part of the island.



Idealized section through the orebody at Undu mine showing the situation where a feeder complex reaches the surface and forms an exhalative center (N.B. the vertical scale is exaggerated).

Figure 33 (Colley and Rice, 1975)



Section through the Undu mine area showing conditions at the time of formation of the Undu ore deposit.

Figure 34 (Colley and Rice, 1975)

This igneous complex covers an area of approximately 1200 square miles and is an area of thin crust, as indicated by the large positive gravity anomaly. The tectonic setting is interpreted as being an oceanic mobile eugeosyncline with the Troodos complex, representing an ophiolite environment which has been obducted onto the crust due to thrusting to the north. The Troodos complex has a Cretaceous age and contains the oldest rocks on the island.

The Troodos complex consists of two parts, a plutonic complex at the center and around the edges consisting of a differentiated ultramafic complex with dunite, serpentinite, pyroxenite, gabbro, and granophyre, and an intervening sheeted zone consisting of diabasic rocks. The volcanic rocks containing the sulfide bodies overlie the ultramafic and mafic rocks. The lower series of volcanic rocks consists of 2000 feet of dacitic and andesitic units and contemporaneous dikes and sills of similar composition. The upper series consists of 1000 feet of basaltic extrusive and intrusive rocks. The mafic nature of the volcanic units increases upward, and the last stages of volcanism are represented by well preserved pillowed flows. Intercalated with the upper volcanic units, and overlying them, are thin clastic sediments consisting of manganiferous shales, chert, tuffs, and some pyritic shales. The copper-rich pyrite deposits occur conformably within the upper basaltic units. The highest grade deposits occur at the very top of the sequence where sedimentary units constitute the hanging wall.

Modern mining in this area began in 1880, where at least 23 deposits were mined. Many other occurrences are known. The total tonnage of ore was about 30 million tons, about half of which came from one deposit at Mavrovouni. The latter averages 3.5 to 4.5% copper and 0.5% zinc. One small deposit of 50,000 tons contained 4% copper and 8 to 9% zinc.

Most of the sulfide lenses are tabular and flat-lying, and frequently have broad synclinal forms. The latter deposits are thickest in the middle and follow irregularities in the underlying lava surface. They consist of major pyrite with lesser amounts of chalcopyrite, sphalerite and traces of galena. Marcasite is present as a secondary mineral, and pyrrhotite is absent. Many of the deposits have been exposed to weathering and secondary copper sulfides are present. Minor amounts of silver and gold occur. The largest deposit contains 0.25 to 1.25 ounces silver and 0.01 to 0.025 ounces gold per ton.

The ores are layered, and colloform banding is common. Large ellyptical bodies up to a foot long occur, which gives the ore a conglomeratic appearance. Banding consists of alternating layers of pyrite, marcasite, chalcopyrite, and small amounts of sphalerite. Fragmental textures also occur where fragments of pyrite are embedded in fine grained friable sulfides. Contacts between sulfides and volcanic units are usually very sharp except where fine stringers occur in and between adjacent pillows.

Alteration is absent in hanging wall rocks but is extensive in the ore horizon and footwall rocks. The most common alteration is chloritization, silicification, and the development of some clays. These deposits are interpreted as a result of submarine sea floor fumarolic activity.

Modern Submarine Fumarolic Systems

Sulfide-depositing hot springs have been discovered recently on the East Pacific Rise west of the Las Tres Marias Islands off the coast of Mexico (Francheteau, and others, 1979). The area of active hydrothermal activity occurs on a spreading center 90 kilometers north of the Rivera and 240 kilometers south of the Tamayo transform faults at a depth of approximately 2620 meters. The total width of the spreading zone is 1.5 km. The area is dominated by a series of horst and graben structures.

The area sampled during the 1978 CYAMEX expedition consisted of lightly sedimented flanks of steep-sided structural depressions about 20 to 30 meters deep, 20 to 30 meters wide, and 600 to 700 meters west of the axis of the spreading center. This area contains the youngest volcanic units. Locally open fissures 2 to 3 meters wide were observed. The mineral deposits were built on a pillow lava terrane with only minor amounts of sediments. The deposits are aligned along boundary faults of the graben structures. They take the form of irregular columns up to 10 m high and 5 m in diameter. These structures are very porous and consist of an interlocking system of tubes. An open vent occurs at the top of the edifices.

Three types of mineralization occur away from the large constructional features: incrustations coating moderately steep surfaces; 10 to 20 cm wide conelets built on sediments; and travertine-like flows drapping nearly vertical scarps. The material in the large mounts is friable and porous and easily fragmented. It shows a variety of colors from yellow to brown, grey and metallic blue, bronze red and white. Native sulfur locally occurs in coatings. The tubes are concentrically zoned where the inner walls are lined with metallic microcrystalline material. The brownish material consists of amorphous iron oxide as secondary alteration of sulfides and is found in the interstices between sulfide grains. The sulfides consist of sphalerite and pyrite with minor chalcopyrite and marcasite. Minor elements found in the sulfides were cobalt, lead, silver, and cadmium. The age of the deposits is estimated to be less than 10,000 to 20,000 years based on the age of the lavas. The area sampled appears to be dormant at the present time as the bottom water was not anomalously hot.

General Models for Origin of Volcanogenic Massive Sulfide Deposits

Hutchinson (1973) summarized the tectonic settings for the formation of the various types of volcanogenic massive sulfide deposits. Figure 35 schematically represents the tectonic environment for the Archean zinc-copper-pyrite type. It consists of an area of volcanism in a thin crustal environment overlying a thick poorly differentiated upper mantle. Figure 36 summarizes the tectonic environment for the Proterozoic lead-zinc-copper-pyrite type. In this case the crust is thicker and more differnetiated and the upper mantle is thinner and more differentiated. Figures 37 and 38 reproduce the tectonic environments in which the zinc-copper-pyriet and lead-zinc-copper-pyrite reappear in Phaneroic time. This environment is the classical subduction zone where the massive sulfide deposits are generated in a submarine island arc area.. The main difference between the two

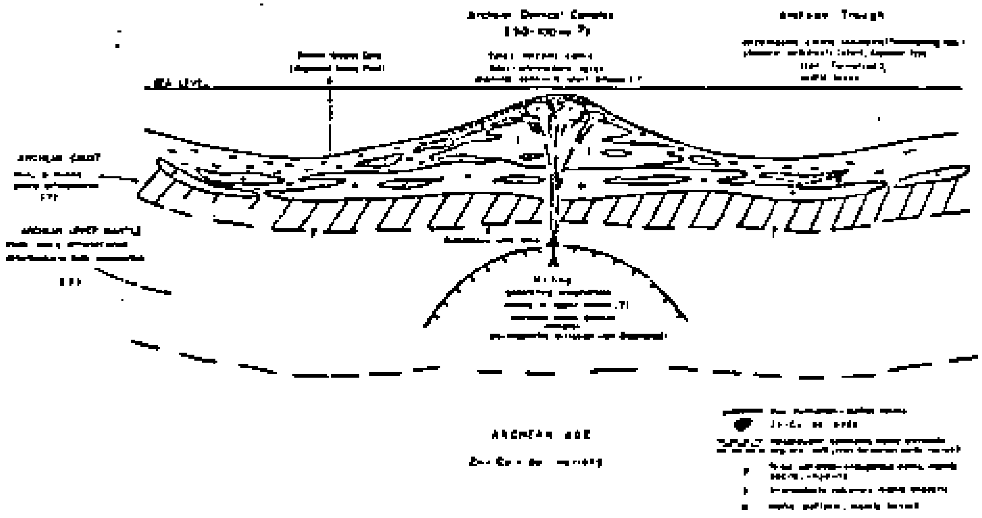


Figure 35 (Hutchinson, 1973)

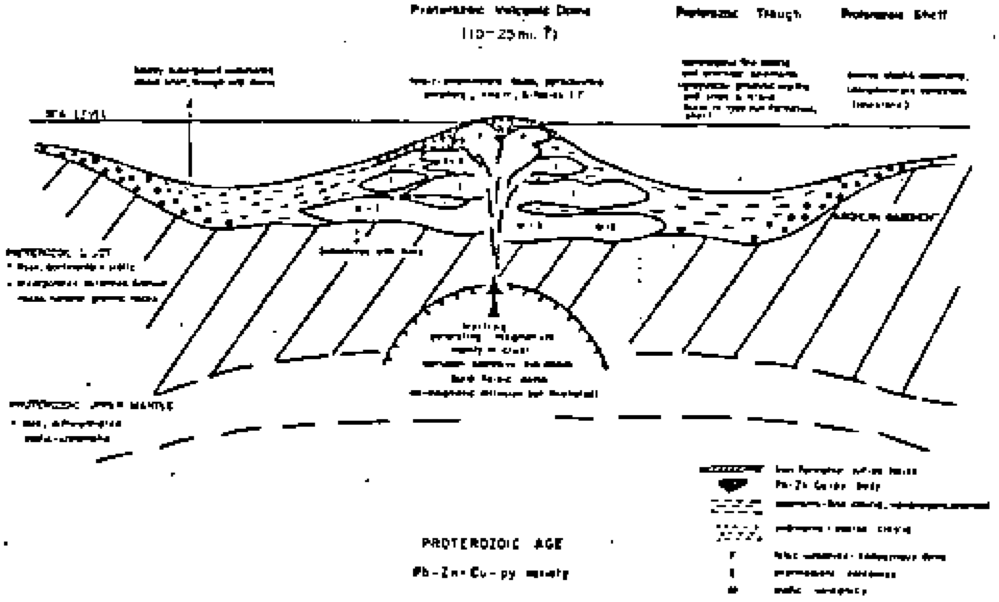


Figure 36 (Hutchinson, 1973)

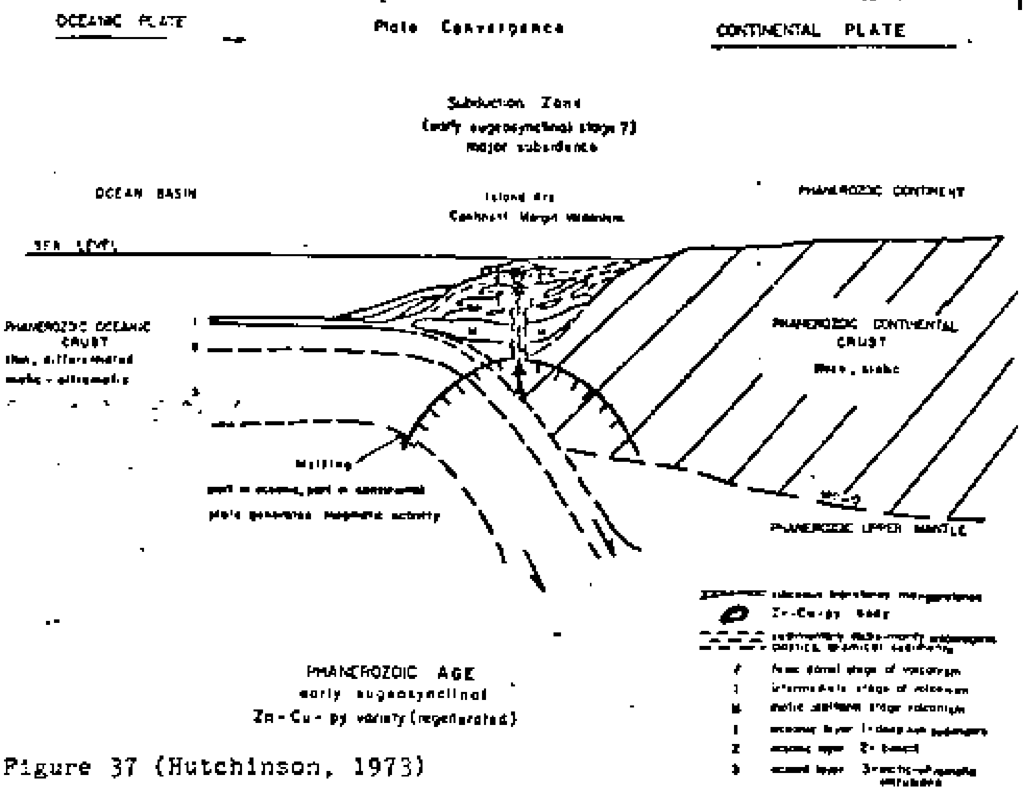


Figure 37 (Hutchinson, 1973)

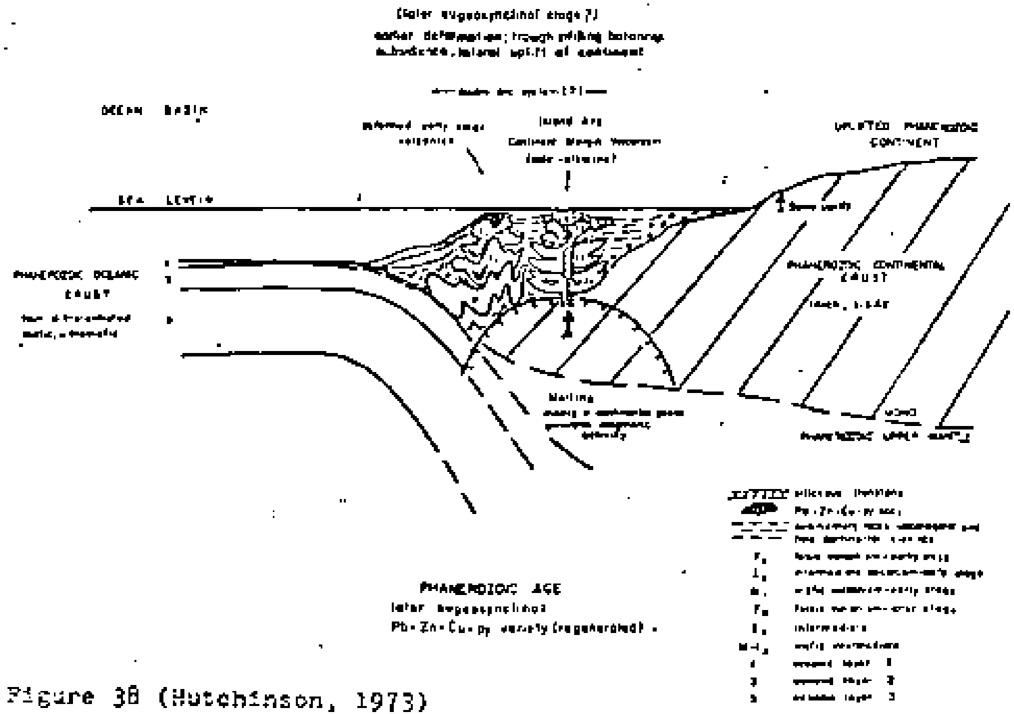


Figure 38 (Hutchinson, 1973)

types is proximity to the continent and the degree of involvement of the latter in the melting process. The lead deposits are more typical of areas closer to the continent.

Figure 39 summarized the environment of formation for the copper-pyrite type. This is the classical spreading center where basaltic volcanism dominates in a crustal extension area. Figure 40 shows the distribution and age of sulfide deposits in California. Hutchinson (1973) interprets the change in type of sulfide deposit in space and time as being the result of the change in tectonic environment from Devonian to Jurassic time (Figs. 37 and 38).

Syngenetic Massive Sulfide Deposits in Sedimentary Rocks

Massive and banded sulfide deposits occur as lenses conformable to eugeosynclinal sediments of Precambrian and younger age. The best example of this type of deposit is the Sullivan mine near Kimberley, British Columbia (Fig. 41). Over 100 million tons of ore have been produced containint 6.6% lead, 5.7% zinc, and 68 grams silver per metric ton (Eithier and others, 1976). Three other smaller deposits occur in the area. The deposit occurs in Precambrian eugeosynclinal sediments on the east flank of the Purcell trench. The rocks are equivalent to the Belt Series, and consist of over 45,000 feet argillaceous and arenaceous sediments deposited from 1700 to 850 million years ago. The massive sulfide lenses occur conformably within argillites and siltstones of the Aldridge Formation deposited between 1700 and 1300 million years ago. The deposits occur at a horizon where sedimentation changed from shallow to deep marine when the basin of deposition began to subside rapidly. The lower Purcell

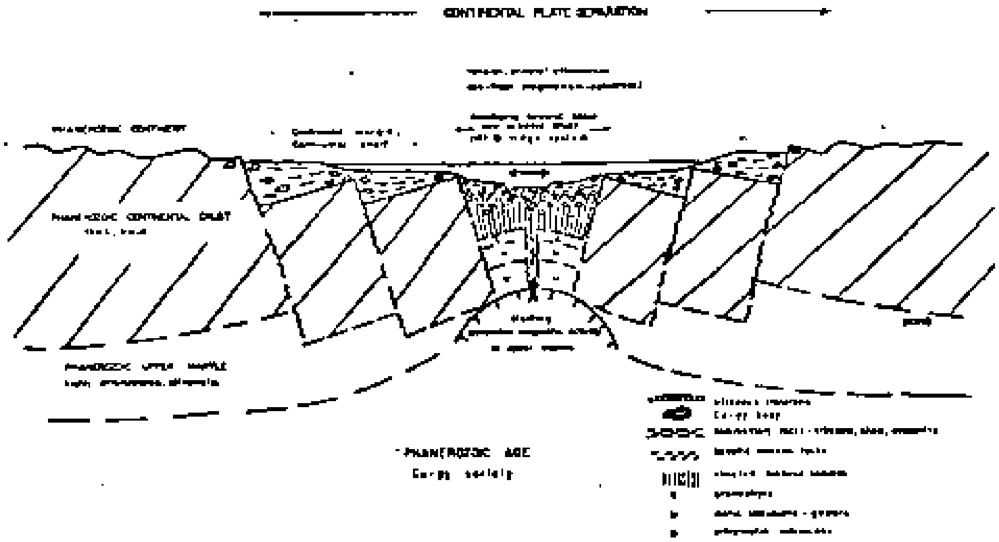


Figure 39 (Hutchinson, 1973)

DISTRIBUTION OF SOME MASSIVE SULFIDE BODIES IN VOLCANIC ROCKS NORTHERN CALIFORNIA

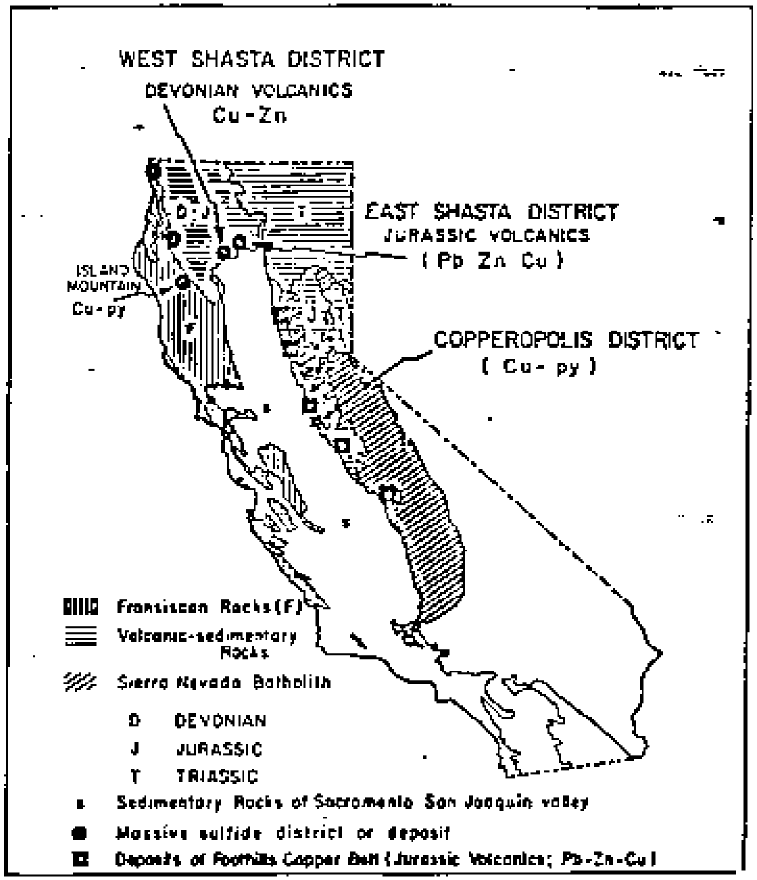
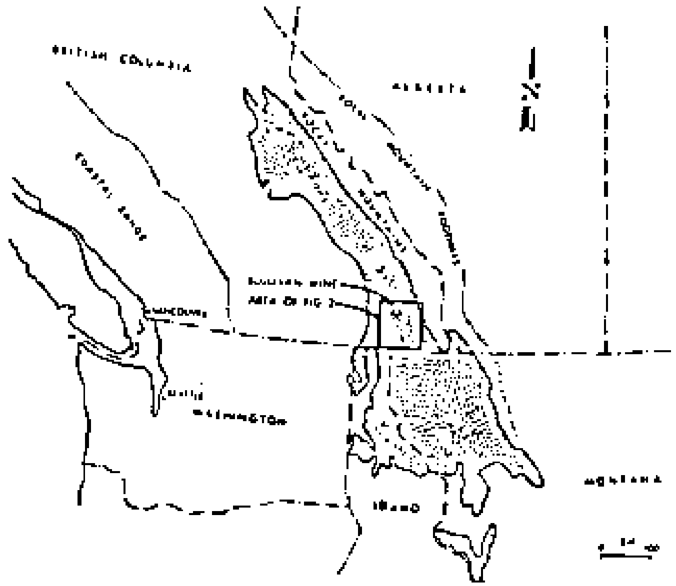
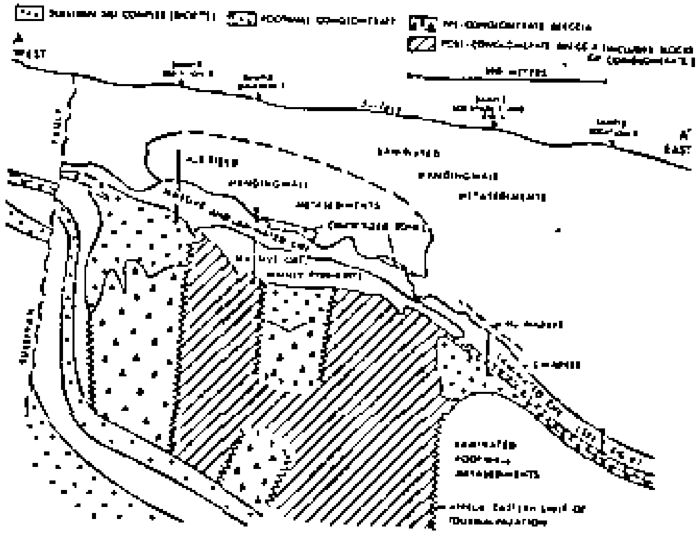


Figure 40 (Hutchinson, 1973)



Map showing extent of Purcell and overlying Windermere rocks (stippled) in western North America and location of Sullivan orebody.

Figure 41 (Ethier and others, 1975)



Schematic east-west structural cross section A-A' showing typical facies relationships of rocks enclosing Sullivan orebody. Location of cross section shown on Figures 4 and 7. Solid vertical bars indicate stratigraphic position and extent of continuous cores or crosscuts sampled for this study. Horizontal and vertical scale the same. (Modified from Jardine, 1966.)

Figure 42 (Ethier and others, 1975)

sequence may represent a deltaic fringe on the craton to the east.

The Aldridge Formation in the vicinity of the deposit contains graded bedding and other features suggesting a turbidite sequence. The main ore lense occurs within a single stratigraphic horizon. Ore has been recovered through a thickness of 200 to 300 feet, along strike for 6000 feet, and 4500 feet down dip. The lense thickens and thins along minor irregularities in the surrounding sediments. Figure 42 is a cross section through the mine area showing the various geologic relationships.

There are igneous rocks in the vicinity of the deposit, such as the Sullivan sill in Figure 42, however it is generally accepted that they are not genetically related to the mineralization.

An important feature in the footwall of the ore lense is the presence of breccia and conglomerate. The breccia is interpreted as a result of collapse of the Aldridge sediments during deposition on a steep slope. This slope could be related to a local fault scarp which, in turn, is related to the initiation of subsidence of the basion. This breccia appears to occur beneath the zone of maximum thickness of the massive sulfides. The depression produced by the collapse is filled with up to 60 meters of conglomerate. The pebbles were derived from lithified Aldridge sediments. Post depositional tectonic activity along north-south zones resulted in the brecciation of conglomerates and other rocks. Brecciation occurred before, during, and after mineralization as the ore is also faulted. Brecciation occurred primarily in the western up-dip portion of the deposit.

Most of the ore shows layering ranging in thickness from less than a centimeter up to a half meter. Some very fine continouous laminations are common and may show crinkling. Soft sediment deformation features are common.

The sulfide ores consist predominantly of pyrrhotite, galena, sphalerite, and pyrite with minor chalcopyrite, arsenopyrite, magnetite, cassiterite, boulangerite, jamesonite, and tetrahedrite. Alterattion consists of tourmalinization in the footwalls beneath the ore lense as a funnel-shaped zone in the western part of the deposit. This alteration zone extends for more than 1500 feet below the footwall and may represent a feeder system for the massive sulfides. Albitization and chloritization occur above the central zone of the ore zone stratigraphically above the zone of tourmalinization.

The ore deposit is zoned vertically and concentrically above the area of most intense alteration but slightly down dip. A central iron zone consisting of mostly pyrrhotite occurs directly above the area of tourmalinization and near the footwall of the ore lense. Pyrite increases towards the hanging wall. Cassiterite is associated with the pyrrhotite as in some of the arsenopyrite. Lead in concentrated in a concentric zone around the central iron zone. The lead to zinc ratio decreases towards the periphery of the deposit and upward above the central zone. Massive pyrrhotite grades upward into well banded galena-sphalerite ore. Towards the hanging wall sulfide bands may be interlayered with siliceous argillaceous material. Silver appears to be most closely associated with galena.

The sulfide lense was deposited on the sea floor at the same time as the associated argillaceous sediments in a rapidly subsiding geosynclinal basin. The overall thickness of the stratigraphic column indicates the sediments are thickened in the mine area because of the addition of the sulfides.

References Cited

Anderson, C.A. and J.T. Nash, 1972, Geology of the massive sulfide deposits at Jerome, Arizona - a reinterpretation: Econ. Geol., v. 67, p. 845-863.

Colley, H. and C.M. Rice, 1975, A Kuroko-type ore deposit in Fiji: Econ. Geol., v. 70, p. 1373-1386.

Either, V.G., F.A. Campbell, R.A. Both, and H.R. Krouse, 1976, Geological setting of the Sullivan orebody and estimates of temperatures and pressure of metamorphism: Econ. Geol., v. 71, p. 1570-1588.

Francheteav and others, 1979, Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise: Nature, v. 277, p. 523-528.

Goodwin, A.m., 1965, Mineralized volcanic complexes in the Porcupine-Kirkland Lake-Noranda region, Canada: Econ. Geol., v. 60, p. 955-971.

Goodwin, A.M. and R.H. Ridler, 1970, The Abitibi orogenic belt: in: Symposium on Basins and Geosynclines of the Canadian Shield; A.J. Baer, ed.; Geol. Surv. Canada Paper 70-40, p. 1-30.

Horikoshi, E. and T. Sato, 1970, Volcanic activity and ore deposition in the Kosaka mine; in: Volcanism and Ore Genesis, T. Tatsumi, ed.; Univ. Tokyo Press, Tokyo, p. 181-195.

Hutchinson, R.W., 1973, Volcanogenic sulfide deposits and their metallogenic significance: Econ. Geol., v. 68, p. 1223-1246.

Kajiwara, Y., 1970, Syngenetic features of the Kuroko ore from the Shakanai mine; in: Volcanism and Ore Genesis, T. Tatsumi, ed.; Univ. Tokyo Press, Tokyo, p. 197-206.

Matsukuma, T. and E. Horikoshi, 1970, Kuroko deposits in Japan, a review; in: Volcansim and Ore Genesis, T. Tatsumi, ed.; Univ. Tokyo Press, Tokyo, p. 153-179.

Ohmoto, H. and R.O. Rye, 1974, Hydrogen and oxygen isotopic compositions of fluid inclusions in the Kuroko deposits, Japan: Econ. Geol., v. 69, p. 947-954.

Ridler, R.H., 1970, Relationship of mineralization to volcanic stratigraphy in the Kirkland-Larder Lakes area, Ontario: Geol. Assoc. Canada Proc., v. 21, p. 33-42.

Sangster, D.F., 1972, Precambrian volcanogenic massive sulfide deposits in Canada: A review: Geol. Survey Canada Paper 72-22, 44 p.

Simmons, B.D., 1973, Geology of the Millenbach massive sulphide deposits, Noranda, Quebec, Canada: 75th Annual Meeting, CIM; Vancouver, 20 p.

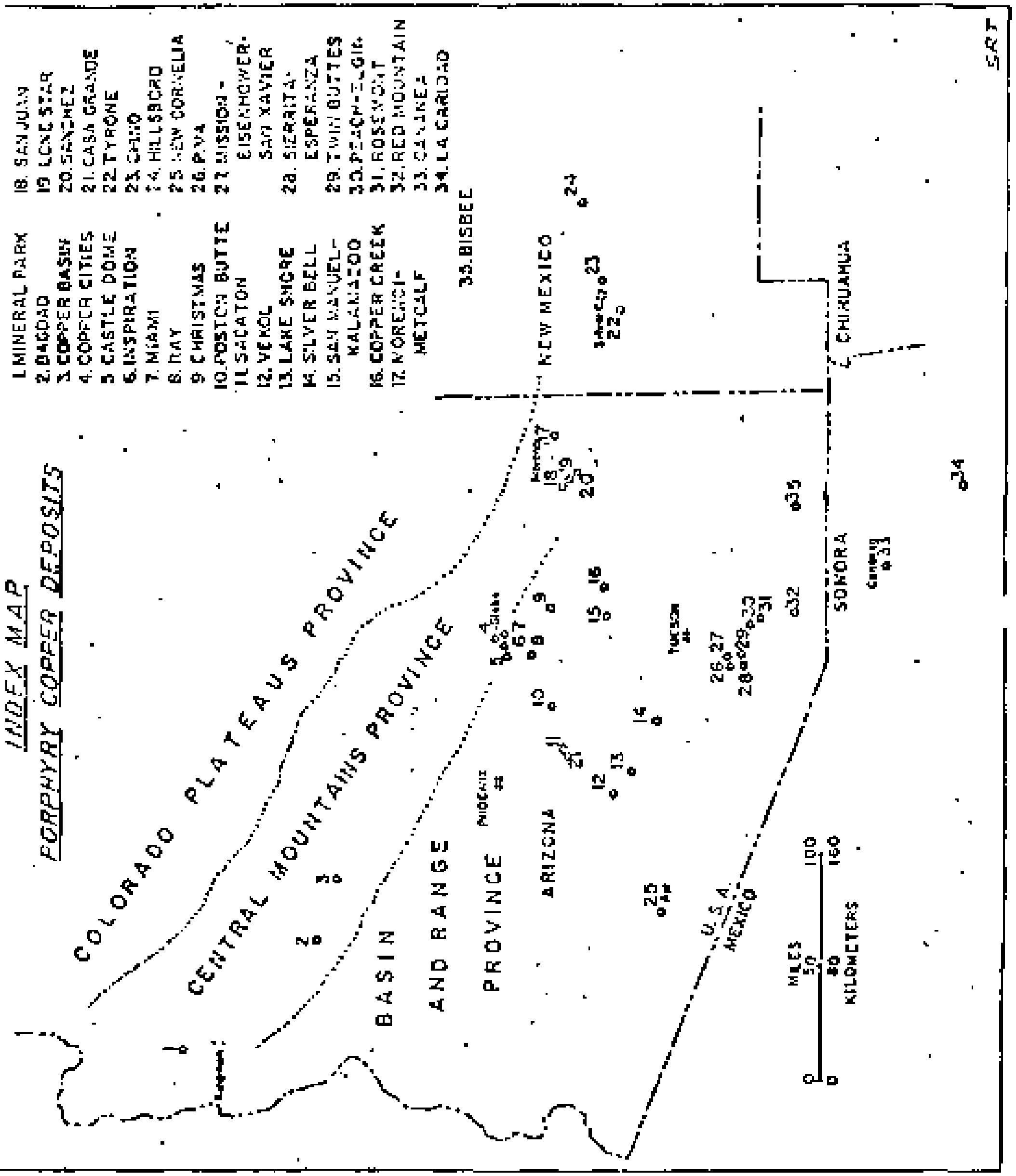
Sinclair, W.D., 1971, A volcanic origin for the No. 5 zone of the Horne mine, Noranda, Quebec: Econ. Geol., v. 66, p. 1225-1231.

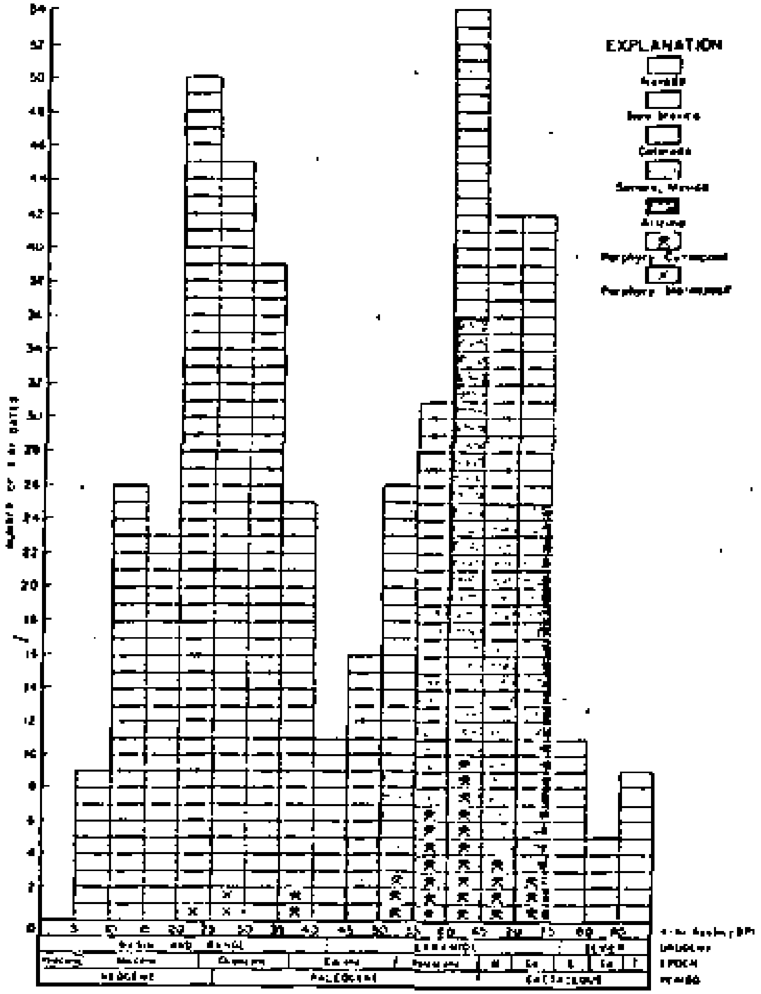
Spence, C.D. and A.F. de Rosen-Spence, 1975, The place of sulfide mineralization in the volcanic sequence at Noranda, Quebec: Econ. Geol., v. 70, p. 90-101.

Tatsumi, T. Y. Sekine, and K. Kanehira, 1970, Mineral deposits of volcanic affinity in Japan: Metallogeny; in: Volcanism and Ore Genesis, T. Tatsumi, ed.; Univ. Tokyo Press, Tokyo, p. 3-47.

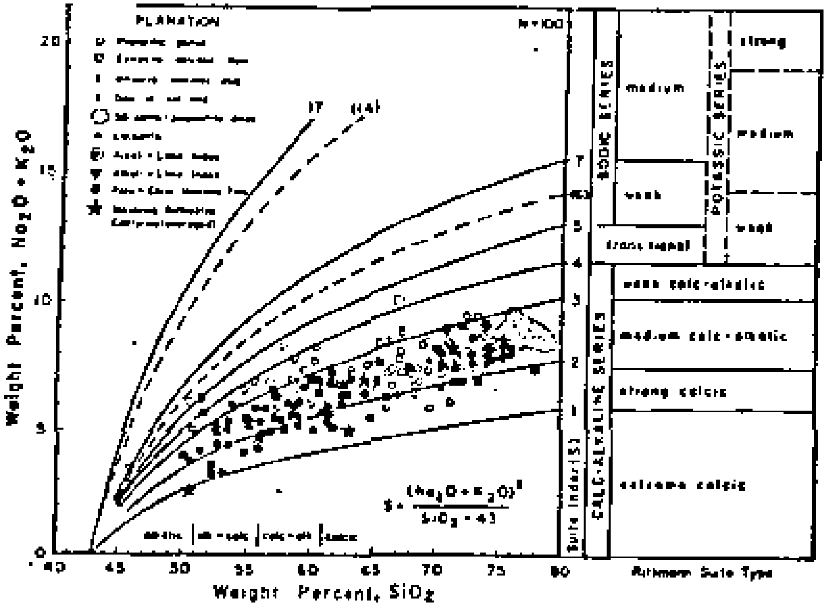
Thurlow, J.G., E.A. Swanson, and D.F. Strong, 1975, Geology and lithogeochemistry of the Buchans polymetallic sulfide deposits, Newfoundland: Econ. Geol., v. 70, p. 130-144.

Walker, R.R., A. Matulich, A.C. Amos, J.J. Watkins, and G.W. Mannard, 1975, The geology of the Kidd Creek mine: Econ. Geoll, v. 70, p. 80-89.

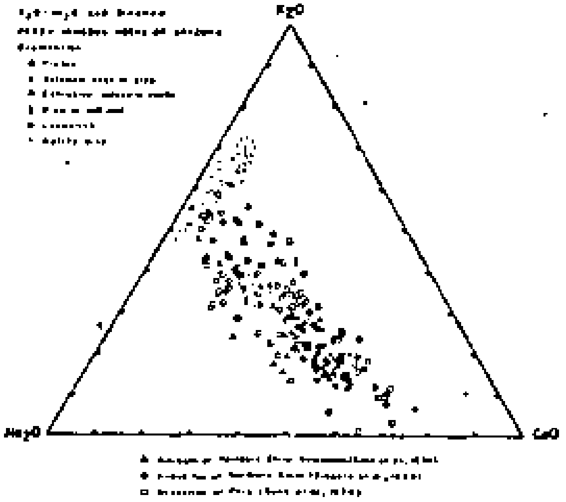




Histogram of K-Ar Ages from Igneous Rocks, American Southwest. -- Plotted data are from hypabyssal plutons and volcanic rocks or their hydrothermally altered equivalents. The post-40 m.y. BP portion of the histogram is after Damon (1971).

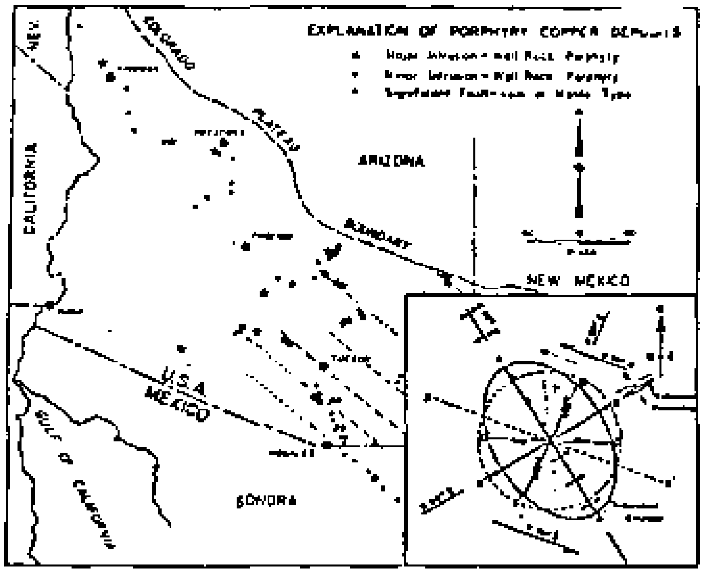


a.

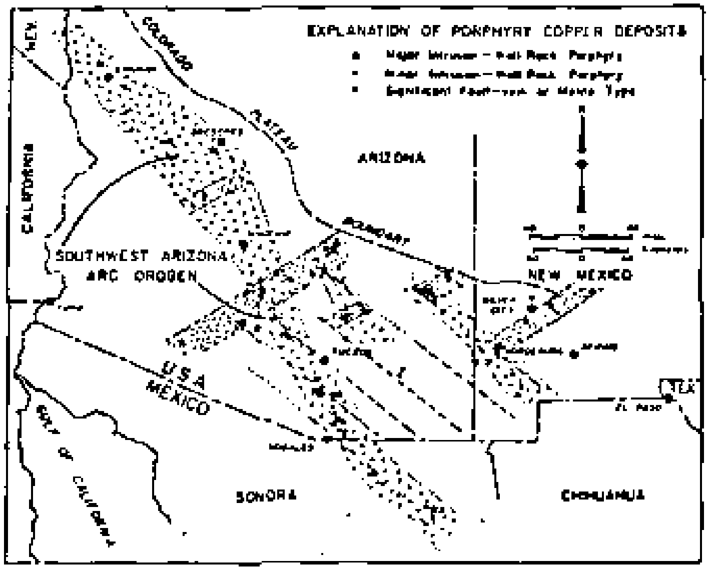


b.

K$_2$O + Na$_2$O - SiO$_2$ and K$_2$O-Na$_2$O-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).

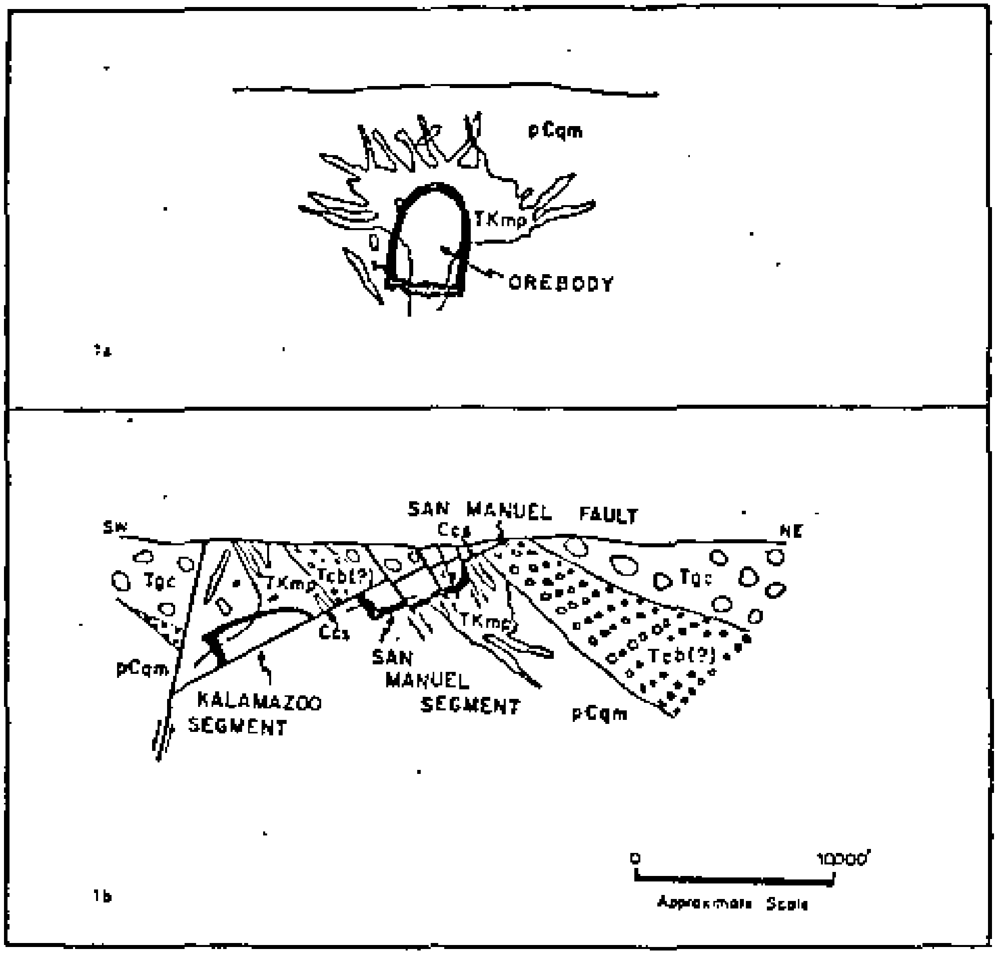


a.

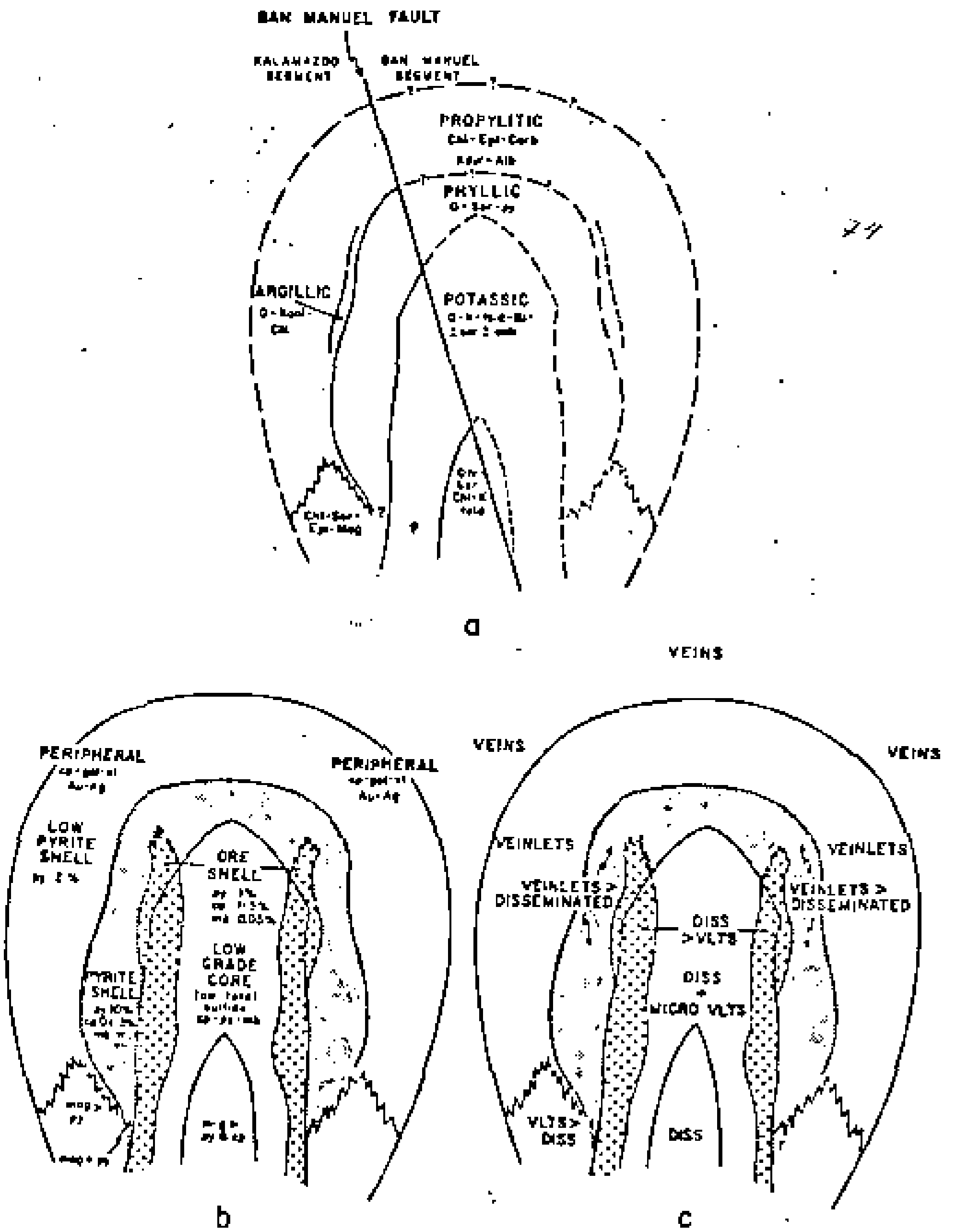


b.

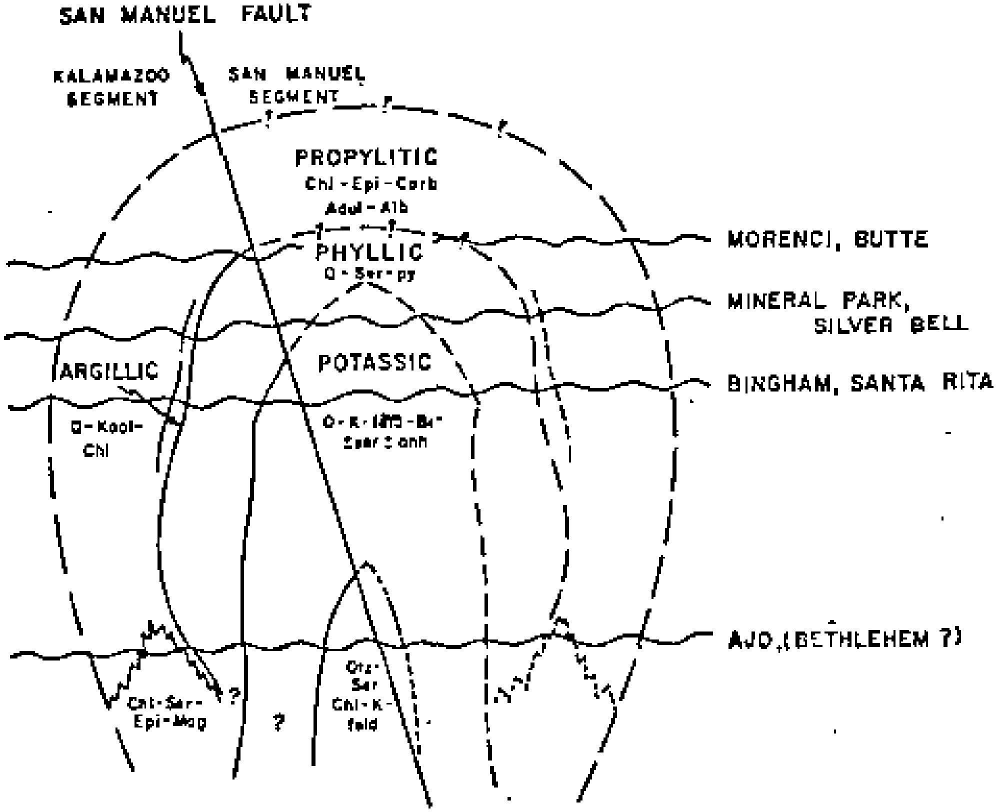
; Laramide volcano-tectonic framework of southwestern New Mexico and southern Arizona showing the distribution of major and minor porphyry deposits (5a), derived intermineral paleostrain field (5a, inset), position of inferred composite Andean arc orogen, and several transverse ENE-trending porphyry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



Idealized Geologic Cross Sections of the Kalamazoo-San Manual Porphyry Copper Deposit; 1a: predeformation reconstruction; 1b: post deformation(Lowell and Guilbert, 1970)



Concentric Alteration-mineralization Zones at San Manuel-Kalamazoo a: alteration zones; b: mineralization zones; c: occurrence of sulfides (Lowell and Guilbert, 1970)



Schematic Diagram of San Manuel-Kalamazoo Porphyry Copper Deposit Showing Exposure Levels of Several Other Deposits (Lowell and Guilbert, 1970)

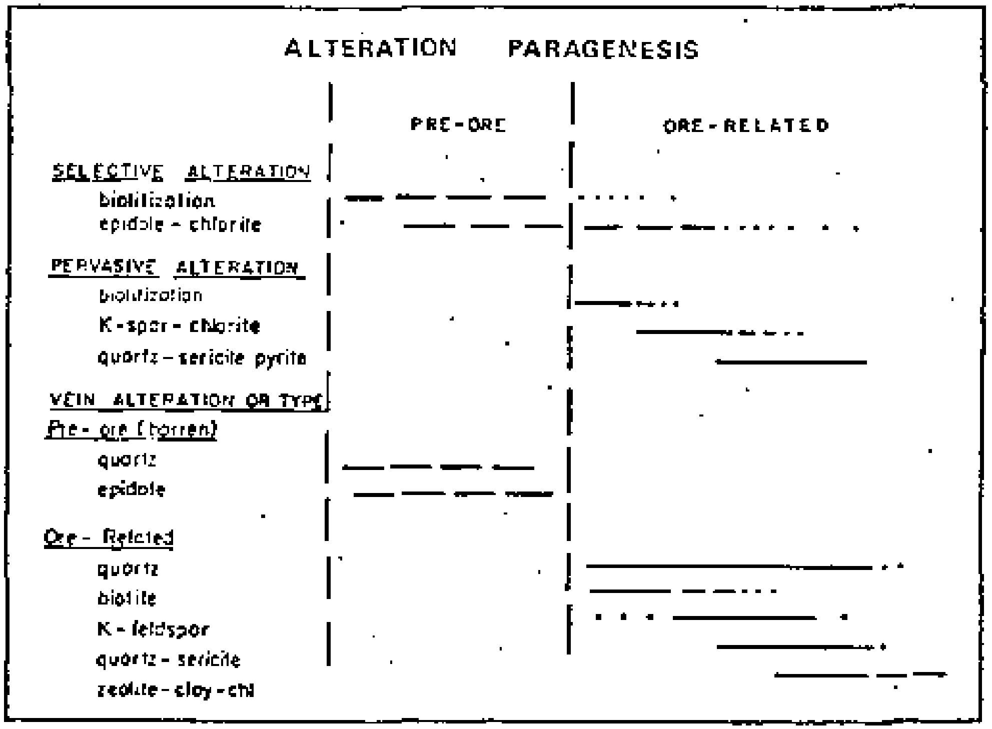


TABLE 1

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

TYPICAL WALLROCK ALTERATION REACTIONS:

Starting material, fresh quartz monzonite consisting of:
40% plagioclase, 40% K-feldspar, quartz, hornblende, minor biotite.

Propylitic zone: ($+H_2O$, H^+, S, CO_2; -little)

$NaCa_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2 \longrightarrow (Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$
Hornblende — Chlorite

$CaCO_3$ Calcite
FeS_2 Pyrite, or magnetite

$K(Mg,Fe)_3(AlSi_3O_{10}(OH)_2 \longrightarrow (Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$ chlorite
Biotite — Pyrite, or magnetite.

$2K(Mg,Fe)_3AlSi_3O_{10}(OH)_2 + 4H^+ \longrightarrow Al(Mg,Fe)_5AlSi_3O_{10}(OH)_8 + (Mg,Fe)^{2+} + K^+ + 3SiO_2$

Plagioclase $(Ca,Na)Al(Al,Si)Si_2O_8 \longleftarrow$ Epidote $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$
Albite $NaAlSi_3O_8$
Calcite $CaCO_3$

$2NaCaAl_3Si_5O_{16} + 2SiO_2 + Na^+ + H_2O \longrightarrow Ca_2Al_3Si_3O_{12}(OH) + 3NaAlSi_3O_8 + H$

Argillic zone (montmorillonite subzone) ($+H_2O$, H^+, S, CO_2: $-Ca^{2+}$, Na^+, SiO_2)

Plagioclase $\longrightarrow$ Montmorillonite, $Al_2Si_4O_{10}(OH)_2 \cdot xH_2O$ (Ca,Na)

Argillic zone (kaolinite subzone) ($+H_2O$, H^+; $-Ca^{2+}$, Na^+, Mg^{2+}, SiO_2)

Montmorillonite $\longrightarrow$ Kaolinite, $Al_2Si_2O_5(OH)_4$
Chlorite $\longrightarrow$ Biotite

Phyllic zone (sericite zone) ($+H^+$, S, SiO_2; $-Ca^{2+}$, Na^+, Mg^{2+})

Everything $\longrightarrow$ Sericite $KAl_2AlSi_3O_{10}(OH)_2$; pyrite; quartz.

$3KAlSi_3O_8 + 2H^+ \longrightarrow KAl_2AlSi_3O_{10}(OH)_2 + 2K^+ + 6SiO_2$

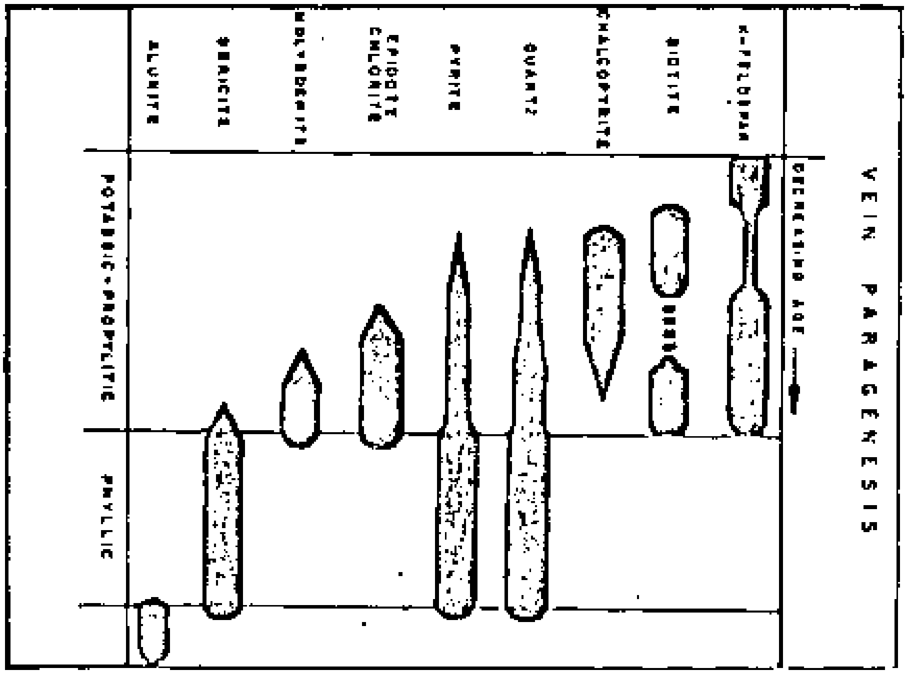
Potassic zone

Reconstruction of K-feldspar, biotite, etc.

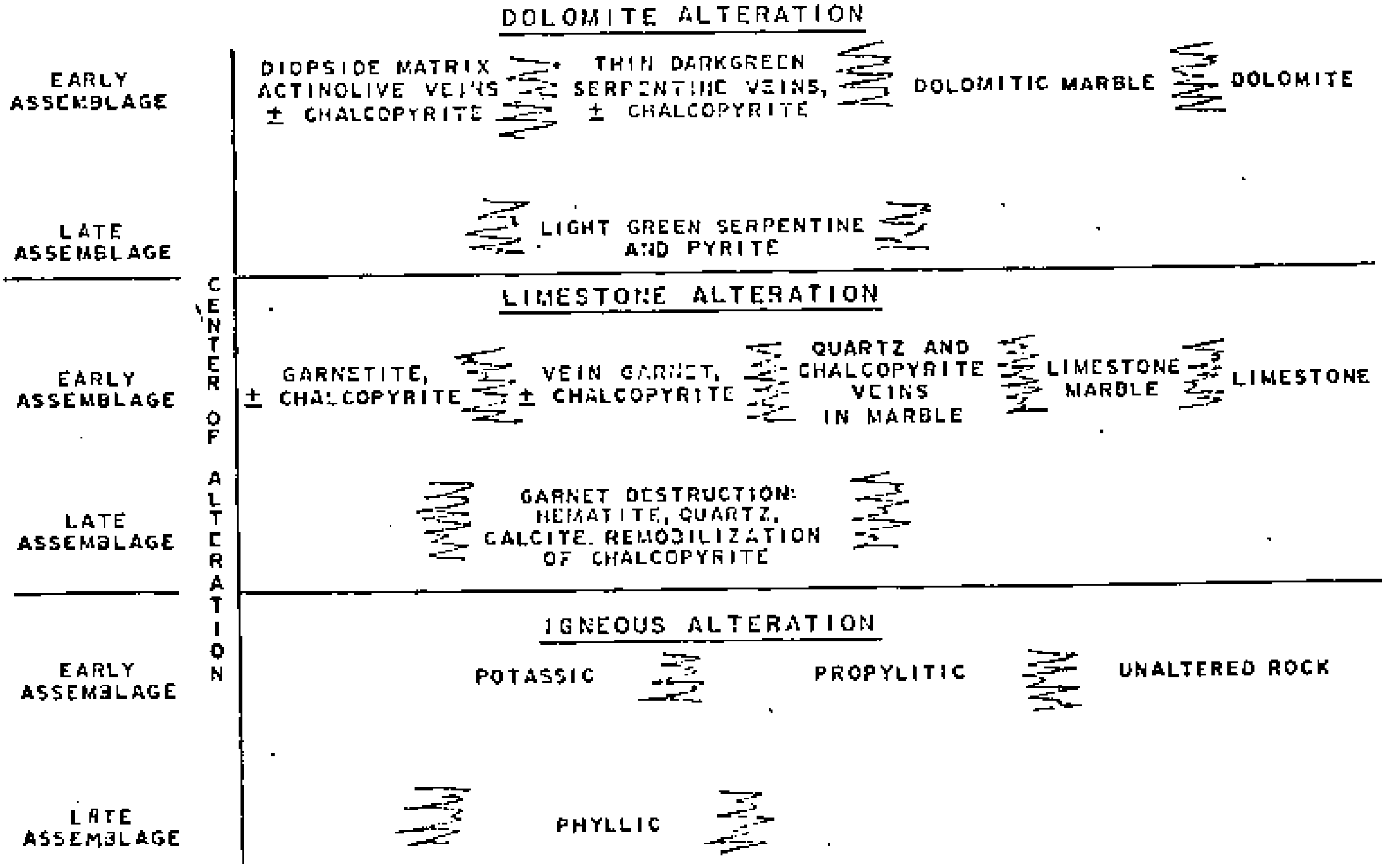
At Butte, Montana:

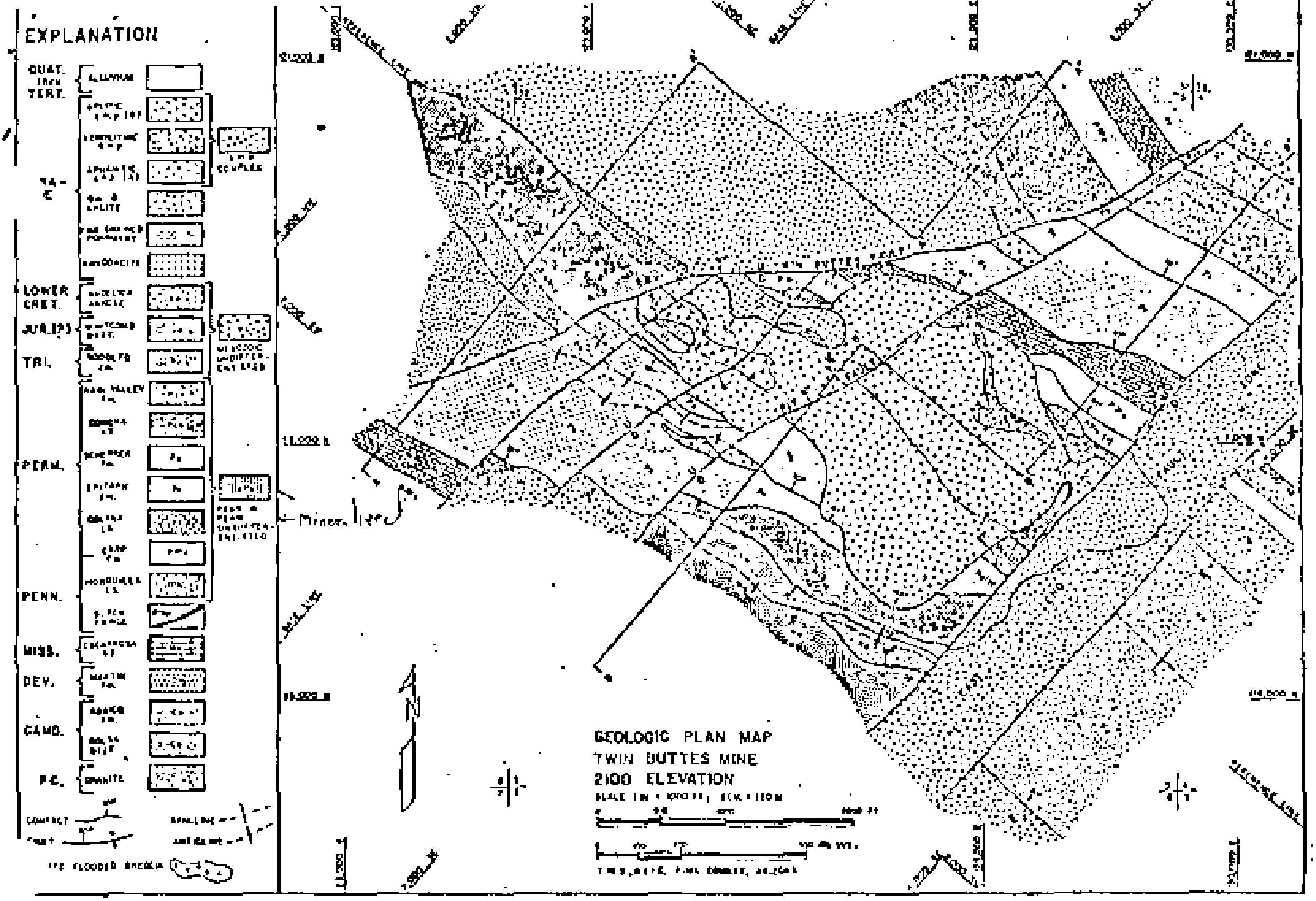
Advanced Argillic zone ($+H_2O$, H^+, SiO_2; $-K^+$)

Sericite $\longrightarrow$ **Kaolinite (dickite)** $Al_4Si_4O_{10}(OH)_8$
Pyrophyllite $Al_2Si_4O_{10}(OH)_2$

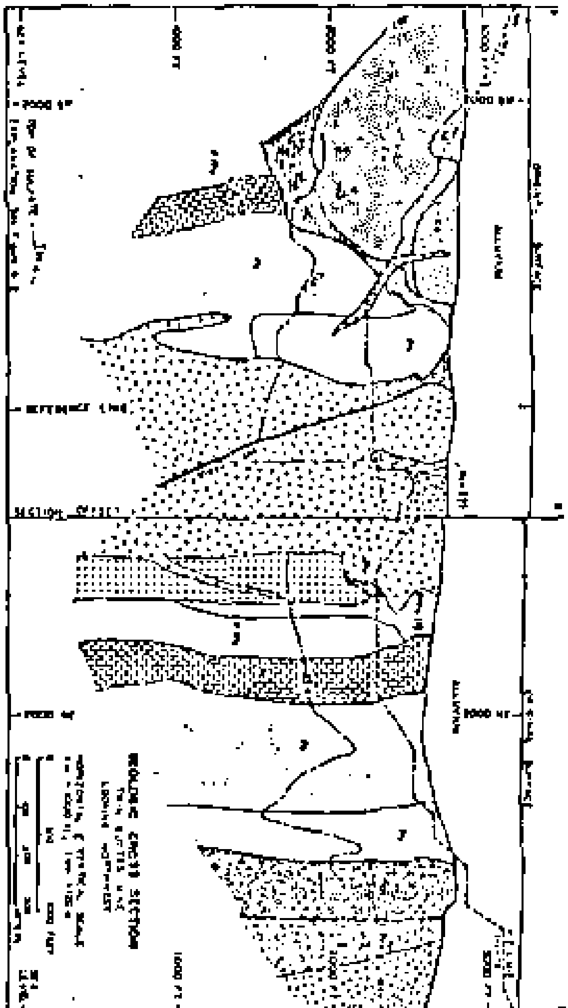


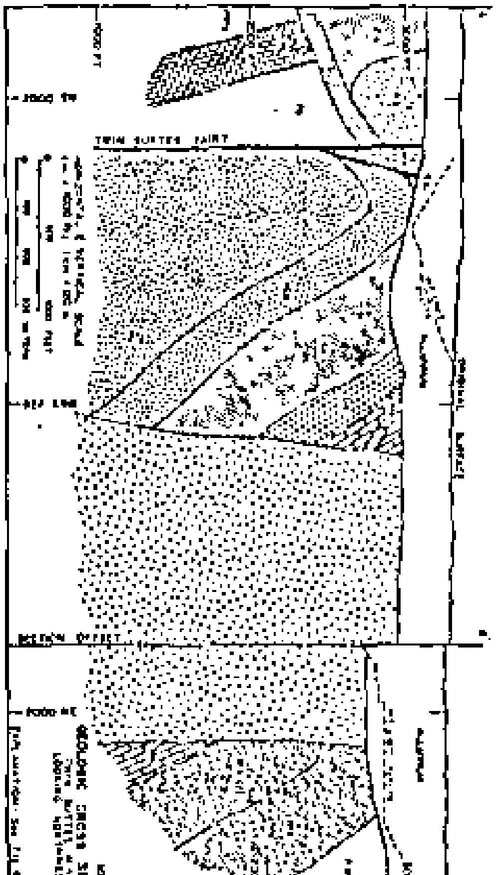
SCHEMATIC OF SKARN ALTERATION

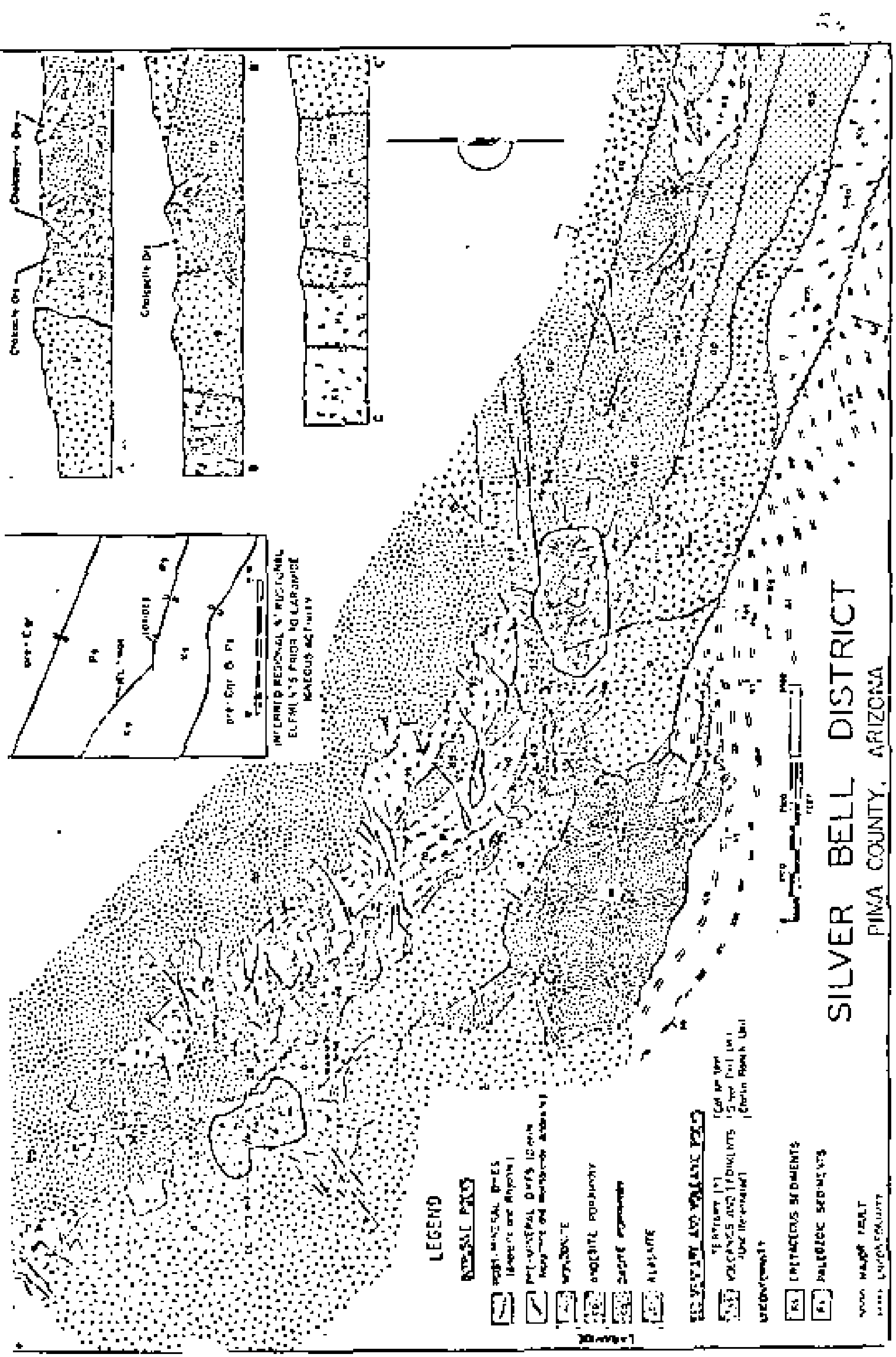


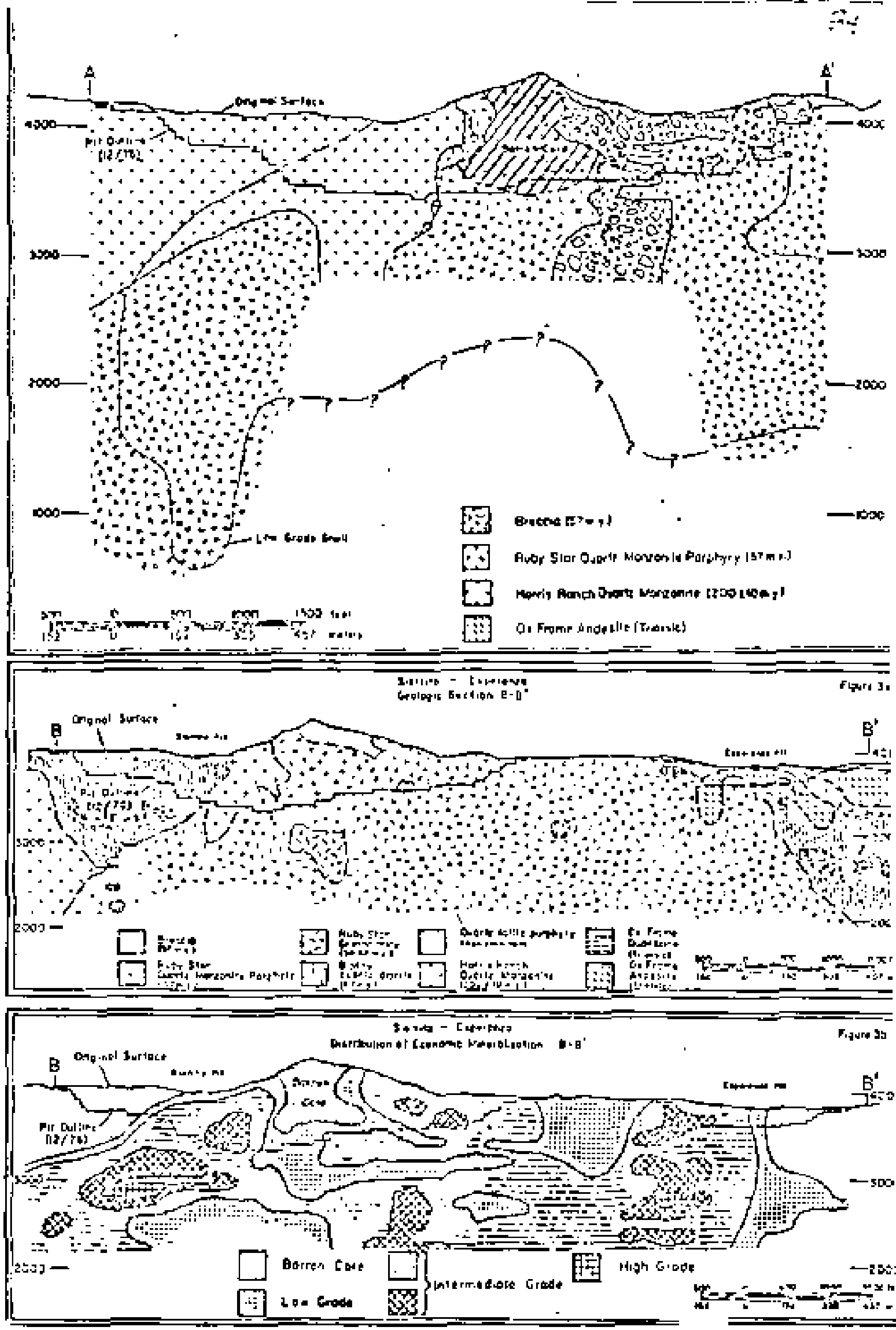


GEOLOGIC PLAN MAP
TWIN BUTTES MINE
2100 ELEVATION

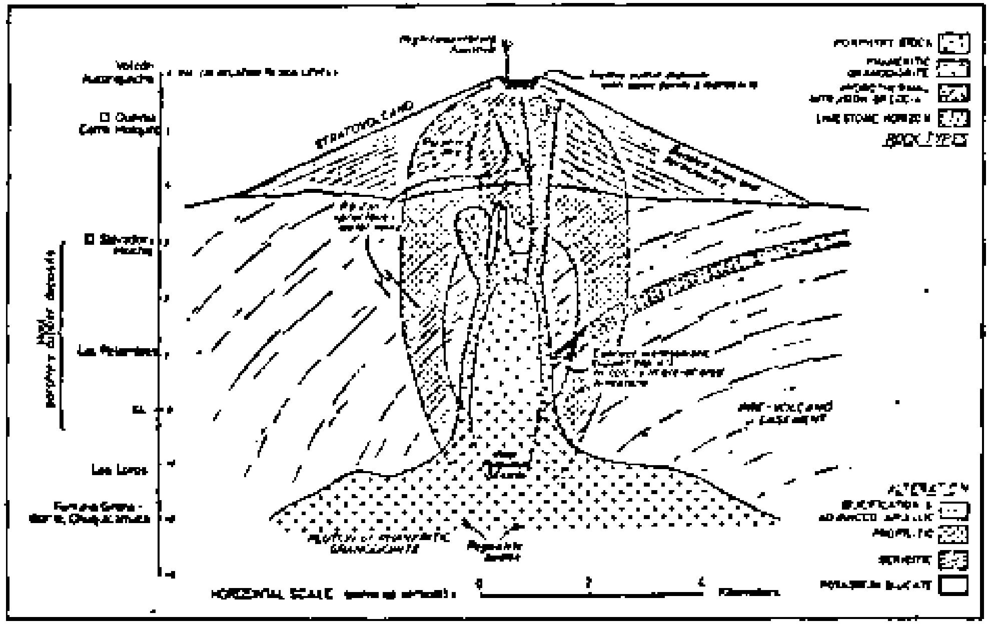




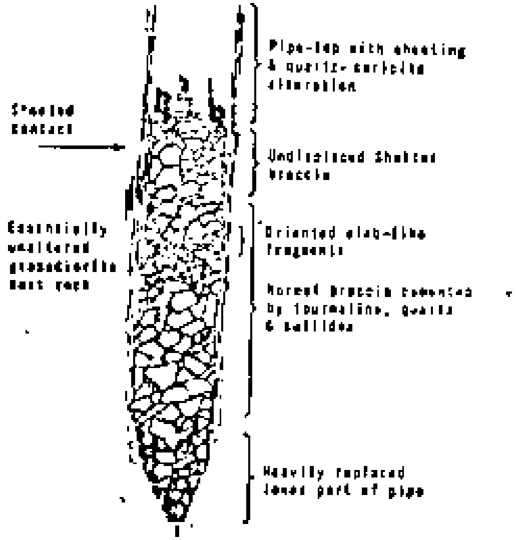




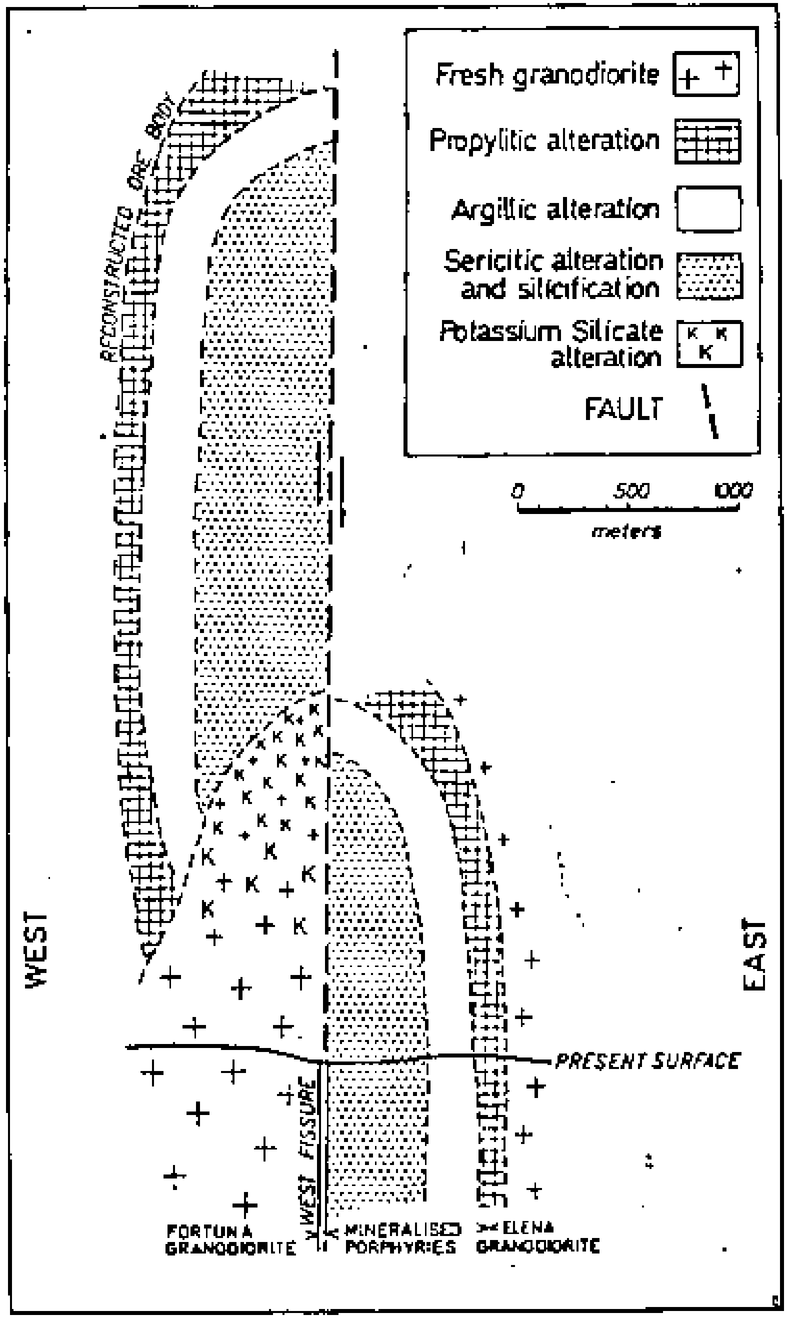
(a) Geology of the Sierrita-Esperanza deposi distribution of economic mineralization



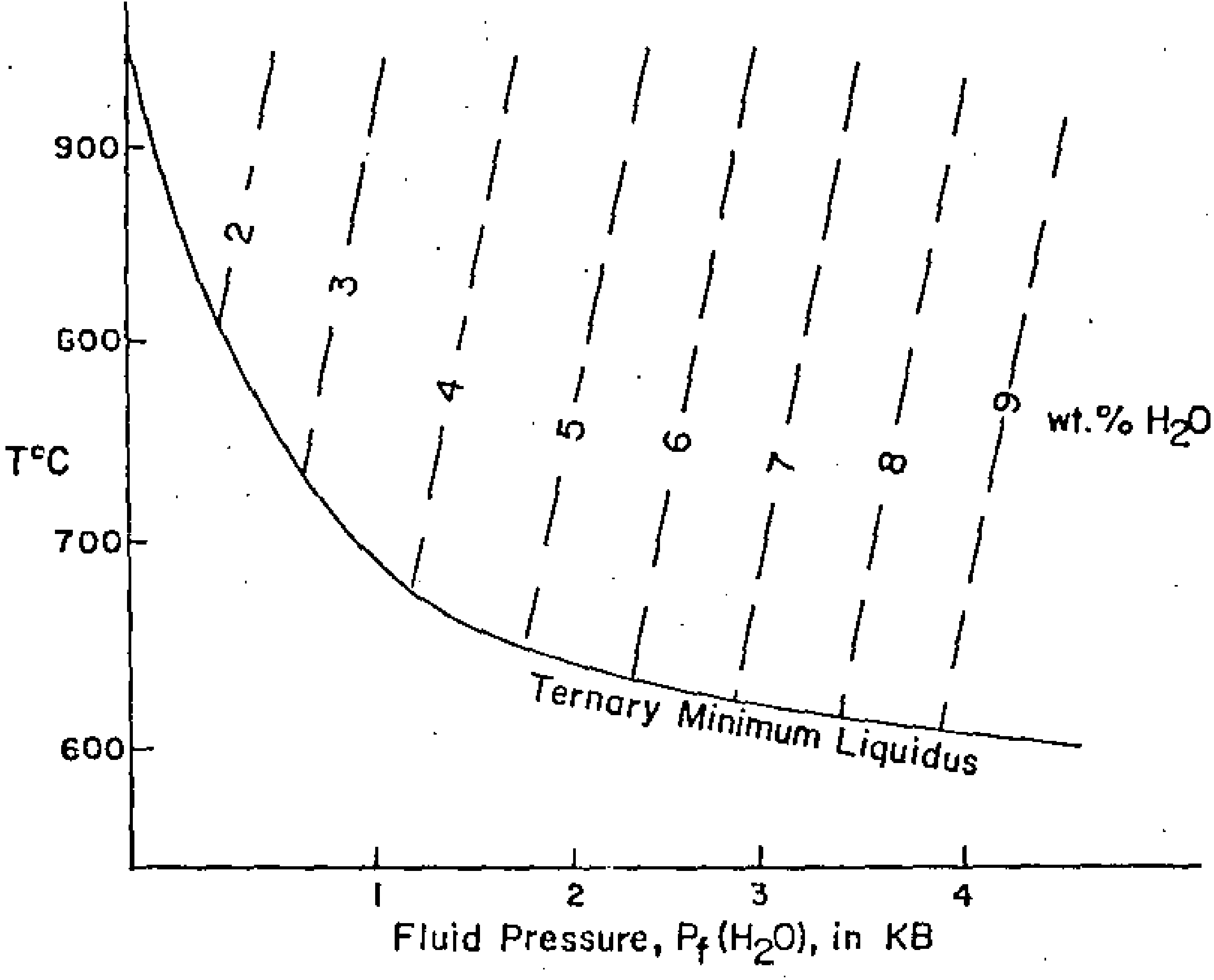
Idealized Cross Section of a Typical Porphyry Copper Deposit within the Volcanic Environment; Dimensions only Approximate (Sillitoe, 1973)



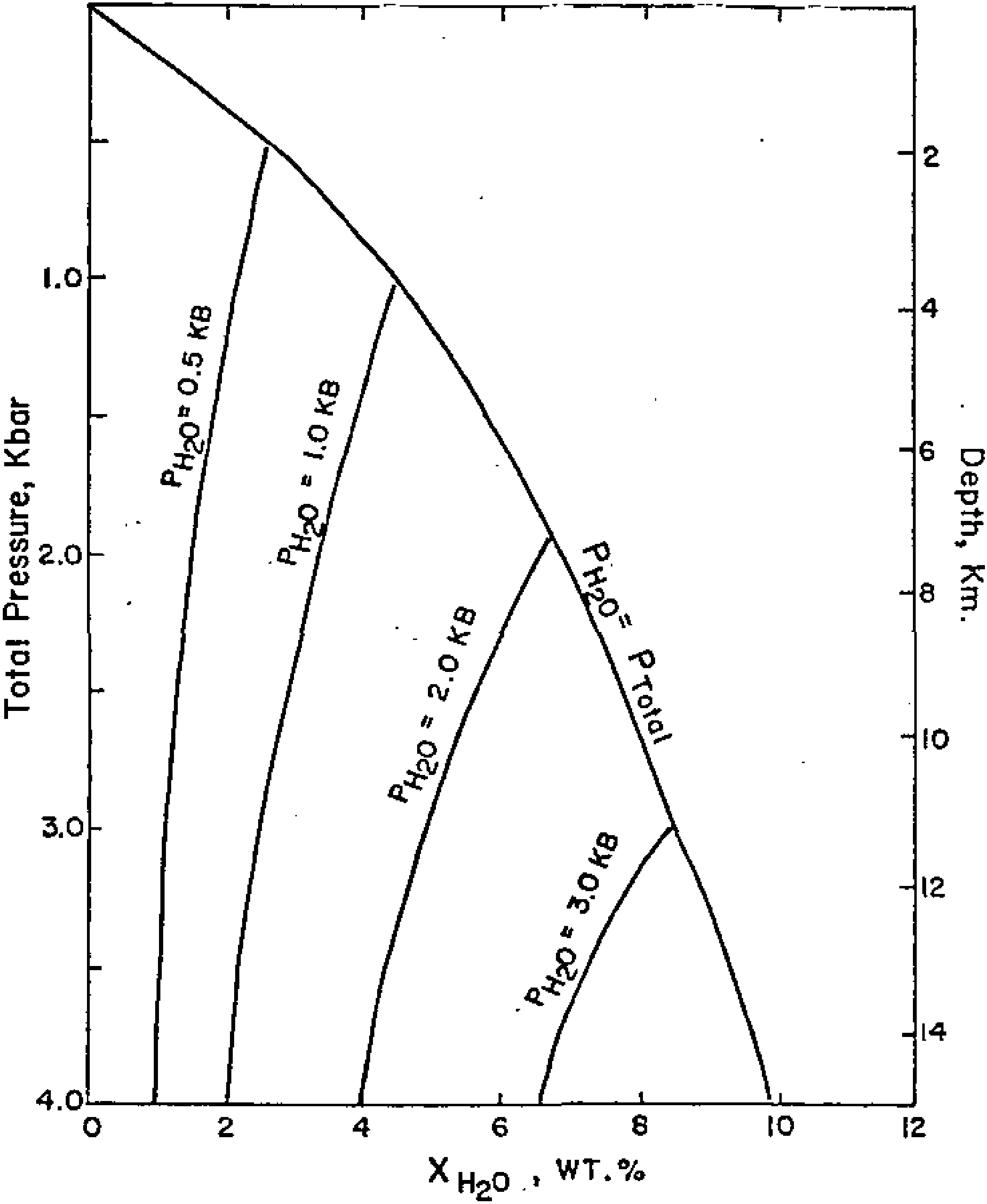
Idealized Cross Section of Typical Breccia Pipe (Norton and Cathles, 1973)



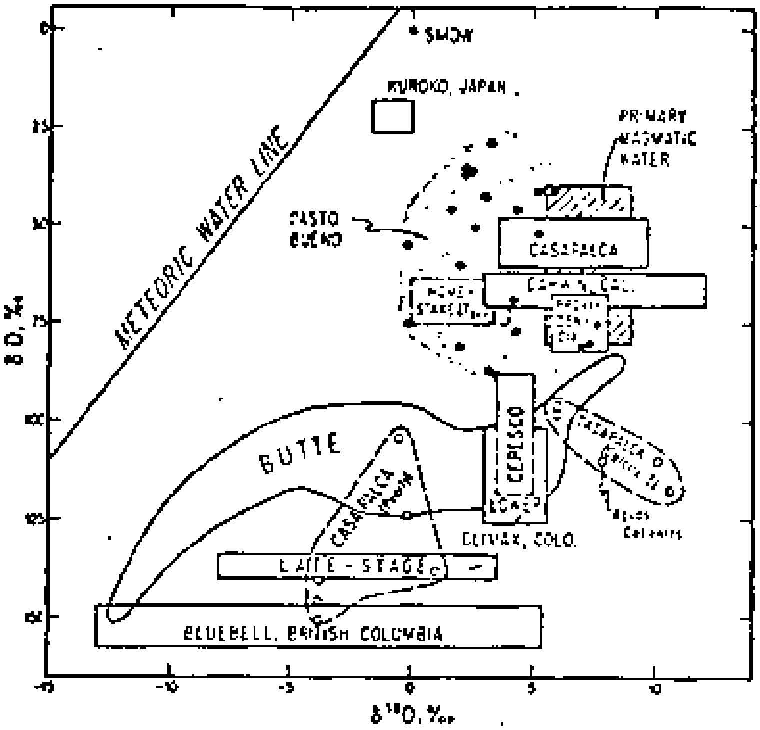
Idealized Cross Section of the Chuquicamata Porphyry Copper System (Sillitoe, 1973)



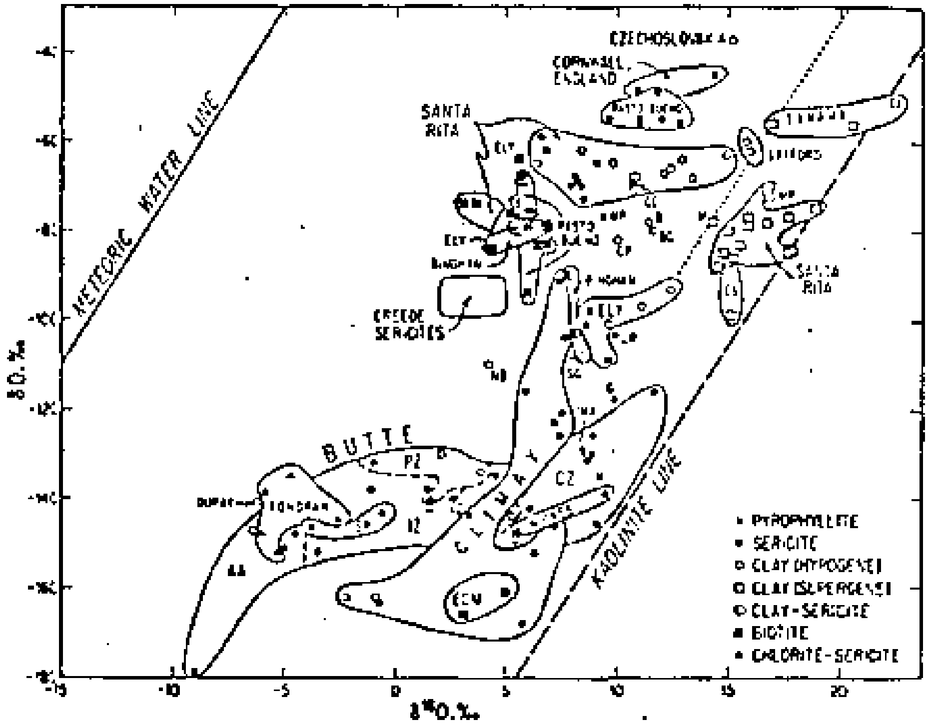
900
800
700
600
T°C
2
3
4
5
6
7
8
9
wt.% H2O
Ternary Minimum Liquidus
1
2
3
4
Fluid Pressure, Pf (H2O), in KB



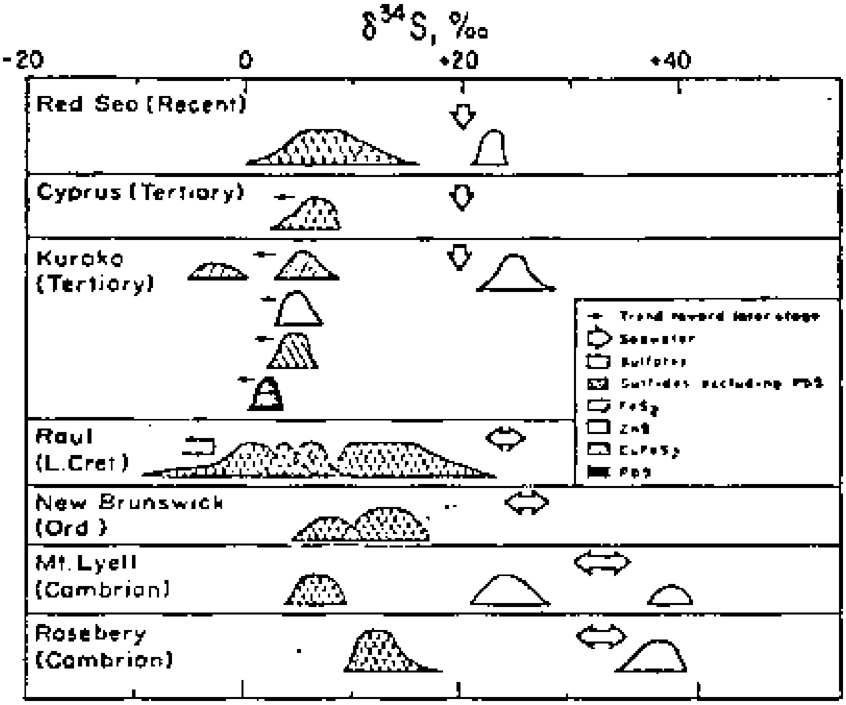
ISOTHERMAL P-X PROJECTION OF THE LIQUID-VAPOR CURVE IN THE SYSTEM $NaAlSi_3O_8$-H_2O SHOWING THE EFFECT OF PRESSURE ON THE SOLUBILITY OF WATER IN SILICATE MELTS, T=945 degrees C.



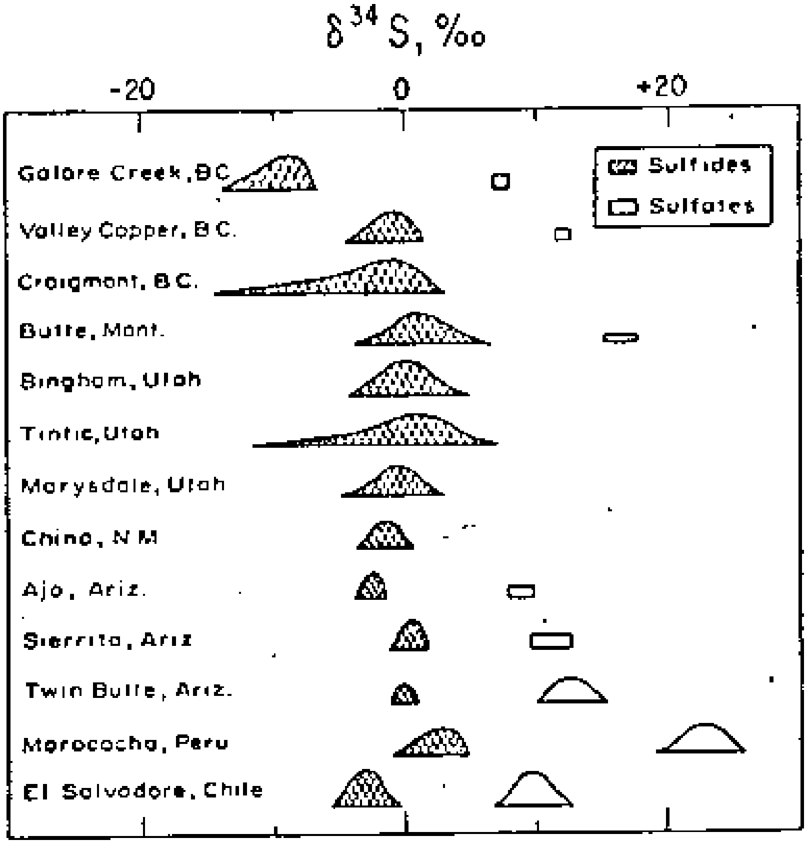
Plot of the range of δD of fluid inclusions vs the calculated $\delta^{18}O$ values of hydrothermal fluids in a variety of ore deposits (Ohmoto and Rye, 1970; 1974; Rye, 1966, Rye et al., 1974b; Rye and Sawkins, 1974; Hall et al., 1974). The black dots and the heavy stippled pattern indicate the isotopic range in the Pasto Bueno veins (Landis and Rye, 1974), excluding the extreme late-stage meteoric-hydrothermal fluids, which have δD = −110 to −145. For the Homestake district, only the Tertiary mineralization is indicated (Rye and Rye, 1974). Also shown are the calculated Main-Stage fluids at Butte (Sheppard and Taylor, 1974).



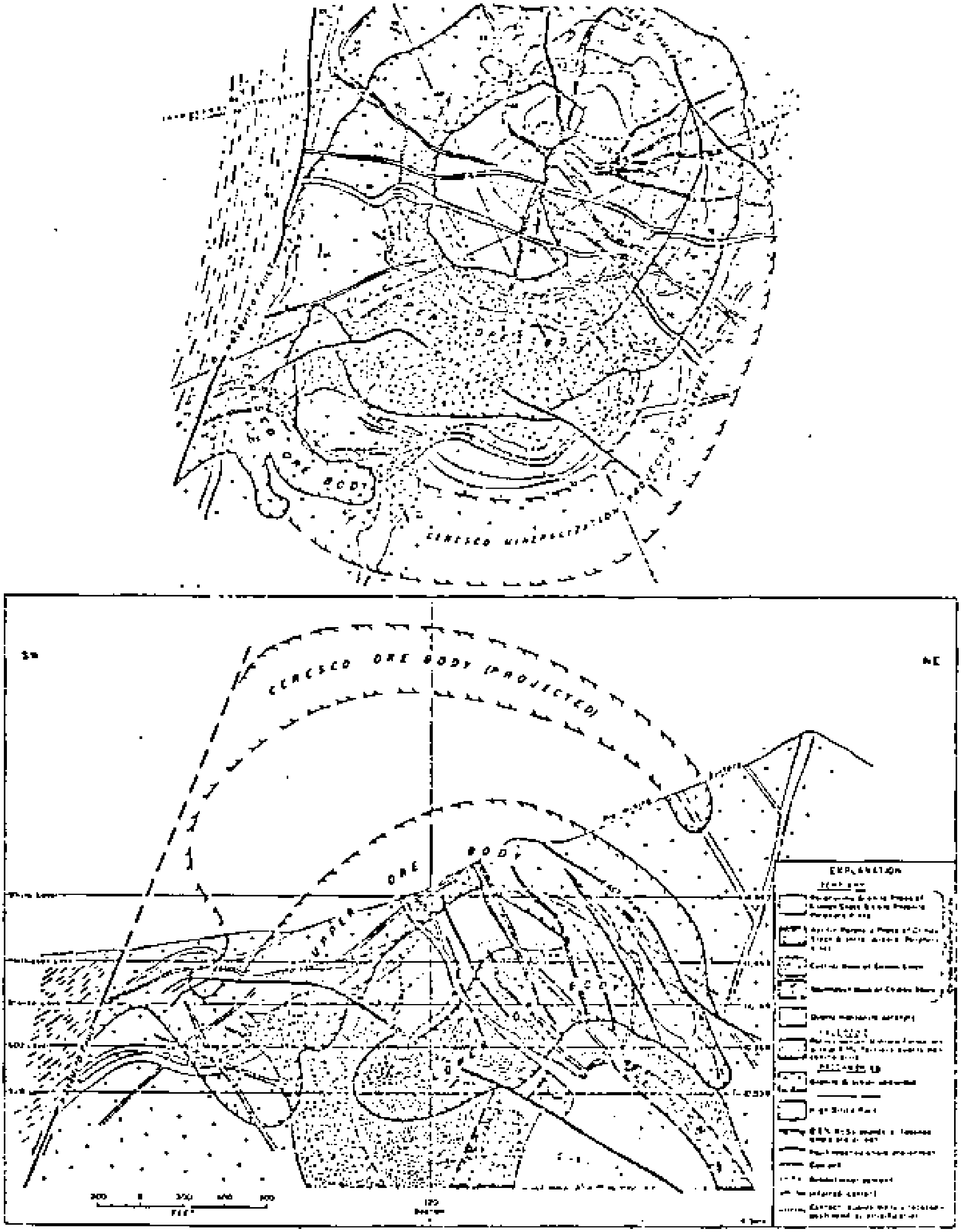
Plot of δD vs $\delta^{18}O$ for most of the presently available analyses of OH-bearing minerals from ore deposits (Sheppard et al., 1969; 1971; Sheppard and Taylor, 1974; Hall et al., 1974; Landis and Rye, 1974); Bethke et al., 1973; and Taylor, 1973). The kaolinite line of Savin and Epstein (1970a) is shown for reference. The dotted line is drawn merely to emphasize the separation of supergene and hypogene clays. Abbreviations: CP = Cerro de Pasco, CC = Copper Creek, B = Bethlehem, M = Morenci, ES = El Salvador, MP = Mineral Park, LR = Lost River, Alaska, BC = Bond Creek, Alaska, G = Gilman, SG = St. George, NB = New Boston, and at Butte AA = Advanced Argillic alteration; PZ = Peripheral Zone, IZ = Intermediate Zone, CZ = Central Zone, EDM = Early Dark Micaceous alteration. The stippled pattern indicates the range of isotopic values in biotites from porphyry copper deposits.



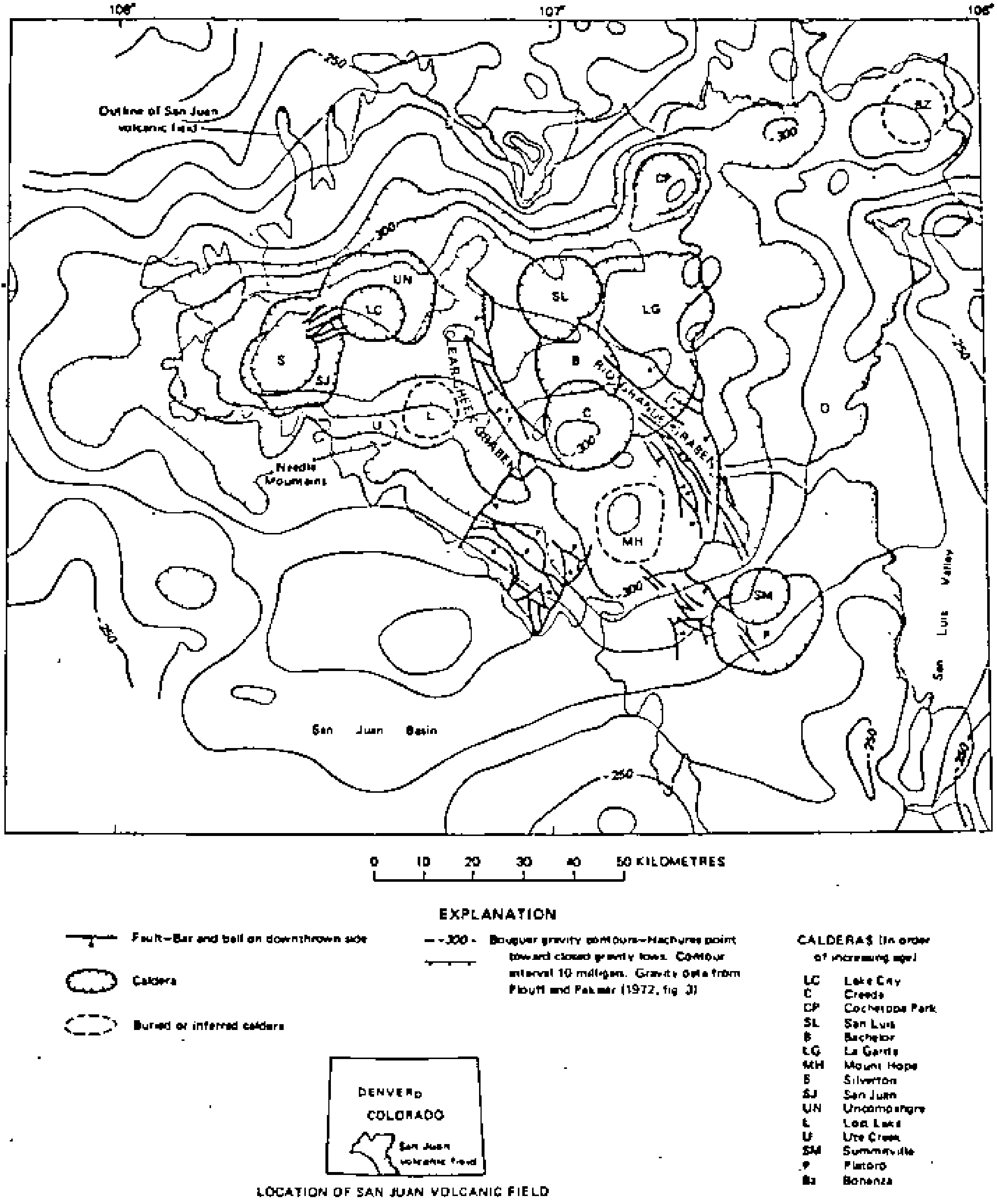
Schematic presentation of sulfur isotopic data of some stratiform massive sulfide deposits associated with submarine volcanism. The sources of data on Cyprus, Kuroko, and New Brunswick are summarized in Rye and Ohmoto (1974). The data on Red Sea are from Kaplan et al. (1969) and Shanks and Bishoff (1975), on Raul deposits from Ripley and Ohmoto (1977), and on Mt. Lyell and Rosebery deposits from Solomon et al. (1969).



Schematic presentation of sulfur isotopic data of some porphyry copper deposits (modified from unpublished data of Field, 1975).

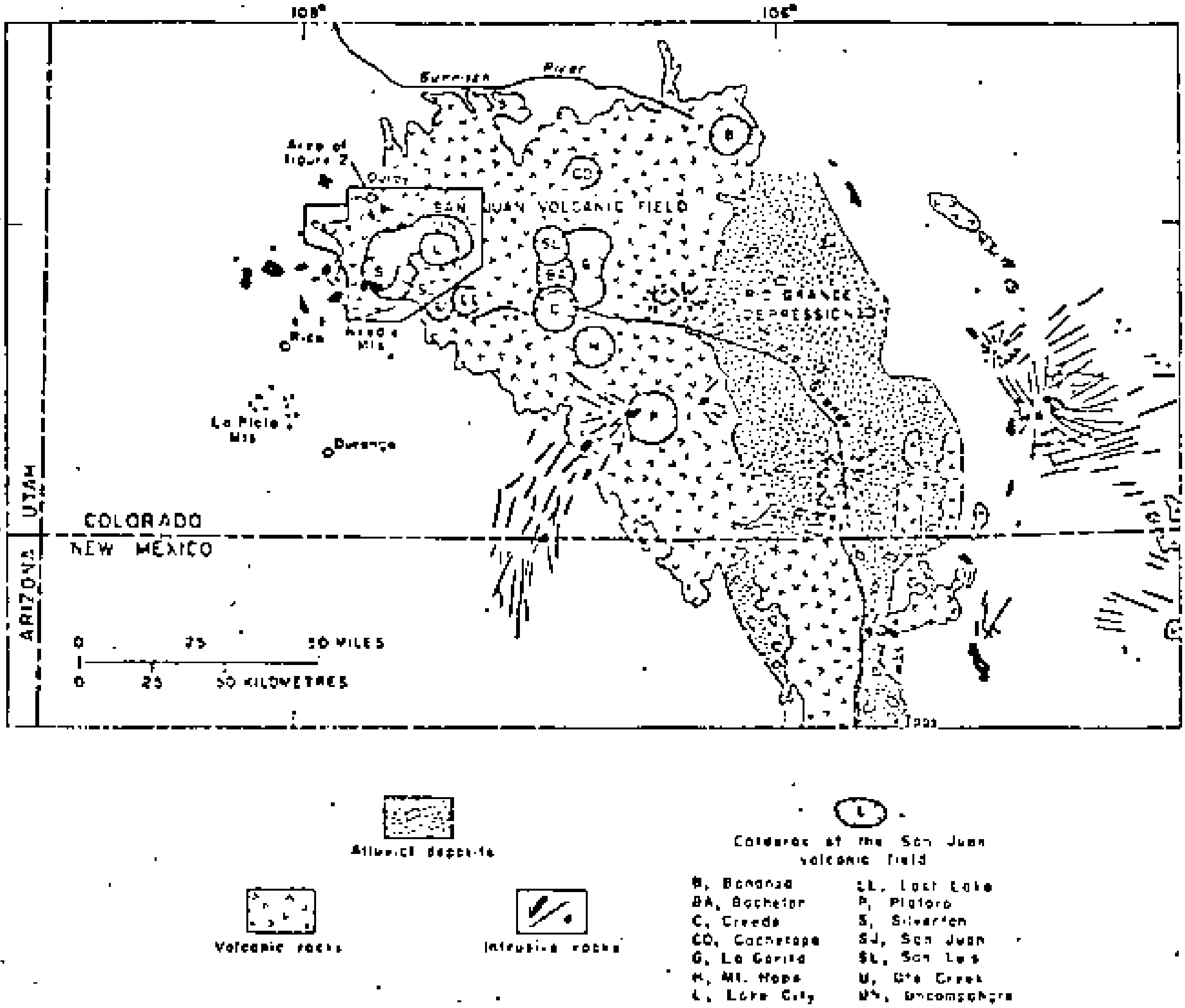


Geologic Map and Cross Section of the Climax Porphyry Molybdenum Deposit, Colorado (Wallace and others, 1968)



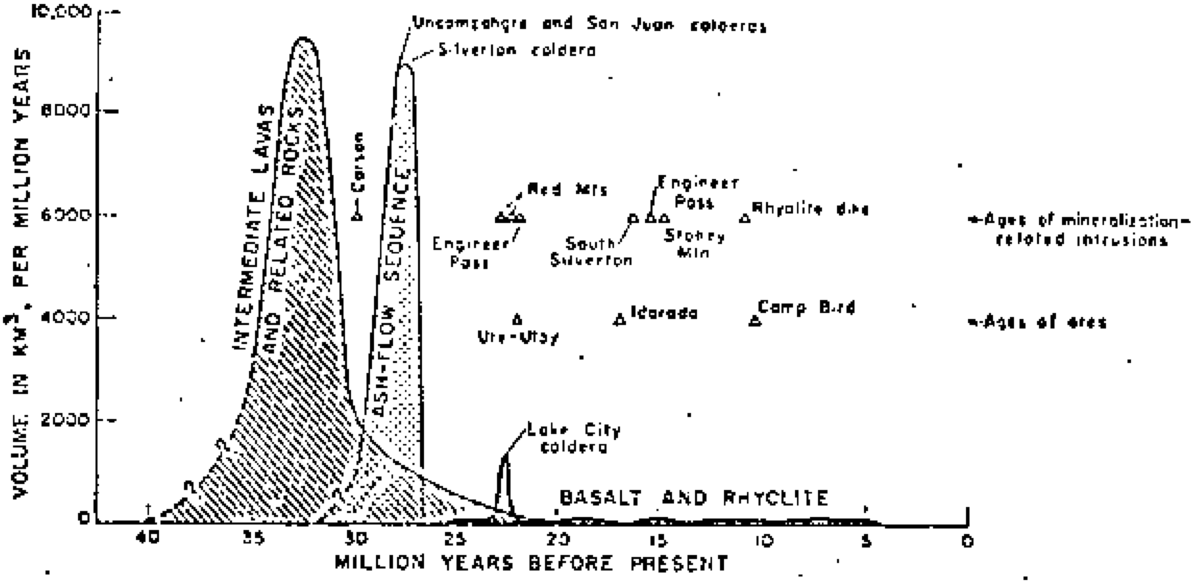
—Calderas in the San Juan volcanic field (patterned) in relation to Bouguer gravity field.

Steven and Lipman (1976)



Index map showing the San Juan volcanic field, the western San Juan caldera complex (illustrated in more detail in Fig. 2), and adjacent mineralized areas.

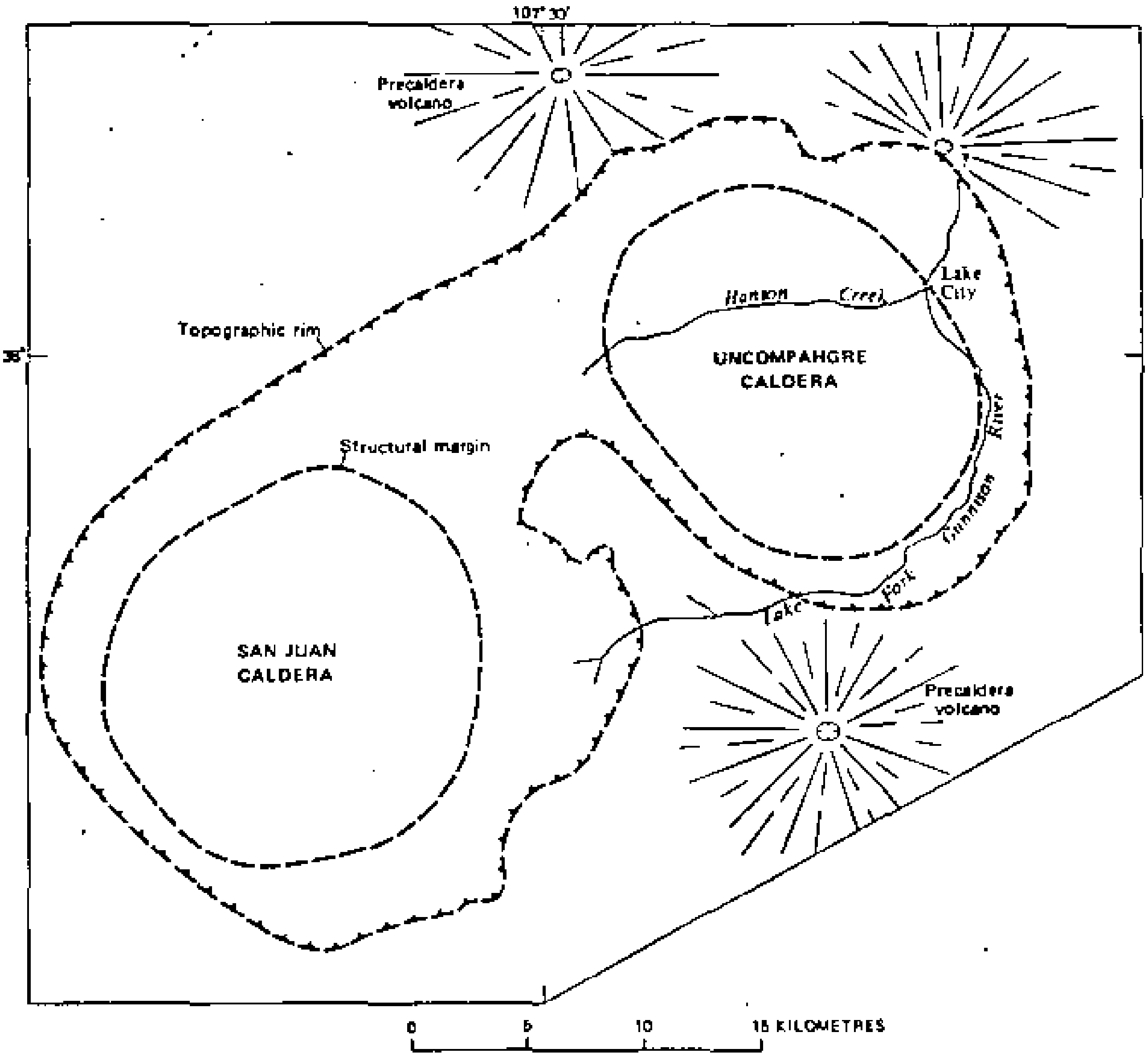
Lipman and others, 1976



Summary of relationships between volcanism and mineralization in the western San Juan Mountains. On left are relationships between petrologic type, volume, and time of volcanism (from Lipman et al., 1970); on right are ages of ores and mineralization-related intrusions in the Silverton caldera area (Table 2, this paper).

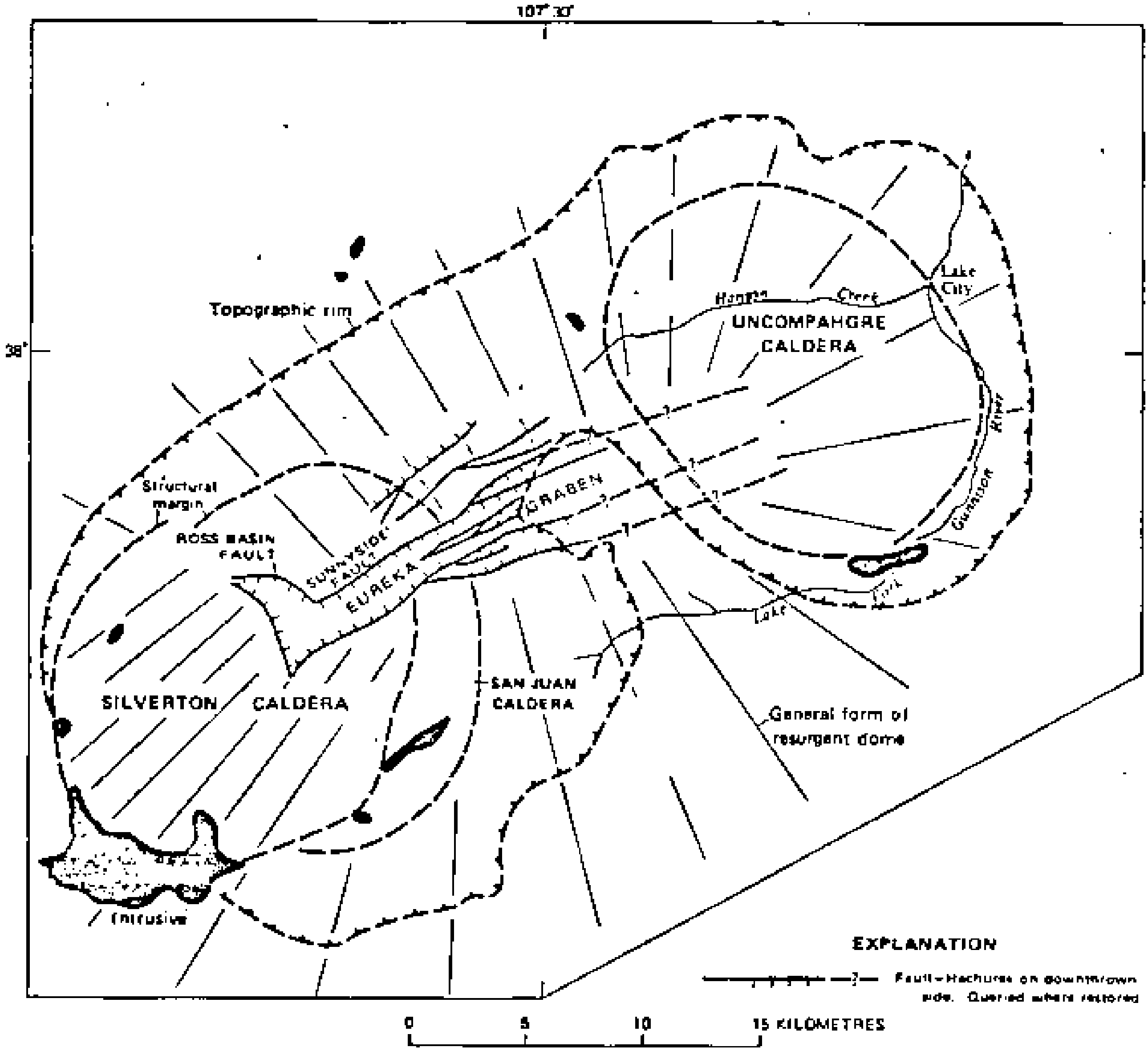
Lipman and others, 1976

WESTERN SAN JUAN CALDERA COMPLEX



-Sketch map of the western San Juan caldera complex after subsidence related to eruption of the Sapinero Mesa Tuff. Control moderate to good where boundaries are shown by solid symbols; conjectural where shown by open symbols.

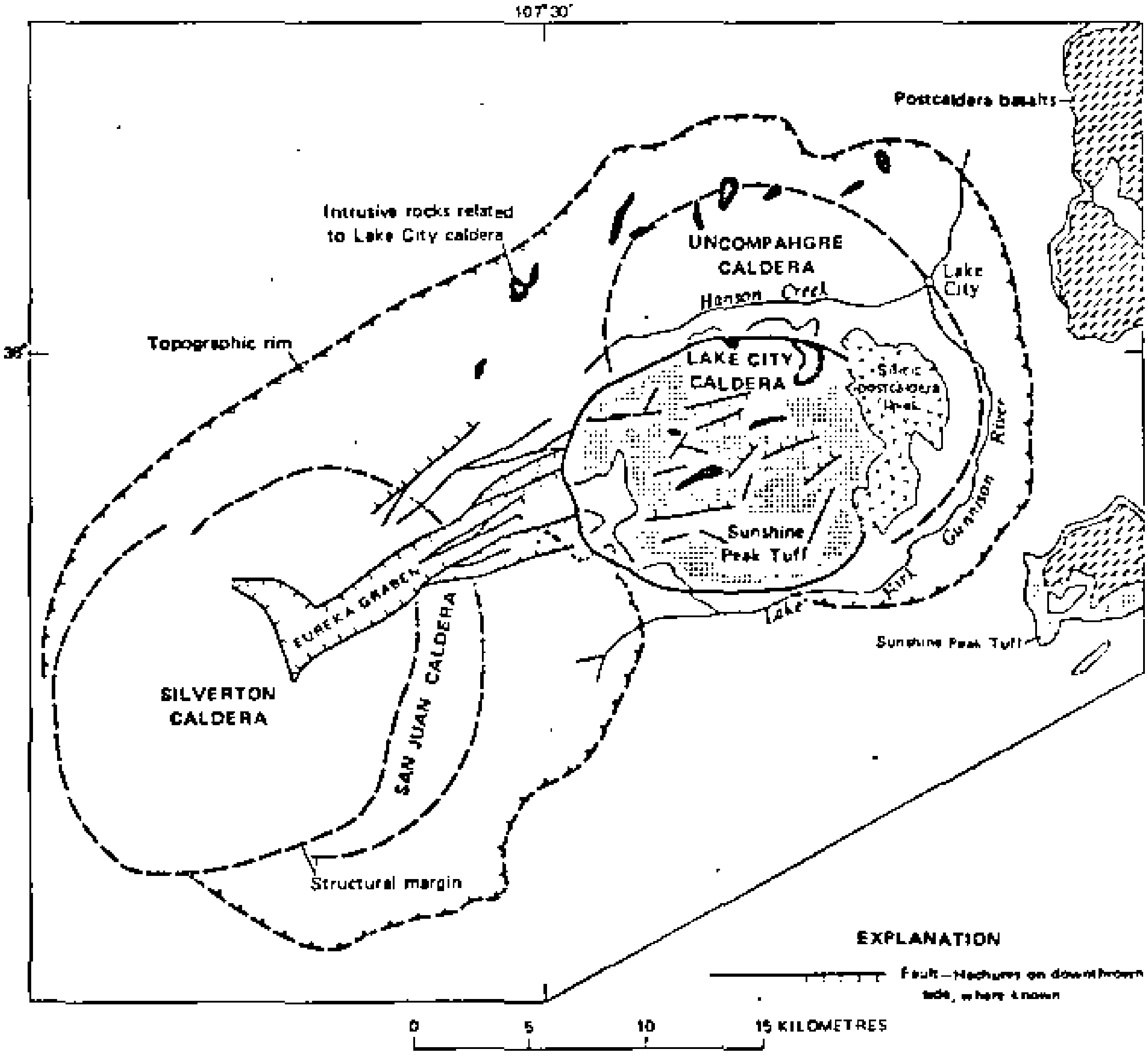
Steven and Lipman (1976)
]



·Sketch map of the western San Juan caldera complex after subsidence of the Silverton caldera and general resurgence. Control moderate to good where boundaries are shown by solid symbols; conjectural where shown by open symbols.

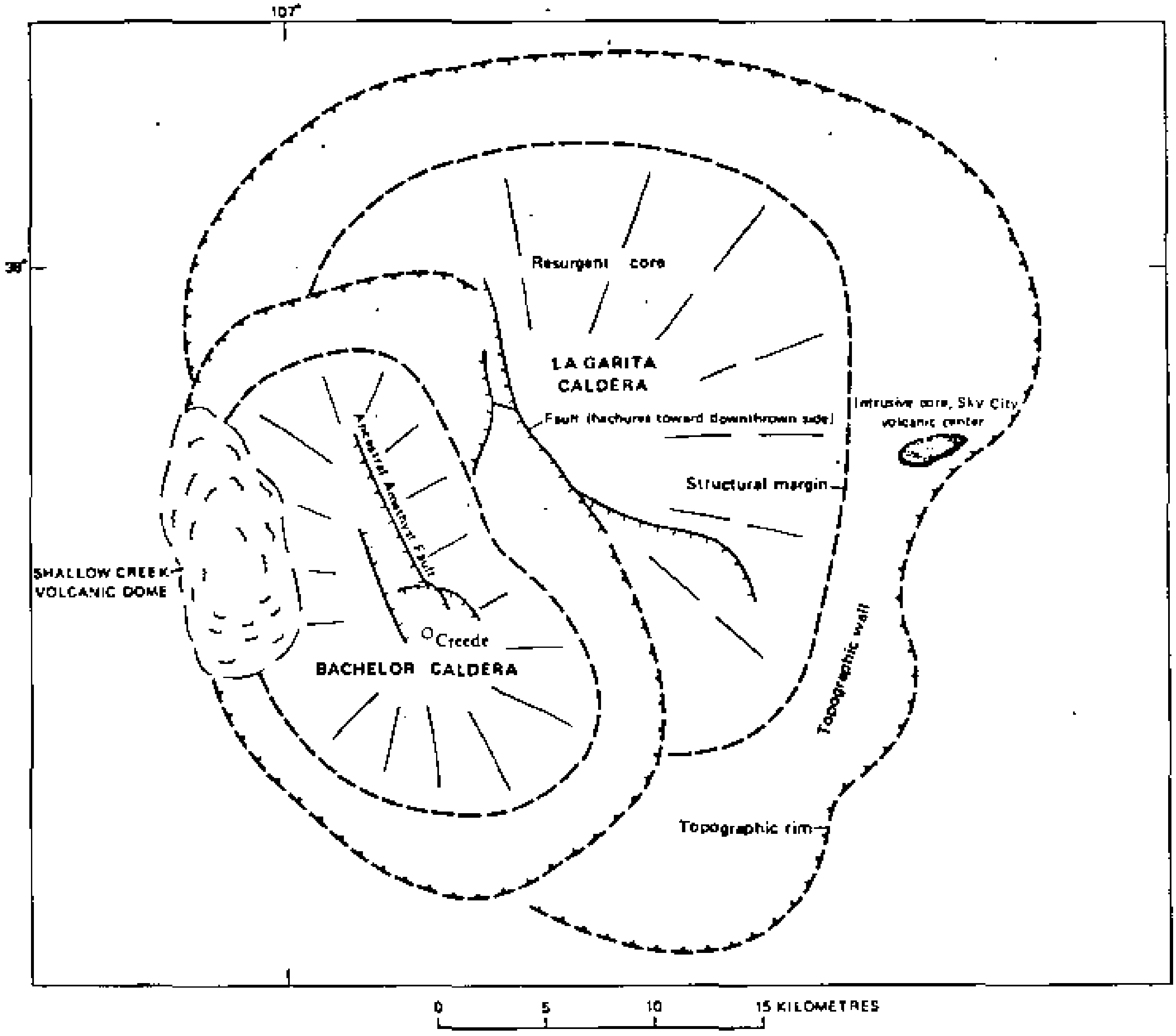
Steven and Lipman (1976)

WESTERN SAN JUAN CALDERA COMPLEX



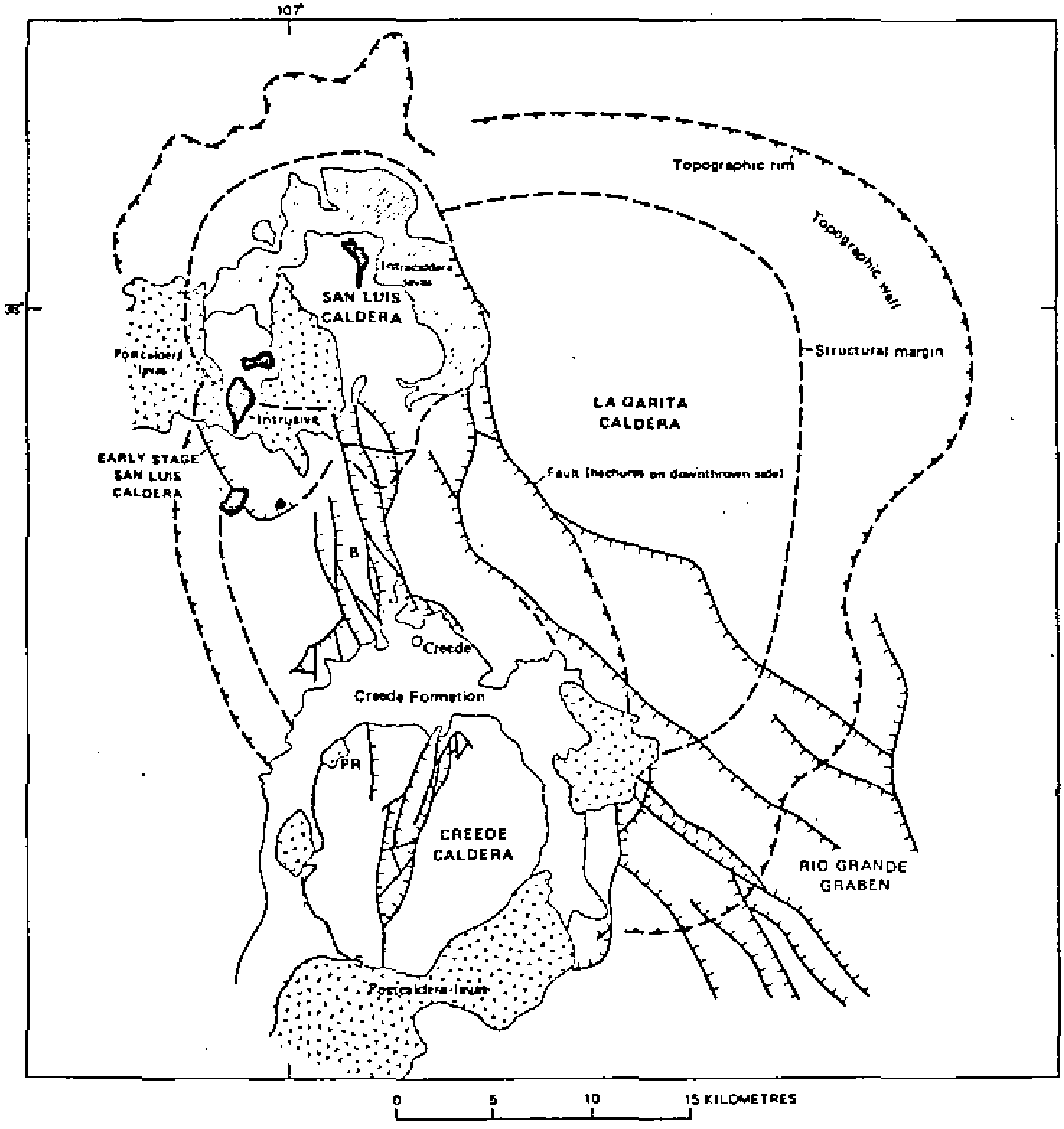
Generalized geology of the western San Juan caldera complex showing distribution of rocks related to the Lake City caldera

Steven and Lipman (1976)



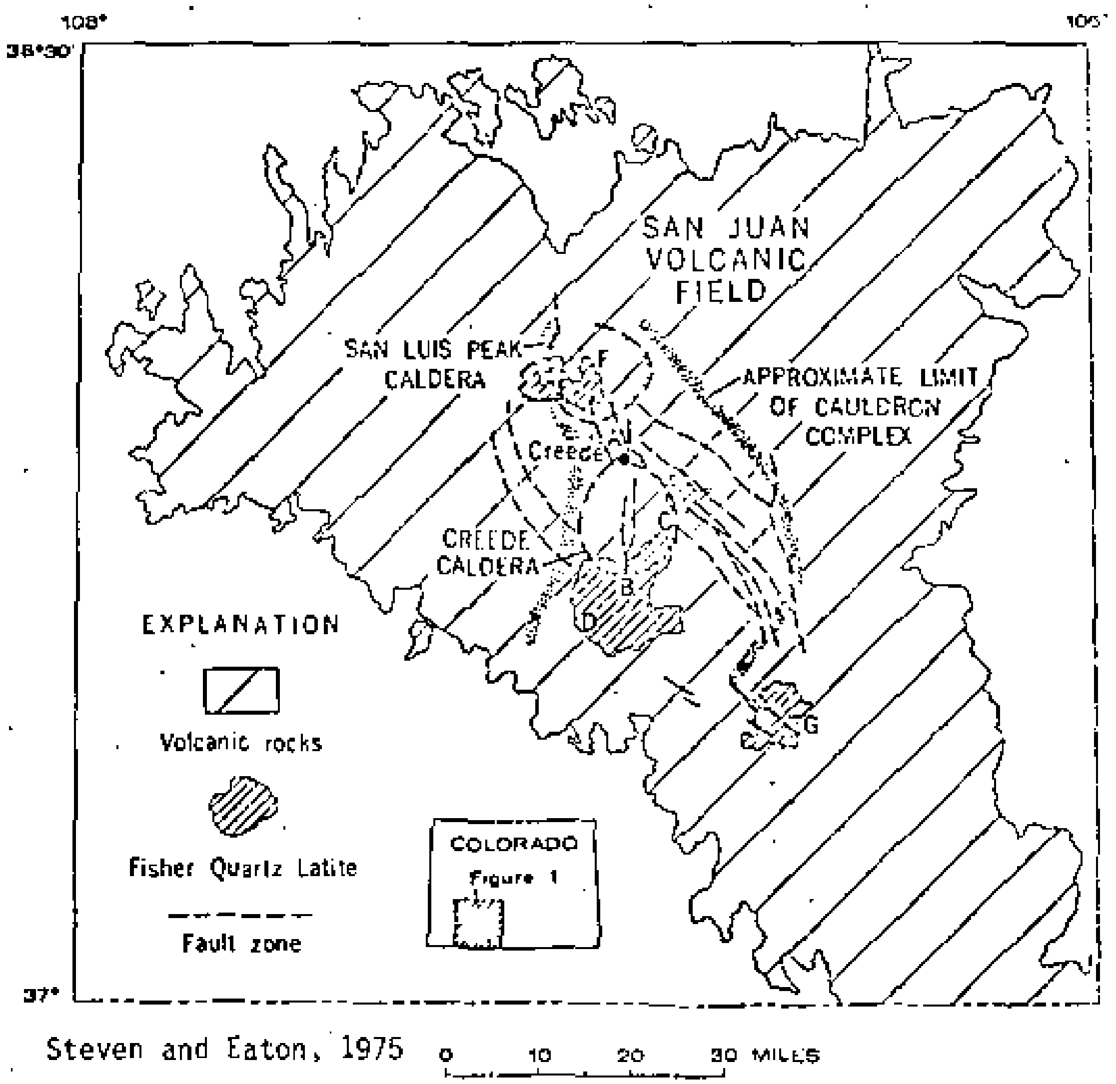
–Restored Bachelor and La Garita calderas. Control moderate to good where boundaries are shown by solid symbols, conjectural where shown by open symbols.

Steven and Lipman (1976)



–Generalized geology of the Creede and San Luis calderas in relation to remnants of the Bachelor (B) and La Garita calderas. Control moderate to good where boundaries are shown by solid symbols, conjectural where shown by open symbols. PR, Point of Rocks volcano; S, Spar City.

Steven and Lipman (1976)



Steven and Eaton, 1975

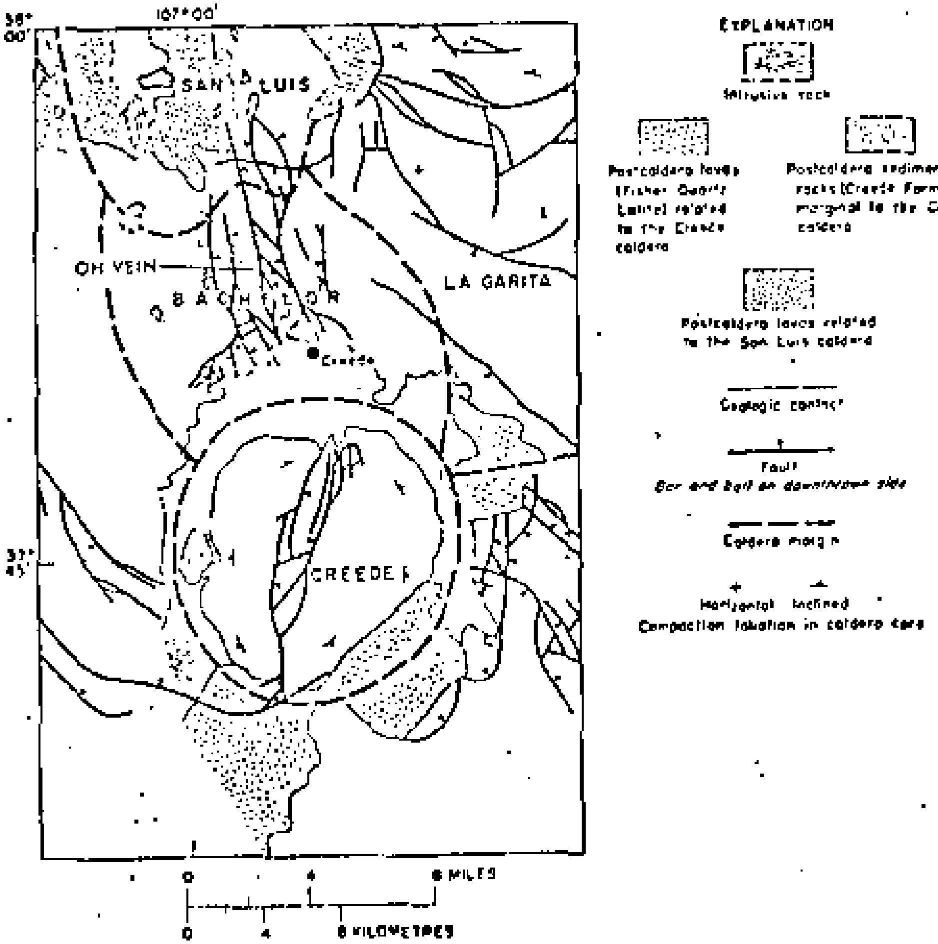
San Juan Volcanic Fields.

Volcanic Stratigraphy of the Central San Juan Mountains

Steven and Eaton, 1975

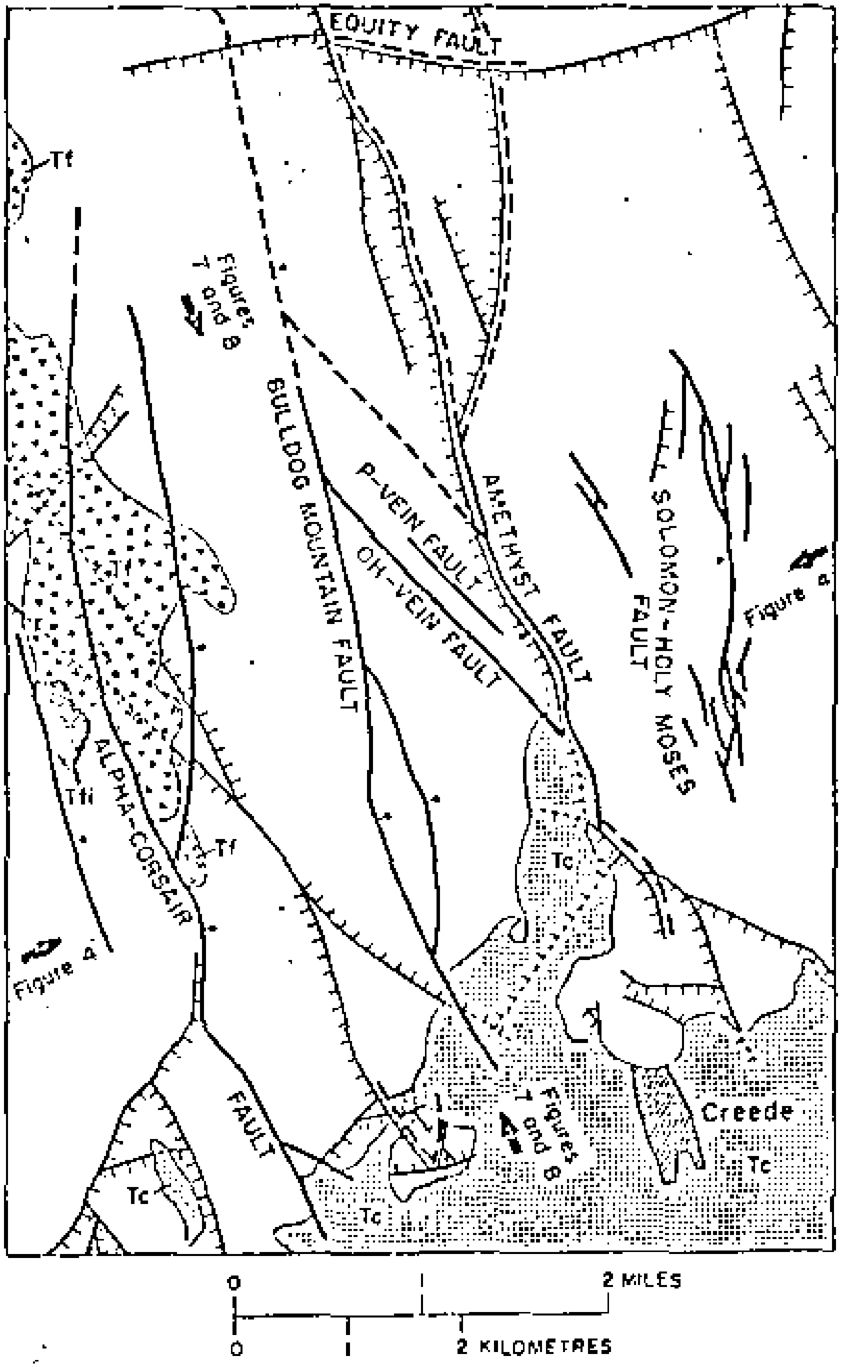
Lavas and sedimentary rocks	Ash-flow tuffs (caldera sources)	Composition	Remanent magnetic polarity	K-Ar age (million years)
Fisher Quartz Latite and Creede Formation		Fisher: quartz latite lavas and breccias Creede: stream, lake, and pyroclastic deposits and travertine	+	26.4
	Snowshoe Mountain Tuff (Creede)	Phenocryst-rich quartz latite	+	>26.4 < 26.7
	Nelson Mountain Tuff (San Luis)	Phenocryst-rich quartz latite	+	>26.4 < 26.7
	Rat Creek Tuff	Ranges from poorly welded phenocryst-poor rhyolite to densely welded phenocryst-rich quartz latite	+	>26.4 < 26.7
Local rhyolitic, quartz latitic, and andesitic flows and breccias between ash-flow units	Wason Park Tuff	Phenocryst-rich rhyolite	−	>26.4 < 26.7
	Mammoth Mountain Tuff (Mammoth Mountain?)	Ranges from phenocryst-poor rhyolite to phenocryst-rich quartz latite	−	26.7
	Carpenter Ridge Tuff (Bachelor)	Phenocryst-poor rhyolite	−	>26.7 < 27.8
	Fish Canyon Tuff (LaGarita)	Phenocryst-rich quartz latite	+	27.8
Conejos Formation		Andesitic flows and breccias		35–30

Remanant magnetic polarity: +, normal magnetic polarity; −, reverse magnetic polarity. K-Ar ages from Lipman, Steven, and Mehnert (1970).



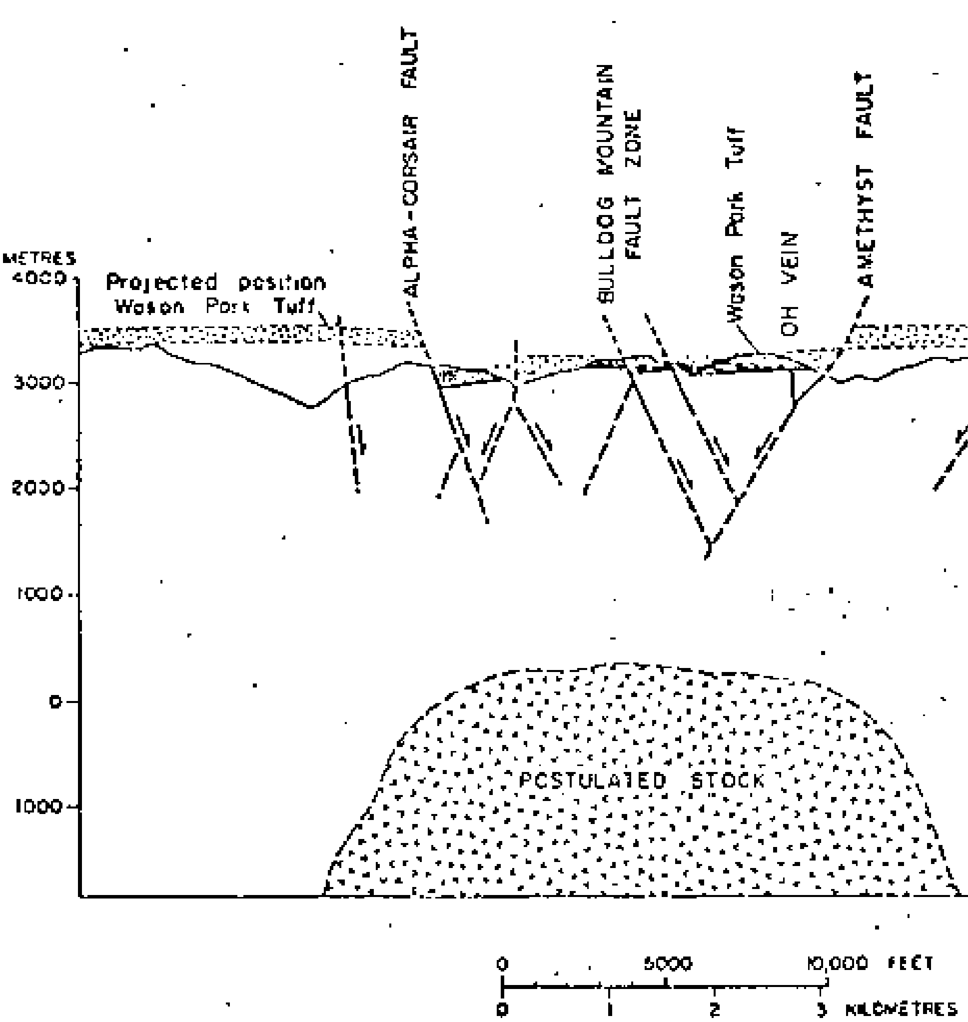
Generalized geologic map of the Creede district showing the relationship of the OH vein to the LaGarita, Bachelor, San Luis, and Creede calderas. Open areas underlain by ash-flow tuff sequence derived from caldera complex. Redrawn from Steven and Eaton (1975).

Steven and Eaton, 1975



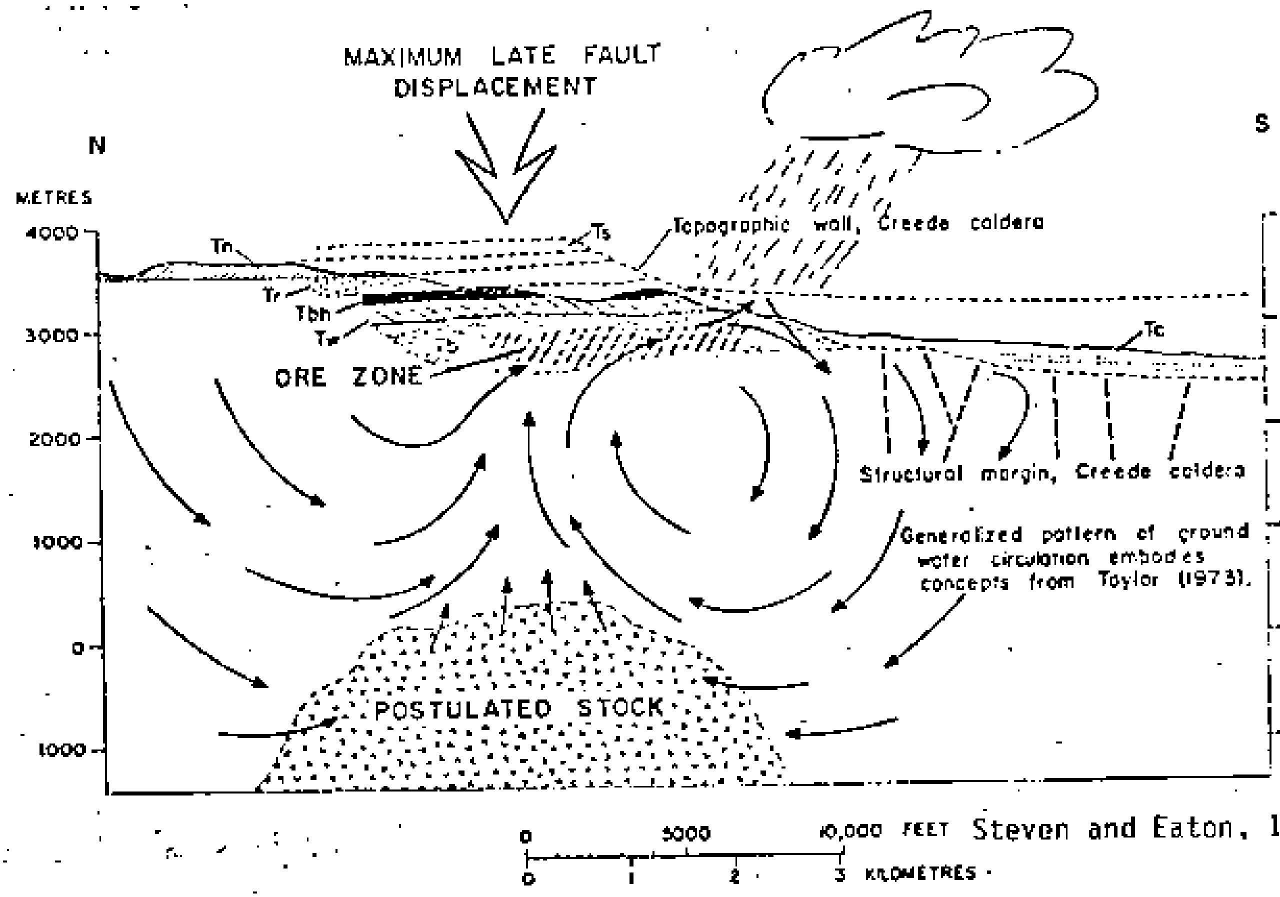
Generalized geology of the Creede mining district.

Steven and Eaton, 1975



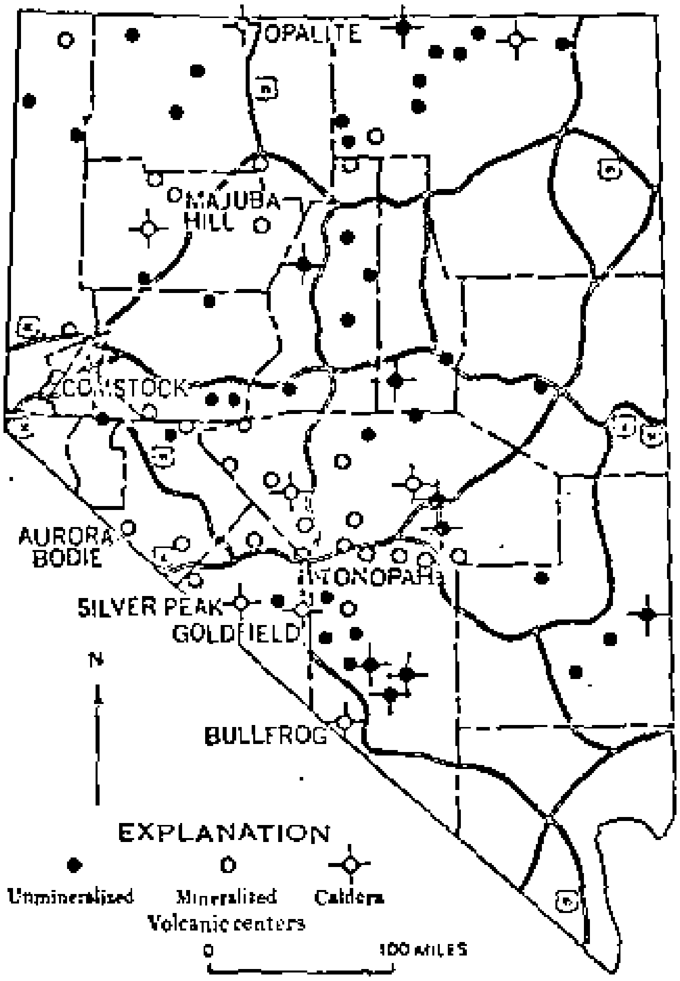
Steven and Eaton, 1975

Idealized northeast-trending section across the Creede district. Modified from Steven and Ratté (1965, pl. 1). Depth to top of stock conjectural.



Steven and Eaton, 1975

Idealized north-south section through the Creede mining district. Existing rocks are patterned; restored rocks, open. Tc, Creede Formation; Ts, Snowshoe Mountain Tuff; Tn, Nelson Mountain Tuff; Tr, Rat Creek Tuff; Tbh, andesite of Bristol Head; Tw, Wason Park Tuff; Tb, Bachelor Mountain Member, Carpenter Ridge Tuff. Coarse stipple in the [illegible] at the top of the Bachelor Mountain Member indicates soft, relatively impermeable tuff.



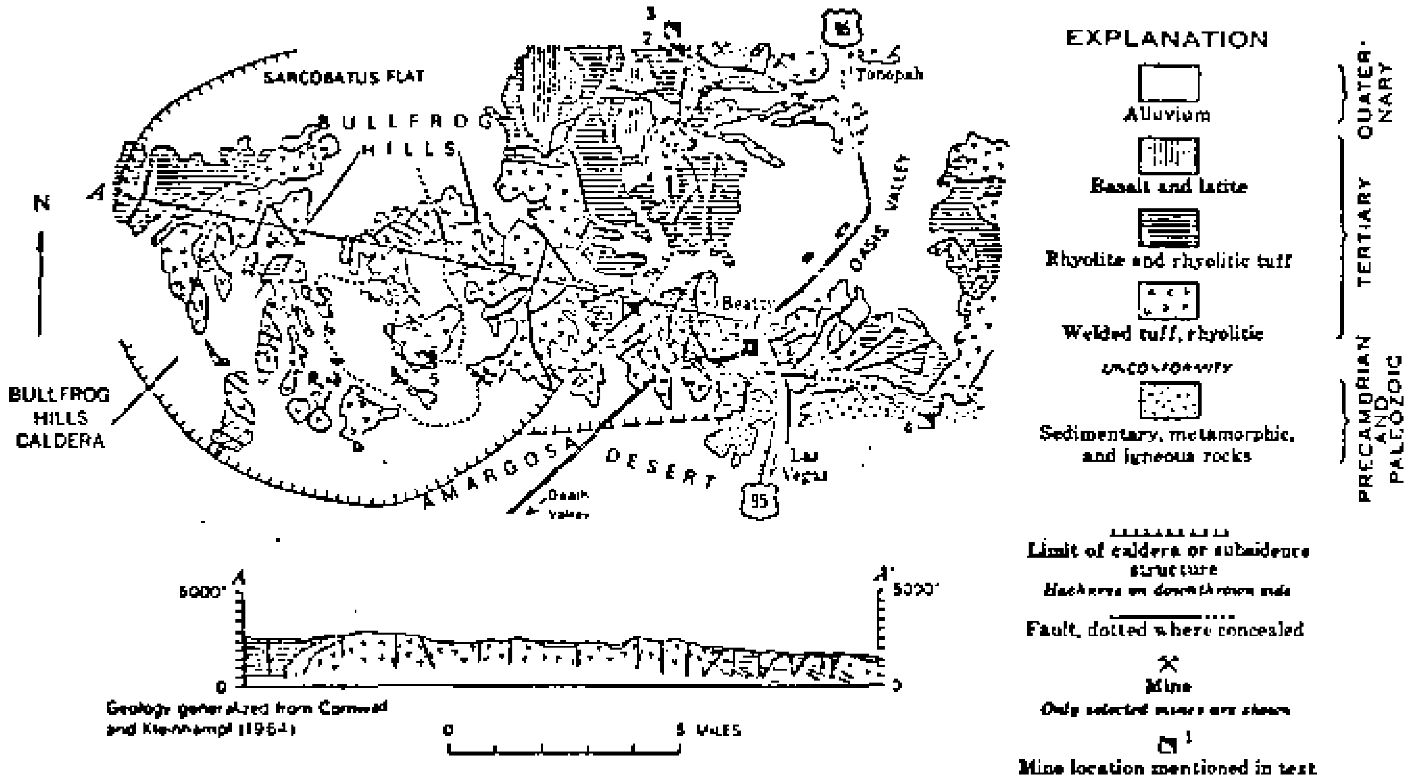
-Tertiary volcanic centers, Nevada.

Albers and Kleinhampl (1970)

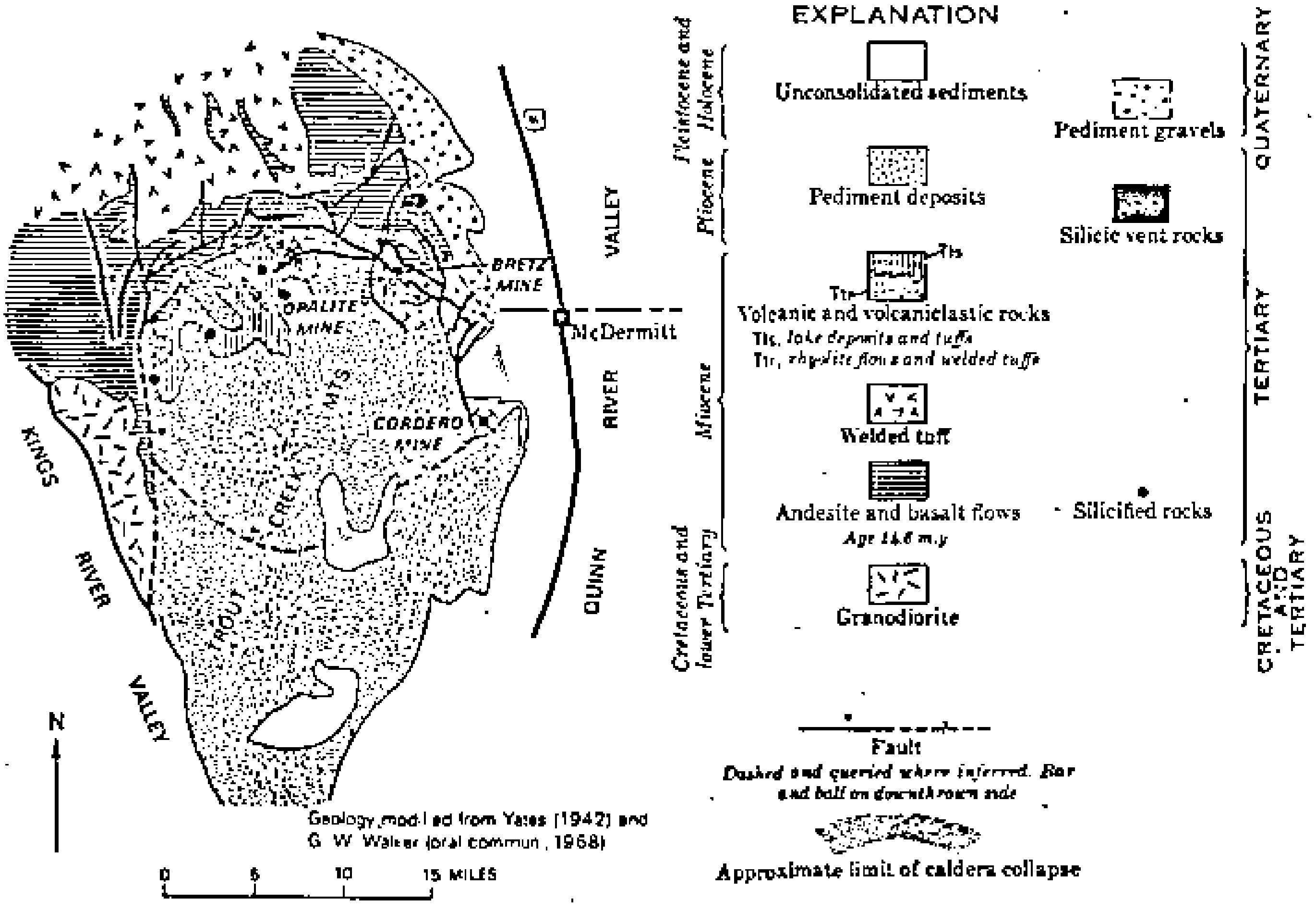
—*Brief description and age of mineralization at major mining districts associated with volcanic centers*

District	Type of center	Type of deposit	Age of mineralization [1] (millions of years)	Source
Aurora	Volcanic center, undifferentiated.	Veins	>12.5	Gilbert and others (1968, p. 283); Yehya Al-Rawi (oral commun., 1968).
Bodie	Intrusion, with uplift(?).	do	7.9 (adularia)	M. L. Silberman (oral commun., 1969).
Bullfrog	Caldera	Deposits along rim fracture zones (veins and bonanza ore).	<11	H. R. Cornwall (oral commun., 1969).
Comstock	Intrusion, with uplift(?).	Veins	13 (adularia)	D. H. Whitebread (oral commun., 1968).
Goldfield	Caldera(?) and (or) intrusion, with local uplift.	do	±21	H. R. Cornwall (oral commun., 1969).
Majuba Hill	Intrusive complex (heart of volcanic center).	Veins, some replacement of rhyolite and breccia.	Tertiary(?)	Trites and Thurston (1958, p. 158, 200–201).
Opalite	Caldera	Deposits along rim fracture zones.	<13	G. W. Walker (oral commun., 1965).
Silver Peak	do	Veins	<5.9	Robinson, McKee, and Moiola (1968, p. 595) taken from J. P. Albers and J. H. Stewart. Unpublished data.
Tonopah	Intrusion, with uplift	do	>17.5, probably >22.	[2].

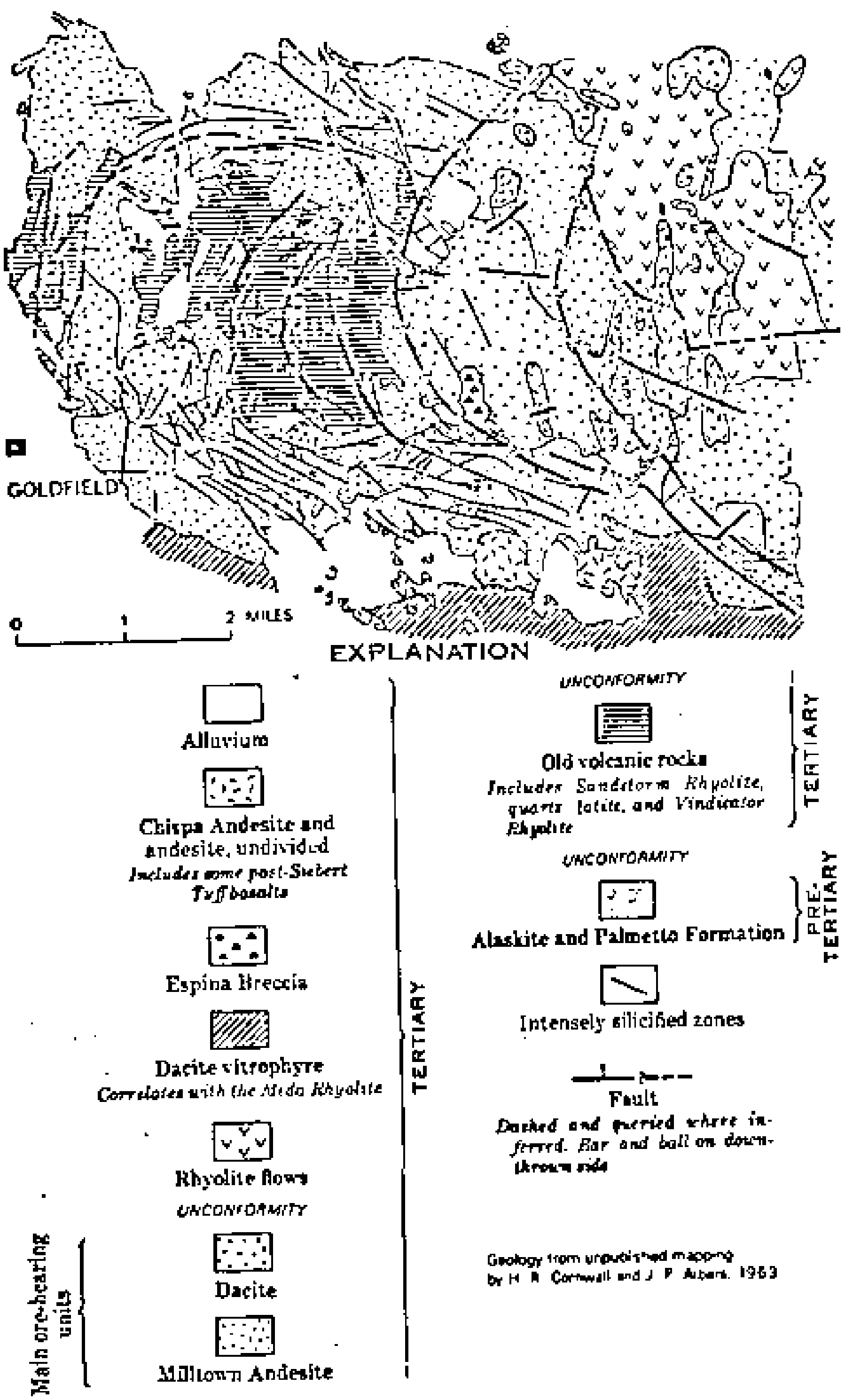
Albers and Kleinhampl (1970)



Albers and Kleinhampl (1970) -Bullfrog district, Nevada.



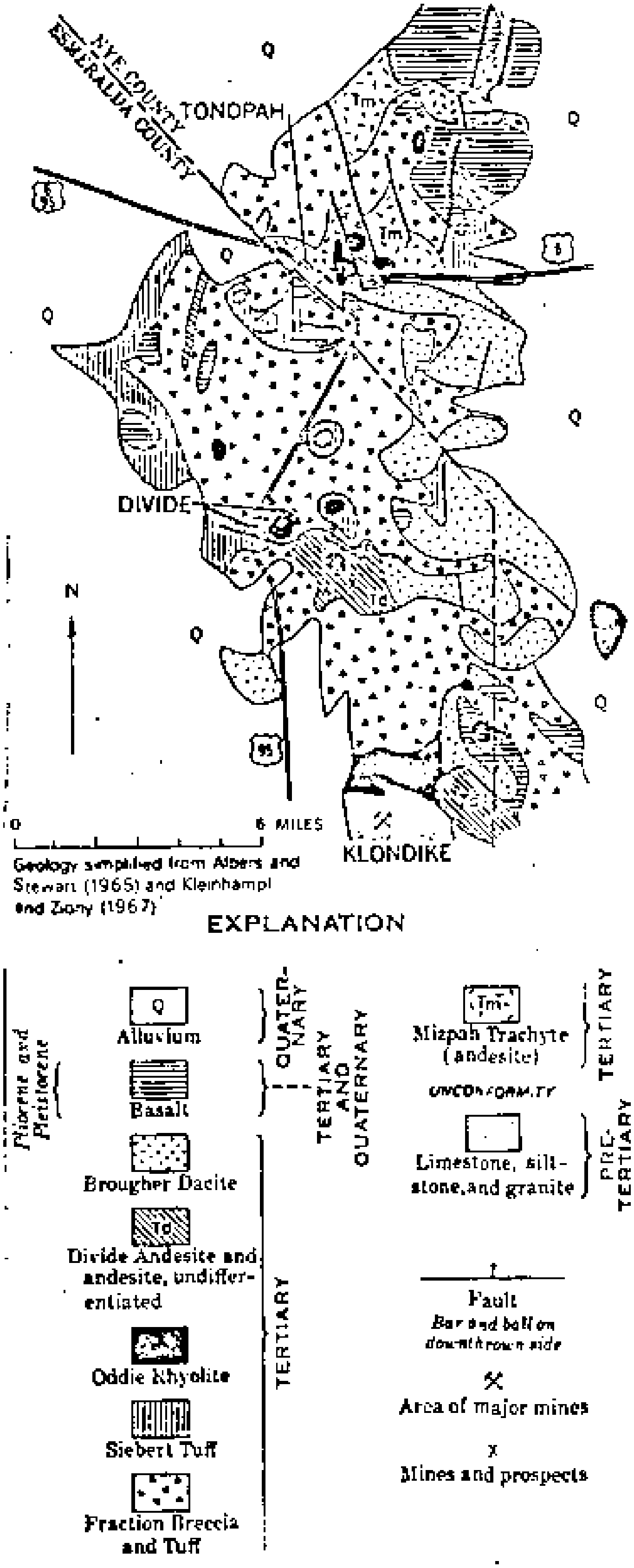
Albers and Kleinhampl (1970) quicksilver district, Oregon-Nevada.



Geology from unpublished mapping by H. R. Cornwall and J. P. Albers, 1963

—Goldfield district, Nevada.

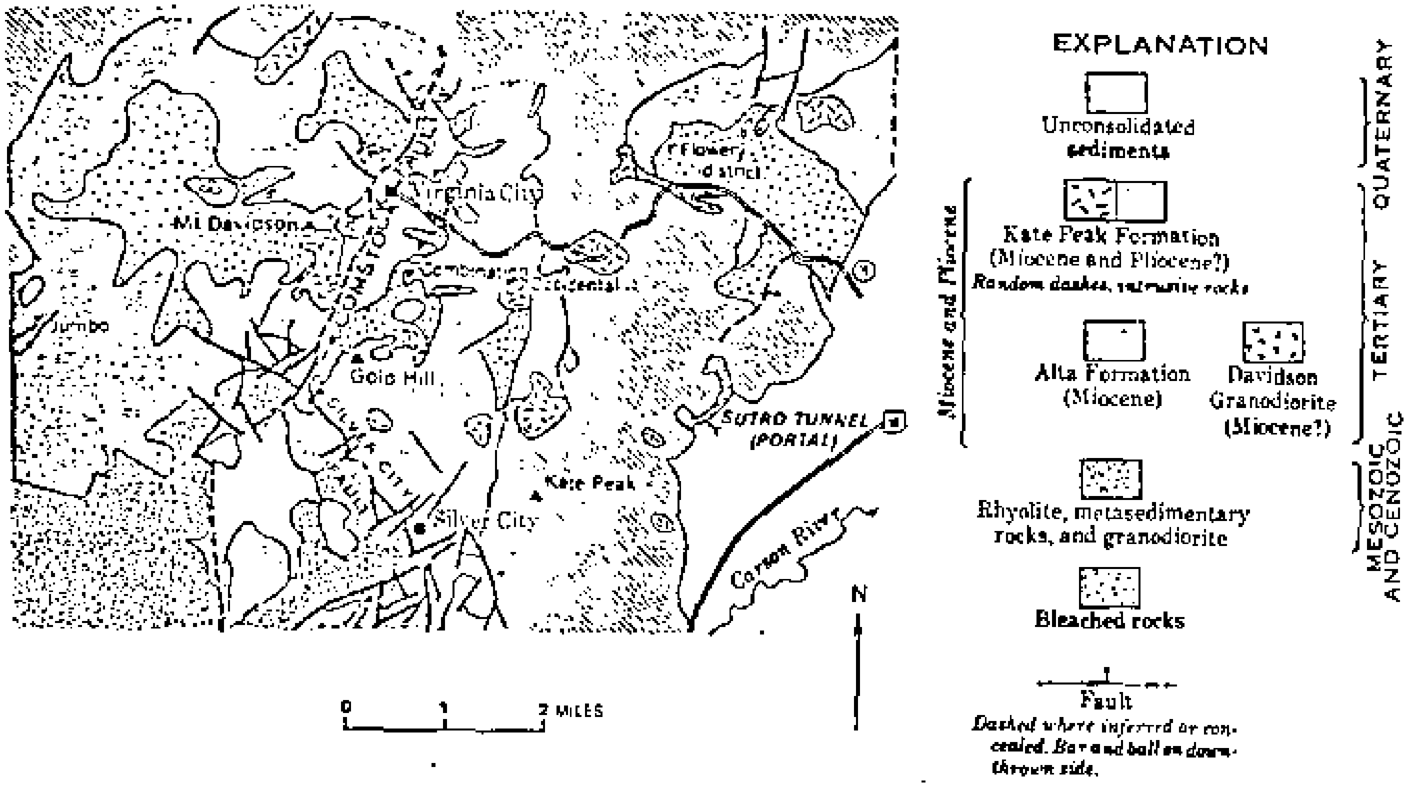
Albers and Kleinhampl (1970)



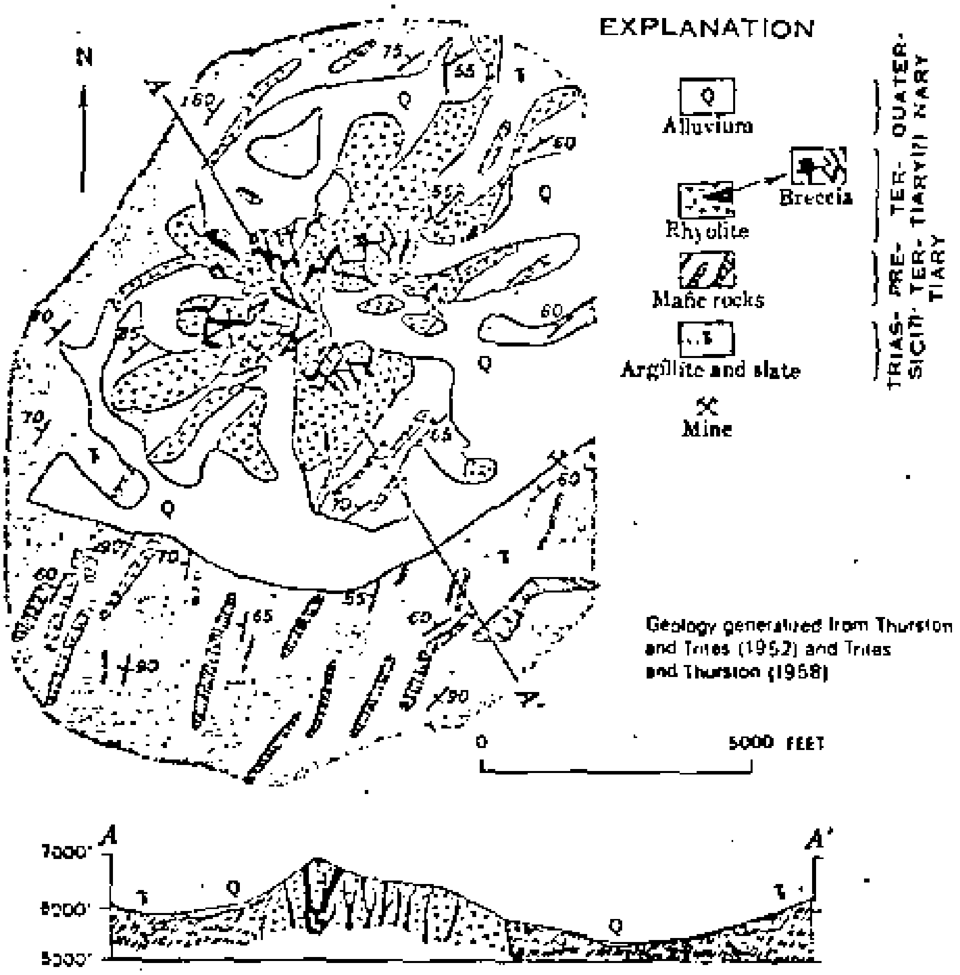
Geology simplified from Albers and Stewart (1965) and Kleinhampl and Ziony (1967)

Tonopah area, Nevada.

Albers and Kleinhampl (1970)

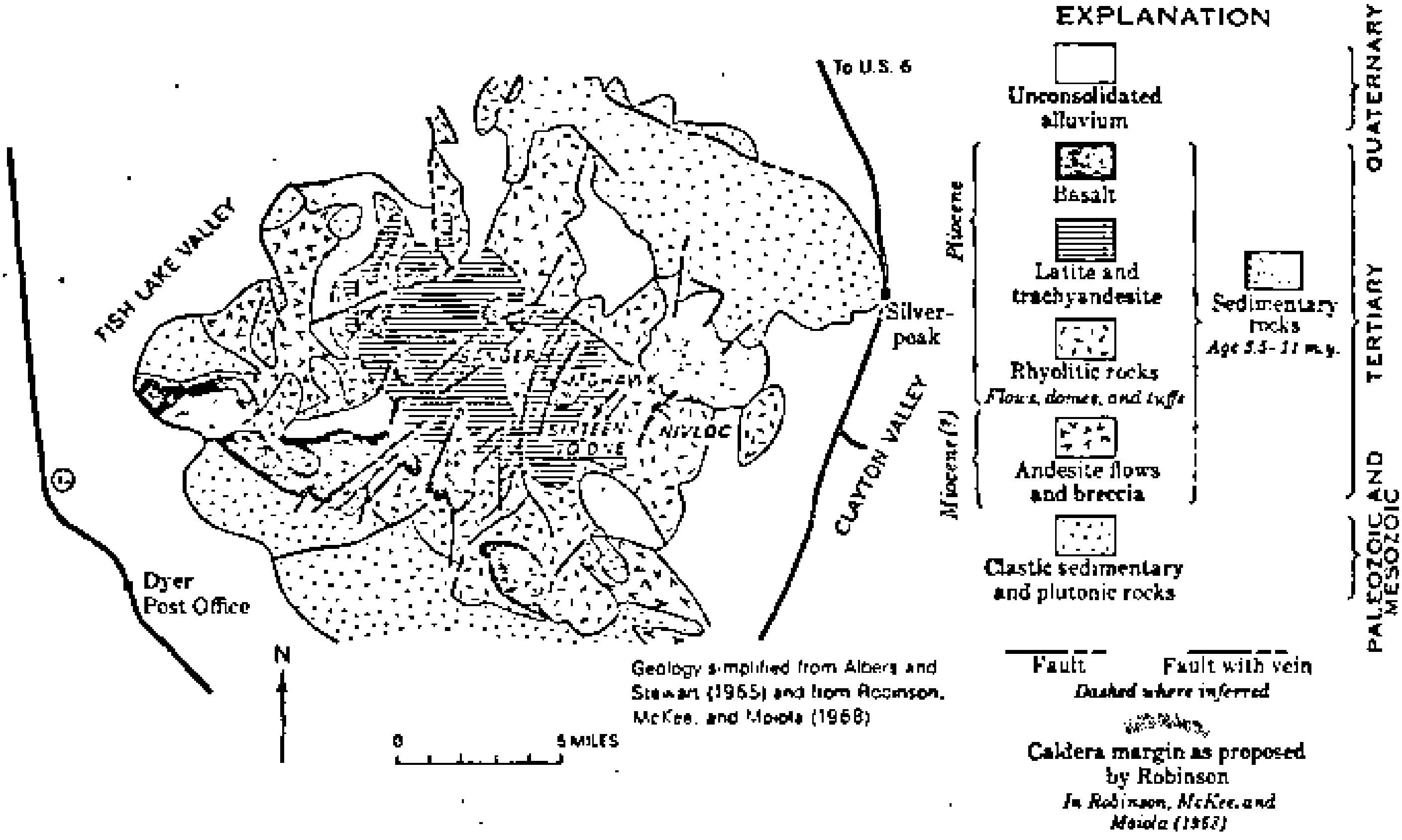


Albers and Kleinhampl (1970) Comstock district, Nevada.



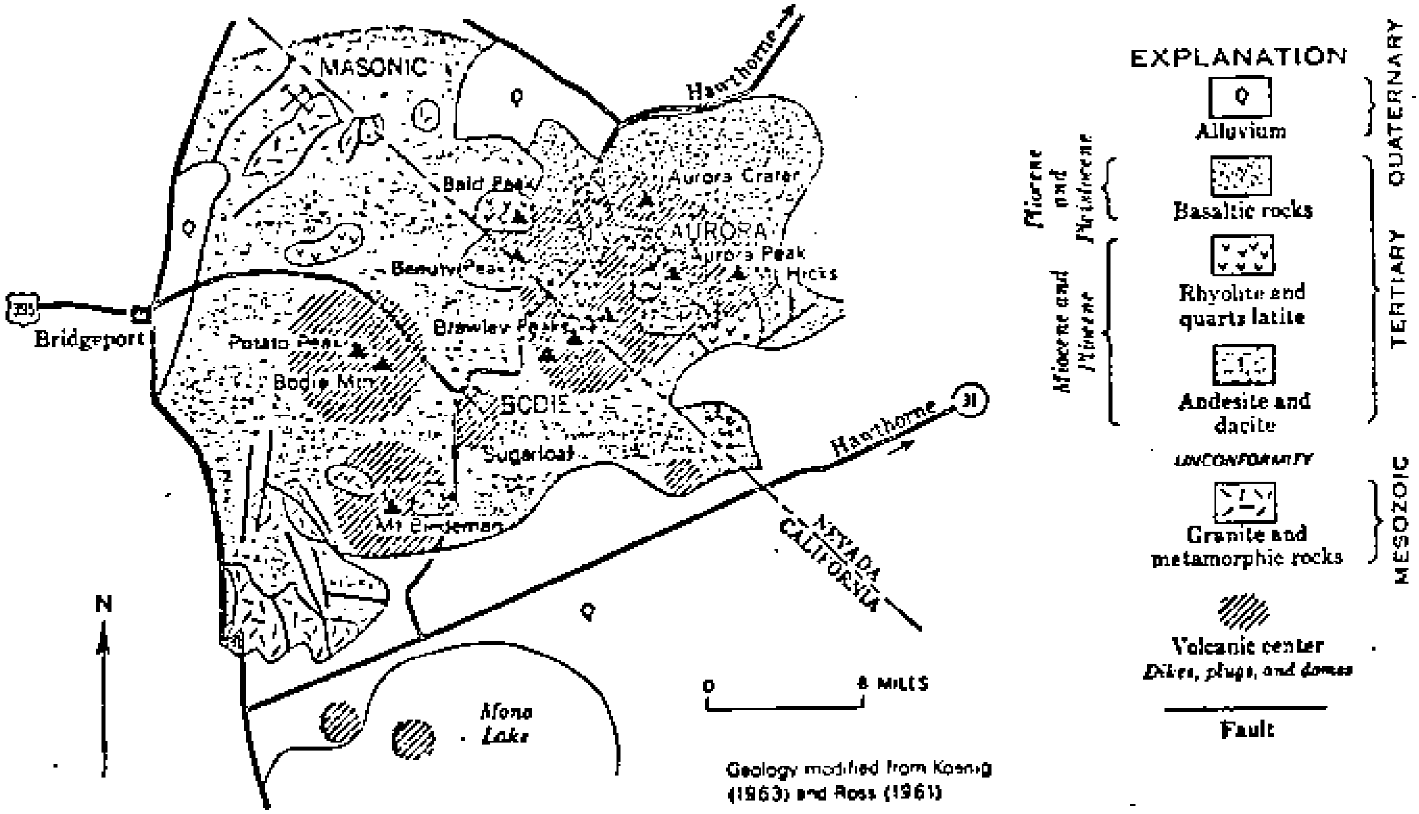
Majuba Hill, Nev.

Albers and Kleinhampl (1970)



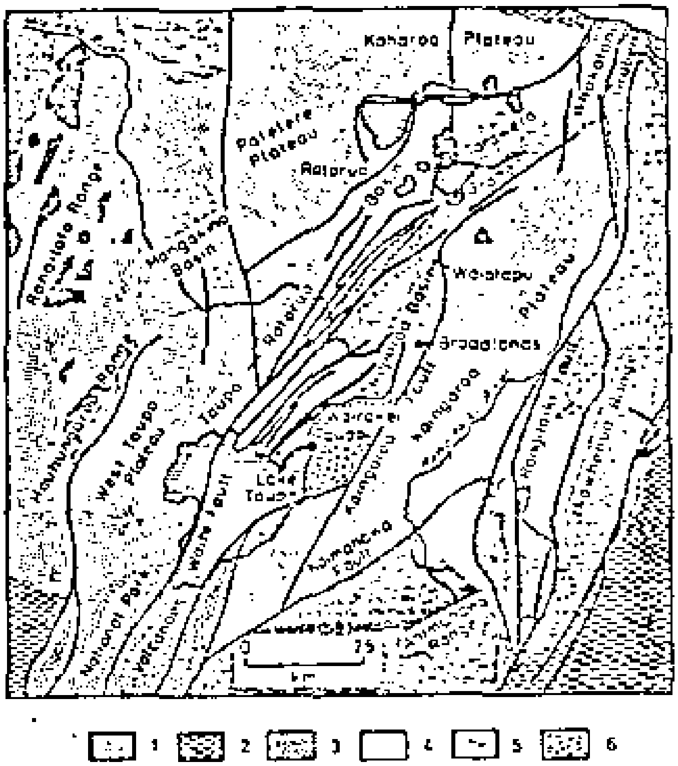
Silver Peak Range, Esmeralda County, Nev.

Albers and Kleinhampl (1970)

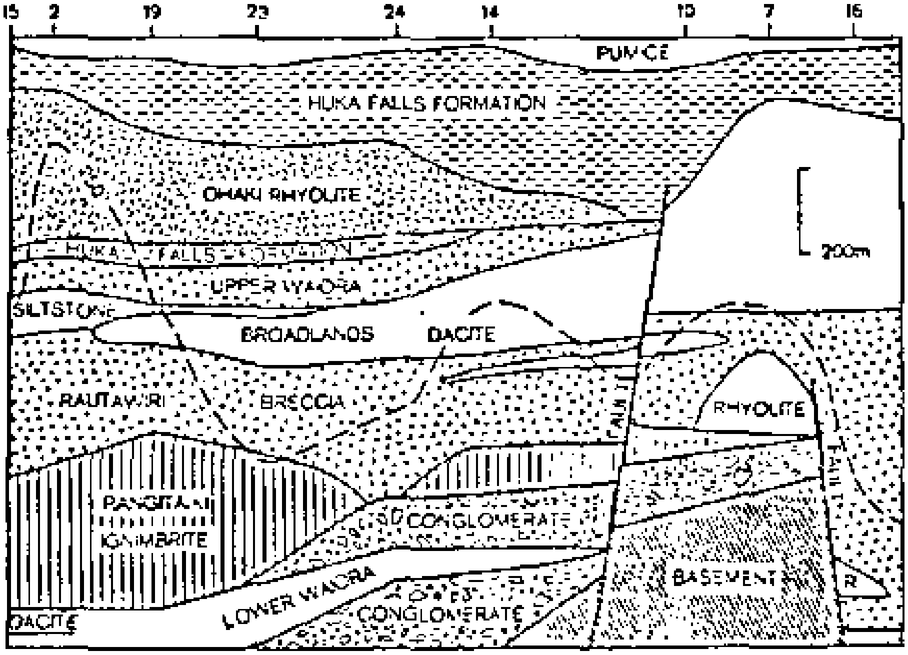


Aurora-Bodie area, California-Nevada.

Albers and Kleinhampl (1970)



Map of the Taupo Volcanic Zone showing surface geology and major structural features (adapted from Grindley, 1965a). 1, Quaternary freshwater sediments, lake beds, rhyolite domes, and pyroclastics; 2, Tertiary-Quaternary marine sediments; 3, Quaternary andesite (National Park); 4, Quaternary ignimbrites with minor rhyolites, andesites, and basalts; 5, Permian-Mesozoic greywackes and argillites; 6, Holocene pumice pyroclastics.



Geologic cross-section of the Broadlands, New Zealand, geothermal field.

Table 1. Spectrographic analyses of chemical precipitates, Steamboat Springs thermal area, Nevada; in ppm except where noted[1].

	T, °C	Au	Ag	As	Sb	Hg	Tl	B	Cu	Zn	Pb
-50, siliceous mud, Spring 24	95.5	15	150	700	1.5%	100	700	500	20	50	7
-310d, sinter & stibnite, Spring 8	95	1.5	1	50	1.0%	30	70	1,000	1	0.2	---
-941c, metastibnite & opal, erupting Nevada Thermal #4 well	96	60	400	600	>0.2%	<80	2,000	>2,000	>2,000	>2,000	400
GS-5 drillcore, depth in ft (m)											
11 (3.4) opaline sinter	42	0.3	2	150	700	2	10	1,000	15	15	n.d.
19 (5.8) " "	52	n.d.	0.3	30	500	500	5	500	3	5	n.d.
42 (12.8) " "	80	0.2	0.5	300	3,000	500	70	200	10	10	n.d.
84 (25.6) chalcedonic sinter	122	n.d.	<0.2	70	100	3	1.5	20	1.5	7	n.d.
113 (34.5) vein chalcedony	137	1.5	30	30	50	n.d.	1.5	15	5	15	n.d.
174 (53.1) " " -calcite	153	0.7	20	50	50	n.d.	1.5	15	10	10	n.d.
231 (70.1) " " "	163	0.3	70	70	30	n.d.	n.d.	15	3	30	n.d.
273 (83.2) " " "	168	n.d.	100	50	30	n.d.	n.d.	20	10	7	n.d.
346 (105.4) " " -quartz	171	n.d.	15	5	20	n.d.	n.d.	10	1	7	n.d.
363 (110.6) " " -calcite	172	n.d.	100	30	30	n.d.	<1	20	5	30	n.d.
446 (135.8) " " -quartz-calcite	171	n.d.	0.7	1.5	20	n.d.	n.d.	15	2	10	n.d.

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[1] Semi-quantitative 6-step spectrographic analyses by Chris Heropolous, U.S. Geological Survey, including short wavelength radiation data; Bi, Se, and Te below detection; data on Be, G, and Sr not included.

DIVISION DE EDUCACION CONTINUA
FACULTAD DE INGENIERIA U.N.A.M.

CLASIFICACION ACTUALIZADA DE YACIMIENTOS MINERALES

THE PORPHYRY COPPER (MOLYBDENUM) SYSTEM

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ABRIL, 1981

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CHAPTER 21

The Porphyry Copper (Molybdenum) System:

The following comments are excerpts from a paper presented by Paul Eimon in 1970 summarizing fifty years of worldwide porphyry copper discoveries. Economically, porphyry copper deposits are defined as large, roughly equi-dimensional deposits that contain commercial amounts of copper and varying amounts of molybdenum, silver, and gold, and that can be mined by open pit or underground bulk mining methods. Geologically, the deposits are closely associated with igneous complexes intruding a wide variety of rock types. The associated igneous rocks are generally porphyritic wit quartz or feldspar phenocrysts in an aphanitic groundmass. They show concentric mineralization and alteration patterns that often overlap both the intrusive and host rocks, and may be accompanied by breccia pipes or similar structures. Most common hypogene minerals are chalcopyrite, bornite, and molybdenite, although pyrite is ubiquitous.

Porphyry copper deposits are found within belts of Laramide and younger tectonic activity and are associated with large features such as the Western Cordillera of the Western Hemisphere, th fringes of the Colorado Plateau, the Iranian orogenic belt, and the Pacific arc. They are associated with zones of intrusives ranging from late Tertiary to Triassic age. They are often found in areas of recent volcanic activity.

Porphyry copper deposits are found in a wide variety of host rocks. Alteration and mineralization features vary more in response to the character of wall rocks and the porphyry intrusive than anything else. Crustal depth of the mineralizing process is a factor in alteration and mineralization features. As we see

them today, each deposit may represent a different position in a total vertical model of as much as several miles vertical scale. The following is a list of similarities exhibited by porphyry copper deposits:

1. A depth of formation relatively close to the surface.
2. Association with felsic to intermediate stocklike intrusives characterized by an aphanitic groundmass containing quartz or feldspar, or both.
3. Ubiquitous pyrite.
4. Age ranging from 1 to 200 million years, with some exceptions.
5. Concentric zoned halos of alteration and mineralization that vary in geometry and intensity.
6. Alteration halo considerably larger than the ore body, grading inward from propylitic through phyllic.
7. Mineral zoning grading inward from an outer pyrite halo containing traces of other metals to a pyrite shell with small amounts of copper and molybdenum surrounding a low pyrite core rich in copper and/or molybdenum.

The following is a list of differences observed among these deposits:

1. Presence and quantity of tourmaline.
2. Variation in grade and ratio of copper, molybdenum, gold, and silver and other metals.
3. Composition of the intrusive and character of the host rock.
4. Ratio of metal values occurring as actual disseminated sulfide grains to those as a stockwork or thin veinlets along fractures.
5. Degree and history of leaching and enrichment.
6. Intensity of total or local alteration.

Eimon concludes that the most promising areas for future exploration are active orogenic belts where clusters or zones of mineralized intrusives are most likely. He also states that the geologist who has the potential for discovering new deposits is one of practical orientation having a good foundation in mapping, a libera supply of common sense, and who knows the costs of mining, the geology of known deposits, and is willing to use this knowledge to search for, find, and evaluate similar deposits in various geographic, geologic, and climatic conditions. We will now look at the characteristics of porphyry copper deposits more closely.

The occurrence of known porphyry copper deposits in recent orogenic zones is characterized by the deposits lying in quite narrow belts, particularly around the Pacific. Two areas differ in this respect, southwestern North America and eastern Europe (Iran), where the deposits occur in broad zones.

The age of most deposits is characteristically young, however a few date back to the Triassic, and some in the Appalachian mountain belt are even older. Some deposits are as young as 1 million years; examples are found in the southwest Pacific. In North America, there is a general decrease in age from the deposit in British Columbia southeastward through Arizona into northern Mexico. The Bethlehem deposit, consisting of in excess of 100 million tons averaging 0.6 percent copper, is associated with Triassic volcanics. The mineralization is associated with a quar diorite intrusive dated at 200 million years. The Endako deposit, consisting of in excess of 100 million tons averaging 0.09 percent molybdenum, occurs in an intrusive, of quartz monzonite to granit composition, in Mesozoic sediments and volcanics. The intrusives have been dated at between 139 and 143 million years. This is the largest molybdenum deposit in Canada. The Bisbee, Arizona, deposit is an exception to the Laramide and younger deposits to t southeast. It has been dated at 163 million years. The Ely, Nevada deposit is apparently 109 million years old. Deposits in

the eastern Rocky Mountain Cordillera, including Bingham, Climax, and Questa, are of mid-Tertiary age. The youngest deposits occur in the southwest Pacific where the Ok Tedi deposit of New Guinea is less than 5 million years old, and the Panguna deposit on Bougainville is 1 million years old. The former has the distinction of being one of the few deposits discovered by geochemical methods. The latter was discovered in 1964, consists of quartz diorite and granodiorite intruded into Tertiary andesites, and is a copper-gold deposit exceeding 500 million tons.

In North America, there appears to be a general zoning from west to east of copper, to copper-molybdenum, to molybdenum in the porphyry deposits.

Although the most common rock type in porphyry systems is quartz monzonite porphyry, deposits may be associated with stocks ranging in composition from diorite to granite. These stocks are intruded into a wide variety of country rocks, however some of the best porphyry systems have developed where carbonate rocks are involved. Multiple intrusions are common, and mineralization may be associated with all intrusions, as at Climax, or the latest event, such as at Bingham. Where there is a sequence of intrusions it is common to see a sequence which suggests magmatic differentiation, such as diorite to monzonite to quartz monzonite to latite and other quartz-rich rocks from oldest to youngest. The late phases are often expressed as late cross-cutting aplitic dikes. Intrusions appear to be shallow, and are often associated with felsic volcanic rocks cogenetic with the intrusives. The volcanics are often mineralized, and here is one place where the transition between a typically mineralized stock and vein type precious metal mineralization may be apparent. Where there is a long history of igneous and volcanic activity, the intrusive most closely associated with the ore is of relatively small volume, usually a stock, sometimes irregular in shape, with an average size of 4000 by 6000 feet in plan cross-section. The mode of emplacement is described as passive, involving the apparent replacement, stoping, or assimilation of wall rock, rather than forceful injection. However, important exceptions do occur, as at Climax. A common feature associated with the deposits are breccia pipes which may or may not be mineralized. Brecciation appears to be an important feature associated with mineralization and implies a relatively shallow depth.

The ore bodies consist of: disseminated sulfides in host rock; major vein systems; replacements associated with skarns; and replacements in carbonate units, when the latter are present. The grade of ore is characteristically low, and very often the economics of a porphyry copper deposit will depend on supergene enrichment and mineability by large volume surface methods (in addition to the market, location, and extractability). The average grade of primary mineralization is usually less than 0.5 percent copper and/or 0.015 percent molybdenum, and secondary mineralization averages about 0.8 percent copper. Molybdenum does not normally exhibit secondary enrichment. Chuquicamata, Chile, probably the largest porphyry copper deposit in the world, has gone through a complex oxidation and supergene enrichment history. The average grade of ore here is about 1.2 percent copper. The Braden, Chile, deposit averages 1 percent copper in the primary ore, and 2.25 percent copper in the supergene ore. The La Caridad deposit, Sonora, Mexico, averages 0.8 percent copper, primarily as supergene ore. This deposit supposedly contains 750 million tons of ore. Some of the Arizona deposits contain primary mineralization as low

as 0.1 percent copper, and some mine supergene ore as low as 0.45 to 0.5 percent. In some of the deposits mining higher grade material, even low grade ore has proved economically recoverable through dump leaching. In molybdenum deposits, Climax averages 0.24 percent, Questa 0.15 to 0.18 percent, and Henderson greater than 0.3 percent molybdenum.

The average reserve tonnage of North American porphyry copper deposits is about 150 million tons. Bingham, Butte, Chuquicamata, and Climax exceed 500 million tons. The Petaquilla, Panama, deposit promises to be one of the largest in the world, as do some of the relatively unexplored deposits of the southwest Pacific.

Pyrite is the most important sulfide. Chalcopyrite, molybdenite, and lesser amounts of bornite are the primary ore minerals. Chalcocite, and small amounts of covellite are the most important secondary minerals, although in some deposits the latter is found to be primary.

One of the most characteristic features of porphyry deposits is the hydrothermal alteration associated with and enveloping mineralization. This alteration has received significant attention in exploration programs. The alteration is zoned concentrically around the deposits. The mechanisms of zoning are not well understood, however it may be related to gradients in temperature, pH, and chemical potential of dissolved components.

Lowell and Guilbert illustrate alteration zoning using the Kalamazoo-San Manuel deposit complex as a model. The following diagrams at the top summarize the local geology of the deposit. The 2 deposits actually represent one which has been cut in half by the San Manuel fault, a low angle normal fault. Note the supergene enrichment blanket formed previous to tilting and faulting.

The top diagram restores the deposit to its pre-tilting, pre-faulting, position, and shows the typical inverted cup-like distribution of mineralization about the intrusive.

The lower diagram shows the distribution of alteration typical of many porphyry copper deposits, concentrically zoned around the center of mineralization. The alteration can extend for thousands of feet out from the deposit, and will effect the country rocks as well as the stock. Contacts between zones are gradational over a few hundred to a few tens of feet, depending on the size of the deposit and zones. Propylitic alteration is the lowest grade and is found in the outer zones of mineralization in contact with fresh rock. Briefly it involves the alteration of ferromagnesian mineral to chlorite and plagioclase to epidote. Pyrite and calcite may also be found in this zone. The phyllic zone involves the reconstitution of pre-existing phases to sericite, quartz, and pyrite. This zone may be separated from the propylitic zone by a thin argillic zone where clays, either montmorillonite or kaolinite, result from the alteration of pre-existing plagioclase, chlorite, etc. The potassic zone represents the reconstitution of all previous minerals to potassium feldspar, biotite, quartz, and commonly anhydrite. It is the highest grade alteration observed.

This zoning differs slightly from the classical case at Butte where the alteration zoning enveloped individual veins in the shallow lode deposits. In the latter, the argillic zone was very important volumetrically, and was divided into an outer montmorillonite zone and an inner kaolinite zone, where the latter resulted from the breakdown of the former. In addition, adjacent to the veins at Butte in places an advanced argillic zone was observed where sericite was converted to kaolinite and pyrophyllite. When speaking of hydrothermal alteration care must be taken to distinguish between grade and intensity, the latter describing the degree to which minerals have been converted and not the alteration mineral assemblages. The following table summarizes the possible chemical reactions taking place during alteration, and the gains and losses in components observed, starting with a quartz monzonite composition.

The subsequent diagram compares the alteration zoning, the mineral zoning, and the zoning in occurrence of minerals. An inner barren core is surrounded by the ore shell where ore sulfides equal or exceed pyrite content. The ore shell grades outward into a high pyrite, low metal, zone, which grades outward into low grade disseminated mineralization. The scale will depend on the overall size of the system. Note that the degree of fracture development increases outward, which is related in part to confining pressure. Variations in alteration and mineralization will occur, and these will be mostly related to anisotropism in the structure and/or composition of the invaded rocks. For example, elongation of the zonal pattern may occur along a prominent pre-mineralization fault. Where carbonate replacements occur in the outer vein zone, alteration normally consists of dolomitization, silicification, and recrystallization.

Where limestones or dolomites are present in the invaded environment, sulfide replacement bodies are usually present, but in most cases are small with the exception of Bingham, Bisbee, and Santa Rita. In many cases early mining of these replacement bodies has lead to the recognition of porphyry deposits. These replacement deposits are similar to those where the association with a porphyritic intrusive is obscure, or where the latter is small relative to the volume of country rock mineralized, such as Park City, Utah or Leadville, Gilman, and others in the Colorado Mineral Belt. Here again a problem arises when we choose to be too restrictive in our definition of the porphyry system.

Characteristically, the carbonate replacement deposits associated with porphyry copper-molybdenum deposits contain mostly lead-zinc or lead-zinc-silver mineralization with subordinate copper. The most common minerals are sphalerite and galena with smaller amounts of silver minerals, chalcopyrite, tetrahedrite, gold, pyrite, rhodochrosite, and complex sulfosalts. There may be a zoning within the carbonates outward from the source of the solutions towards lower temperature mineral assemblages. In a stratigraphic sequence consisting of alternating limestones and quartz-rich sediments, replacement is highly selective towards the carbonate units. The only mineralization in the quartz-rich units may be disseminated pore fillings and coatings along fractures. This selectivity is very well illustrated in the Bingham district.

The development of skarns where porphyries intrude carbonates must be noted. These are very commonly sites of important copper mineralization, but the latter is usually paragenetically later than the skarn minerals. The latter are typical of a contact metamorphic assemblage of garnet, diopside, epidote, forsterite, wollastonite, tremolite, magnetite, idocrase, tourmaline, fluorite, and others, depending on the composition of the original carbonate. Some deposits have been mined principally for their skarns.

When considering the porphyry copper-molybdenum system as a whole an overall mineral zoning is apparent which consists of, from center outward: (1) chalcopyrite, pyrite, bornite, molybdenite; (2) pyrite, chalcopyrite, molybdenite, bornite; (3) pyrite, chalco-

pyrite; (4) sphalerite, galena, silver minerals; (5) galena, silve gold; (6) antimony, mercury.

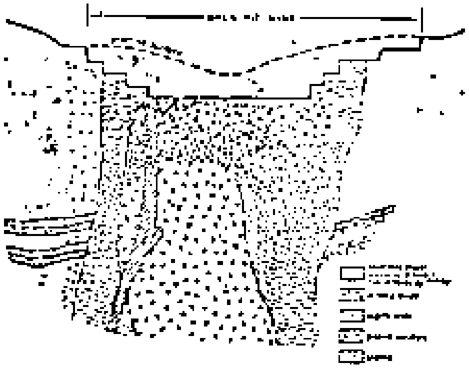
CHAPTER 22

There have been a number of attempts to place known porphyry copper-molybdenum deposits in a general model, where what we see today is related to the depth of erosion in the porphyry system. This was done on the first diagram of the previous chapter for Morenci, Butte, Mineral Park, Silver Bell, Bingham, Santa Rita, or Ajo. The following is a similar attempt by James for Bingham, Chino (Santa Rita), and Ray. Because the Bingham district is quite representative of porphyry copper deposits, it is worth describing its geology in a little detail.

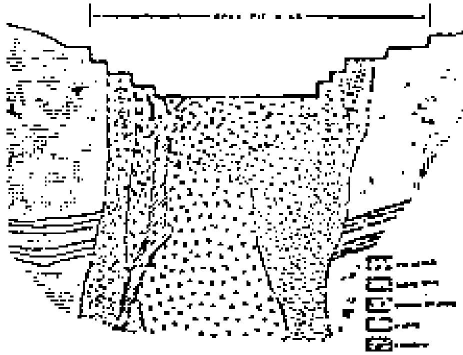
The Bingham District, Utah

The primary mineralization at Bingham occurs as an inverted cup superimposed over what is refered to as a granite porphyry stock. The molybdenum envelope is coincident, but slightly inside the copper envelope. The granite is actually a body which represents a quartz monzonite which has been altered to the potassic grade. The grade of the primary ore is 0.71 percent copper, 0.05 percent molybdenum, 0.008 ounces gold and 0.08 ounces silver per ton. Reserves are estimated at 1.7 billion tons, and the deposit has in excess of a 50 year life. About 112,000 tons of ore and 250,000 tons of waste are removed from the pit each day. Even though the gold content of the ore is low, Bingham is the second largest gold producer in the United States by virtue of the large tonnage mined. The central part of the present pit runs as high as 1 percent copper. The secondary enrichment blanket has already been mined off. It ranged in thickness from 200 to 600 feet and 1.5 to 2 percent copper.

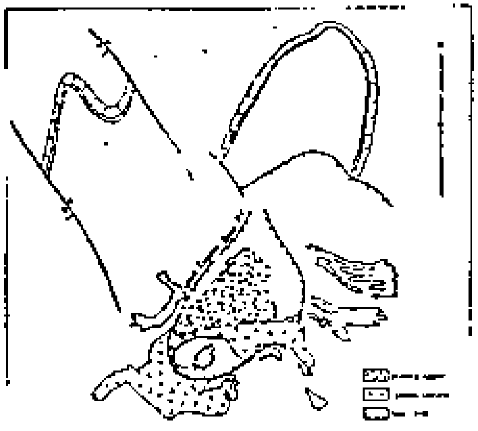
In the cross-section, the Bingham Stock is the largest of the



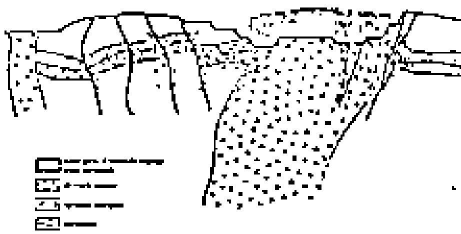
PRIMARY COPPER
DIAGRAMMATIC INTERPRETATION
BINGHAM, UTAH



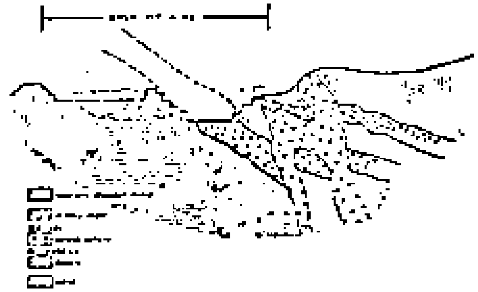
MOLYBDENITE
DIAGRAMMATIC INTERPRETATION
BINGHAM, UTAH



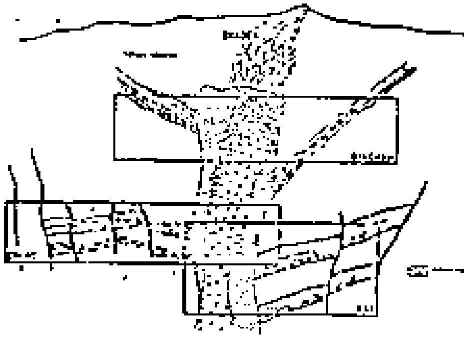
DIAGRAMMATIC INTERPRETATION
BINGHAM, UTAH



DIAGRAMMATIC INTERPRETATION
CHINO, NEW MEXICO



DIAGRAMMATIC INTERPRETATION
RAY, ARIZONA



DIAGRAMMATIC MODEL OF PORPHYRY COPPER IGNEOUS COMPLEX

3 intrusives and is an equigranular monzonite intruded into Precambrian basement and folded Pennsylvanian and Mississippian carbonates and quartzite. Adjacent to the Bingham Stock on the southwest lies the Last Chance Stock, also an equigranular quartz monzonite, however the latter is unmineralized. Mineralization appears to be associated with a porphyritic "granite" phase intruded into the Bingham Stock as shown in the cross-section. In the vicinity of the stock the limestones act as favorable hosts for replacement mineralization. Some quartzite is also mineralized. In addition, contact metasomatic, or skarn, mineralization contains significant amounts of copper, gold, silver, with small amounts of zinc and lead. One such deposit adjacent to the present pit, the Carr Fork property, has recently been announced and consists of a skarn zone up to 300 feet thick and several hundred feet long. The copper content jumps to 2 percent, and the gold and silver are 3 times their content in the main pit area.

Replacement deposits in carbonates have been mined as far as 10,000 feet away from the contact with the porphyries, and to a depth of 5000 feet. Both lateral and vertical zoning occurs with copper and gold grading outward to zinc, lead, and silver, with copper increasing at depth. Stibnite, realgar, orpiment, and cinnabar are found in minor amounts at the fringes.

According to the porphyry model given in the lower right, Bingham lies close to the top of the system, and therefore has not been eroded very deeply.

Santa Rita District, New Mexico:

The Chino pit is part of the larger Santa Rita District. Here the copper mineralization is associated with early Tertiary granodiorite porphyry stocks intruded into older sediments, and Precambrian metamorphic and igneous rocks. Replacement deposits in adjacent Paleozoic carbonates contain chalcopyrite with minor galena and sphalerite. The primary mineralization in granodiorite is low grade below the supergene blanket, which averaged 1 percent copper. The latter probably came from richer primary ores which have been eroded away, and therefore it is suggested that the level of erosion here is deeper than at Bingham. Present mining is in skarn deposits containing magnetite as well as chalcopyrite.

Ray, Arizona:

The mineralization at Ray is associated with Tertiary quartz monzonite porphyry, with an age of 63 million years, intruded into the Precambrian Pinal schist. The latter has been intruded by diabase dikes. Even though the monzonite intrusive appears to be the ore carrier, only a small amount of ore occurs in it close to the contact. The remaining porphyry is largely barren containing 0.1 to 0.2 percent copper. The quartz monzonite may have originally been richer, as suggested by the position of the supergene blanket in the schist, but now has largely been eroded off. Presently, diabase is the most important primary host, however this unit is barren away from the quartz monzonite. The overall distribution of the mineralization suggests it is intimately related to the emplacement of the porphyry. The richest ore occurs in the supergene blanket which runs as high as 10 percent copper in the schist from which the greatest production has taken place. Considering the grade of ore, it is suggested that a significant column of rock has been leached and eroded above. Therefore the Ray deposit is placed deep in the porphyry model.

The final diagram places all these deposits into the general model where their present geology represents different levels of e [illegible]. In addition, Braden, Chile has been included at the top of the system. This deposit consists of a stockworks of veins in Tertiary felsic volcanic rocks associated with felsic dikes and small plugs. Even though no central porphyritic stock is apparent the depth of erosion may be small, and the presence of such a stock at depth cannot be ruled out.

Sillitoe took the same approach in studying the porphyry copper deposits of the Andean mountains of Chile and Argentina. The age of the felsic volcanics and plutons decreases from the coast, inland until volcanism is quite recent in the high Andes. The known porphyry copper deposits in this region occur along a relatively narrow zone. The coastal areas contain barren intrusives of batholithic dimensions. The next belt inland contains Tertiary intrusives of much shallower depth of emplacement. These are the host for the well known porphyry copper deposits of Chile. The next belt are the volcanics and the recent strato-volcanoes of the high Andes. In the latter there are no intrusives larger than a few dikes and small plugs.

Because the rocks get older towards the coast, the depth of erosion should be greater, as reflected in the deep basement rock and plutons which are exposed along the coast, whereas the volcanoes of the high Andes are quite well preserved. In the latter, alteration is extensive and pyrite is ubiquitous. Sillitoe interpreted this as the outer zones of alteration. From his investigation of deposits associated with porphyritic stocks intruded into volcanic rocks Sillitoe concluded that these were definitely shallow intrusives. The following diagram is the model Sillitoe proposes for porphyry copper deposits. It includes both a volcanic and subvolcanic environment with breccia pipes and replacement

deposits in adjacent carbonates. Along the left side are v[illegible]s porphyry copper deposits placed at their suspected levels of erosion. Note the apparent deep environment for Chuquicamata, which is preserved only because it has been down-faulted adjacent to the Fortuna granodiorite batholith. Its long history is reflected in the complex history of oxidation, supergene enrichment, and subsequent oxidation. Figure 6 below is a reconstruction of one of the Andean occurrences complete with eroded volcano.

This model can easily be applied to porphyry copper deposits around the Pacific basin where the association of mineralization with volcanism is well documented, particularly in the southwest Pacific. An important point, however, is the relatively small environment of porphyry copper mineralization with associated stock, to the overall volcanic environment; the former represents only a small portion of the latter. Elsewhere, the association of volcanism with such mineralization is variable. Younger areas of mineralization very commonly show an association with volcanism, particularly areas such as the San Juan Mountains, yet typical porphyry environments are not apparent. However, this area holds potential for finding porphyry systems, the latter are suspected and some interesting prospects are being explored. In other areas such as Arizona the association of porphyries with volcanism is less certain and care should be used in applying this model to these deposits.

On a local scale, the geology of porphyry copper-molybdenum deposits seems to suggest a common sequence of events in the development of mineralization:

1) Deposition or emplacement of all pre-ore episode rocks, including any structural changes which may control the emplacement of porphyritic intrusives.

2) Structurally controlled volcanism and/or emplacement of plutons. Normally, a series of intrusives are recognized and a differentiation trend towards more silicic rock types is common. Mineralization appears to be associated with a late phase. Stoping and assimilation appear to be more important than forceful injection, and the intrusion of one pluton can take place before complete crystallization of that preceding.

3) Crystallization of the ore-related stock from the walls inward; cooling is not necessary for crystallization, but probably accompanies crystallization at least.

4) Fracturing and shattering of the solidified outer portion of the stock; this may be the stage at which breccia pipes develop.

5) Invasion of the solidified portion by altering, mineralizing, hydrothermal solutions. Mineralization is by replacement and fracture filling, localized by the fractures produced during shattering of the outer shell.

6) Cooling, uplift, and erosion.

7) When the deposit becomes exposed, oxidation and supergene enrichment will occur.

The fracturing appears to be an integral part of the ore emplacement because of its common occurrence in the stocks and as breccia pipes. The fracturing and breccia pipe development may be related to the generation of the hydrothermal fluid.

Vein and replacement deposits associated with porphyritic dikes and sills are common, and are unlike stock occurrences. We may be looking at only minor differences in terms of scale of solution generation and mobilization. Recall the possibility that the intrusion serves only as a heat source and the mineralizing solutions are externally derived.

Breccia Pipes:

Breccia pipes appear to be closely associated with hydrothermal mineralization and should be considered in more detail. They have a wide variety of shapes and sizes, but most commonly appear as an inverted cone or tapered pipe, usually circular or ellyptical in plan. They range from a few hundred to a few thousand

in diameter. Breccia pipes may or may not be altered or mineralized. Rarely mineralization is coextensive with the pipe, as at Toquepala, Peru, and Cananea, Mexico. In many cases the vertical range is unknown. They commonly outcrop on the surface and extend downward beyond the depth of mining or development. They may appear to bottom out in a stock, or in country rock. Some occur at the intersection of fracture zones. Fragments in the pipes consist of wallrock, as does the matrix. The fragments are angular to rounded and range in size from minute grains to blocks weighing many tons. A wide range of transport distances and rotations are observed, and often the fragments can be traced from stratigraphically above their present position.

The pipes commonly have smooth, sharp walls. Sometimes the latter show a transitional nature where the degree of rotation, transport, and rounding increases from the wall inward. Breccia pipes are often bounded by a sheeted zone where concentric fractures decrease in density away from the pipe. Some fragments are completely foreign to the wallrocks, no source can be identified. Fragments may or may not be hydrothermally altered. In zones of intense silicification the matrix has a vitreous appearance resembling porcelain. Breccia pipes appear to have developed close to the end of magmatic activity as they rarely contain igneous material. They also appear to be pre-mineralization as they do not commonly contain fragmented ore.

There have been many origins proposed for breccia pipes, however the most popular is through the mechanism of fluidization, which is the release of pressure built up by the collection of dense fluid at the top of the magma chamber after the beginning of crystallization of the shell. Shattering would be localized along pre-existing zones of weakness. After shattering and during pressure release the fluid would move upward rapidly and semi-forcefully carrying material. The latter would be tumbled and eroded, enhancing the nature of the breccias. Because this fluid is more like a dense vapor than a liquid it does not have the ability to alter as gases are not chemically reactive. After the pressure is released material will fall back into the void, thus the collapsed nature. This would be related to a violent gas eruption of a felsic volcano. After the period of fluidization more condensed solutions can percolate upward using the same channels and mineralize the breccias.

It has also been suggested that the breccias result from collapse in the chamber due to the reduction in volume of the magma during boiling, producing a void.

CHAPTER 23

Origin of Hydrothermal Solutions:

If we agree that the mineralizing solutions are related to th emplacement of these felsic stocks, then we should consider the origin of these solutions. There is good evidence that in many cases the hydrothermal solutions and felsic melts are cogenetic where the former originated by the boiling of the latter. This boiling can take place at any time in the history of differentiation of the magma. This boiling implies there is limited solubility between the silicate melt and aqueous solution. Depending on the compositions and the conditions, the maximum solubility of water in a silicate melt is about 10 percent by weight. There are 3 important factors when considering the behavior of water in silicate melts: 1) The solubility of water in a silicate melt increases as pressure on the system increases; 2) the solubility of water in a melt decreases as temperature increases; 3) liquidus temperatures in silicate systems decrease as the water content increases. All 3 of these factors are expressed graphically in the following diagram which shows the minimum temperature on the liquidus surface for the ternary system quartz-potassium feldspar sodium feldspar as a function of water pressure (in kilobars) over the melt. The sub-vertical contours with a positive slope represent the solubility of water in the melt. Below the curve, crystals of feldspar would be present along with silicate melt, depending on the temperature. Above the curve, only liquid silicate would be present. It is apparent from the diagram that increase of pressure results in an increase in water dissolved in the melt and a corresponding decrease in the melting temperatures in the ternary system. This is due to the ability of water, present in the melt droxyl ions, to reduce the polymerization tendency of the silica. It is apparent from the slope of the water content contours that as temperature increases, the water content decreases. However, because the contours have such a steep slope, the effect of temperature on the solubility of water in a silicate melt is much less than that of pressure. In summary, silicate melts with high water content have low melting temperatures, and when such a melt loses water, its melting temperature will increase. These same principles apply to melt of less felsic composition. It is also apparent from this diagram that just a little water has a large effect on silicate melting temperatures.

The following isothermal diagram in Figure 2.4 shows similar relationships for the solubility of water in a silicate melt of albite composition, again as a function of pressure. Depth is given on the right side for comparison. In the lower left portion of the diagram the melt would be undersaturated with respect to water, and in the upper right saturation would be exceeded so we would have both a liquid silicate phase and a water-rich phase present. Below the curve, which is actually a boiling or saturation curve, only liquid silicate will be present. The curves labelled P_{H_2O} are equilibrium partial pressure of water curves, and when this equals total pressure, a separate aqueous phase will appear. We can use this diagram to help explain how hydrothermal solutions form and how porphyritic intrusives develop. We can als demonstrate that in order for a melt to rise from depth to shallo portions of the crust, it must start out extremely undersaturated with respect to water.

In an ideal situation at constant temperature and where no water is gained or lost by the silicate melt, when a melt begins

[illegible]o rise in the crust responding to pressure gradients, it will along one of the P_{H_2O} contours. Which contour it follows will depend on the initial water content of the melt. Because stoping and assimilation are important processes in the emplacement of our stocks, assuming a closed system may not be valid. However, as long as the initial water content is not modified too drastically, and provided the temperature does not change very much, the above relationships are modified negligibly. The natural silicate melt will be very close to liquidus temperatures because of the crystallization of feldspar (or ferromagnesian silicate) phenocrysts. This often occurs slowly over a period of time as indicated by their large size. Thus, we have a rising magma consisting of silicate melt plus suspended crystals at a relatively constant temperature and water content. The upper portions of the magma wil contain slightly more water than the lower portions. When the depth is reached such that intersection with the boiling curve is attained, a separate aqueous liquid phase will appear. As a result of the loss of this water, the liquidus temperature of the melt increases. As the melt is close to the liquidus temperature to begin with, the effect of the loss of the water and the resultant rise in melting temperature will ha to cause the melt to crystallize relatively rapidly. Therefore, according to the diagram, the less wate in the original melt, the higher it can rise in the crust. For example, assuming a depth of emplacement of about 3 kilometers, the initial water content can only be 1.5 percent. The above process will result in porphyritic rocks as the early formed crystals will be suspended in finer grained material.

There are a number of complicating factors when considering the natural system. As the melt stopes its way towards the sur-it may assimilate water from the country rock. This has 2 effects: lowers the liquidus temperature of the silicate system; raises the water content, or saturation level, of the magma. The former effect may cause resorption of the already formed phenocrysts. The latter effect may influence the level to which the melt will rise. An additional factor is that intrusion may continue for a time following boiling. This is because crystallization is not an instantaneous process.

Geological evidence suggests crystallization of a hood over the stock takes place previous to mineralization and fracturing. The timing of the various events is uncertain. For example, it is possible that the well developed fracturing is tectonically related, and the resultant pressure release causes boiling and crystallization. Or the boiling, itself, causes the fracturing. The liberation of these fluids may also lead to the formation of the breccia pipes. The fluids may eventually condense to form mineralizing solutions as the boiling can take place over a period of time. However, the breccia-forming fluids and the mineralizing solutions may not be related in origin or timing as breccia pipes are not always mineralized.

Regardless of the timing, as soon as the aqueous phase forms there will be a partitioning of material from the melt into the aqueous phase; this will be material more soluble in the aqueous phase than in the melt, including volatiles, alkalis, metals, and so forth. We have little conclusive data on the composition of the typical hydrothermal solution. The best source of data comes from the analysis of fluid inclusions in ore and gangue minerals. However, it must be understood that these are mineral depositing solutions rather than mineral transporting solutions.

The following is a summary of data from the Bingham Distri
Total dissolved solids ranged up to 60 weight percent sodium chloride equivalent. Most of the high salinity inclusions contained daughter minerals, minerals which formed after inclusion closure and cooling began. The most common daughter minerals observed were, in order of abundance, halite, sylvite, anhydrite, and hematite. Several solid phases were unidentifyable, and as many as 10 separate phases were observed in a single inclusion. Corrected temperatures of formation obtained from homogenization experiments are: for quartz from the center of the Bingham Stock, 640° to 725°C; most quartz from veins in the central zone, 460°C; and sphalerite from peripheral lead-zinc deposits, 294° to 330°C. Some inclusions show evidence that boiling of the hydrothermal solutions took place. A vapor rich in CO_2 and having a density between 0.1 and 0.3 grams per cubic centimeter coexisted with saline solutions with a density of 1.3 gm/cc. Boiling of the solutions is a low pressure phenomenon, and suggests a shallow depth or a rapid release of pressure due to fracturing. This could be an additional explanation of breccia pipe formation where the low density vapor produced the fluidization and the high density salin solution lead to subsequent alteration and mineralization.

There has been considerable discussion as to whether or not these hydrothermal solutions are subcritical or supercritical in nature, and therefore if they are able to boil at all. Figure 9.4 is the system sodium chloride-water showing the composition of liquid and vapor as a function of temperature and sodium chloride content. Liquid-vapor curves are contoured at various temperature The most important feature of this diagram is the curve showing the change in critical temperature and pressure with NaCl content.

the curve is quite steep. In most hydrothermal systems the amount of dissolved material is 10 percent or greater. At this composition the critical temperature is 550°C. Even the high temperature inclusions observed at Bingham have dissolved salt contents of 50 to 60 percent, where the critical temperature is indeterminant from this diagram. Therefore, it can be concluded that most hydrothermal systems are subcritical and do indeed have the potential to boil. The liquid-vapor curves of the diagram make it possible to determine the conditions under which various solutions will boil,in terms of temperature, pressure, and total dissolved salts (sodium chloride equivalent).

CHAPTER 24

<u>Butte District, Montana:</u>

The Butte, Montana, District is one of the largest copper producers in the world, and has produced significant amounts of other metals as well. The following summarizes production from 452,216,623 tons of ore during the period 1880 to 1972:

Copper:	18,303,977,874	pounds
Zinc:	4,909,202,540	"
Manganese:	3,762,727,341	"
Lead:	854,797,405	"
Cadmium:	4,306,156	"
Bismuth:	4,042,663	"
Selenium:	316,855	"
Tellurium:	237,256	"
Silver:	677,515,156	ounces
Gold:	2,757,710	"

The ore recovered in the past occurs primarily in veins and veinlets in Butte quartz monzonite, a phase of the larger Boulder Batholith. The mineralization is dated at 5 million years younger than the quartz monzonite, which is about 68 million years old. More recently deep mining and development has revealed a rather typical copper-molybdenum porphyry system underlying the so called main stage veins. In the shallow vein system the alteration zoning is vein controlled. The wider the vein, the wider the alteration envelope, until in areas of high vein density, all intervening rock is altered. The zoning observed from low grade to high grade is: propylitic to argillic, montmorillonite zone, to argillic, kaolinite zone, to sericitic to advanced argillic.

In the deeper zones, alteration is pervasive and centrally zoned. Potassic alteration ommon. In these deep zones there are at least 2 sets of veins which are earlier than the main stage veins and alteration. Early dark micaceous, or EDM, veins are the oldest and commonly consist of quartz, magnetite, pyrite, and chalcopyrite one to ten inches thick. These veins have dark potassium feldspar alteration envelopes extending up to 1.5 feet from the veins. The second set consists of quartz and quartz-molybdenite veins and veinlets without obvious alteration envelopes. The occurrence of these veins suggest they are part of the main stage fracture system filled earlier by quartz-molybdenite, and later by main stage mineralization.

About 1 mile east of the Berkeley pit there is a major north south fault, the Continental fault, which appears to have normal displacement of about 5000 feet, west side down. Movement along this fault has raised deep mineralization, the molybdenum mineralization, and exposed it on the east block of the fault. The early dark micaceous alteration, found only at depth west of the fault, is exposed on the surface east of the fault. This is the present location of a low grade copper-molybdenum deposit which is being developed and will be mined by open pit. The mineralization is similar to what is found in the deep levels of the Berkeley pit, and in the deeper levels of the underground mines. Mineralization has been known in this area for a long time as copper has been mined as oxidized ore from small open pits early in the history of the district.

reverse. Stratigraphic [illegible] tions on these faults are on the order of seve[illegible] ousand feet.

The total Paleozoic section is 4,400 feet thick (10). It is composed predominantly of limestone with a basal quartzite member. The Cretaceous section appears to be more than 5,000 feet thick, but this figure is not a result of careful measurement. Conglomerate, red shale, and arkosic sandstone characterize the lithology. Volcanic and sedimentary rocks of early Tertiary(?) age aggregate more than 2,000 feet in thickness. Three units are recognized by the writers (14): (a) the Claflin Ranch (earliest)—conglomerate and coarse sandstone made up largely of igneous fragments and containing a few pyroclastic interbeds; (b) the Silver Bell—andesite porphyry breccia, principally of mudflow origin; and (c) the Cat Mountain[1]—pyroclastics, composed mainly of ashflows (oral communication, Watson, 1962).

Intrusion of alaskite marked the beginning of Laramide igneous activity. It was emplaced as an elongate stock with its northeast side closely conforming to the major structural line for a distance of nearly 4 miles. The alaskite was at one time regarded as a thrust block of Precambrian rock (6); however, clear evidence of its intrusive relation with Paleozoic limestone and Cretaceous(?) arkose has since been found.

The intrusive activity was at this stage interrupted by an interval of erosion, resulting in partial exposure of the alaskite stock, followed by deposition of the Claflin Ranch, Silver Bell, and Cat Mountain units. (These three units are grouped as Tertiary(?) volcanic and sedimentary rocks on figure 2 herein, and were termed "dacite agglomerate" on figure 2 (12) by Richard and Courtright.) A similar sequence has been recognized by the writers elsewhere in the Southwest (14).

The next event was the intrusion of a large stock or ll of dacite porphyry about 3 miles in width and at east 6 miles in length in a northwesterly direction. Its ain mass is outside and along the northeast edge of he mineralized zone. Although its southwesterly side onsists of irregular stocks, sills, and dikes extending nto the mineralized zone, these apophyses of the acite porphyry are limited in this direction by the ajor structural line. A number of large pendants of olded and faulted Paleozoic sedimentary rocks occur n the southwest edge of the dacite porphyry. Thus, it s inferred that the original major fault between the aleozoic and Cretaceous(?) sedimentary rocks beame a contact between alaskite and Paleozoic sedientary rocks and then a contact between dacite orphyry and alaskite.

Andesite porphyry may have been introduced later an the dacite porphyry, but relations are not clear; it ay be simply a facies of the latter.

Subsequent parallel faulting along the major structural line sliced the volcanic and Cretaceous(?) rocks into horst and graben structures. These faults are remarkably persistent southeasterly, extending several miles beyond the map. They probably extended through the northwest part of the district, but there is little direct evidence. The formation of these faults indicates at that time a still existent deep-seated zone of weakness along the major structural line.

Monzonite stocks and contemporaneous dikes were then emplaced along and near this line, obliterating parts of the faults described in the foregoing paragraph. The stocks are elongate parallel to the major structural line; but the dikes trend across it, for the most part, with an average east-northeast strike. The dikes are elements of an extensive swarm having a general northeasterly trend and occurring throughout the Silver Bell Mountains.

Systems of close-spaced *parallel* fractures then developed. These systems are distributed along the major structural line and generally strike across it.

Alteration and sulfide mineralization took place next. The deposition of sulfides, particularly chalcopyrite, was controlled in detail by the cross-trending fractures. Although these are distributed along the major structural line as a narrow band, it is notable that throughout much of its length there are now no fault structures to account for the trend of this zone.

Post-sulfide dikes of andesite and rhyolite represent the last intrusive activity in the immediate district. Curiously, most of these andesite dikes are parallel to the major structure, although it would seem that the cross-breaking fractures represented available lines of weakness. This serves to emphasize the major structural line as being a profound deep-seated zone of weakness persisting through a long period of time.

Uplift and erosion of the region exposed the lean primary mineralization to processes of leaching and enrichment, resulting in the accumulation in the district of a thin blanket of chalcocite. Two open-pit ore bodies occur in this blanket.

Remnants of flows of andesite and basalt occur in the flats surrounding the Silver Bell range. In at least one locality to the east these flows are nearly flat and overlie conglomerate, which dips about 25° and contains boulders and fragments eroded from *completely* leached capping of the mineralized zone. Damon et al. (3) have determined an age of 27.9 m.y. for these flows. This is particularly interesting because it indicates that, prior to that date, there existed an environment permitting formation of leached capping and, presumably, a chalcocite zone.

STRUCTURAL CONTROL OF HYPOGENE MINERALIZATION

As in the majority of porphyry copper deposits, the principal primary sulfide minerals at Silver Bell are pyrite and chalcopyrite. Although occurring as discrete grains, they are more abundant—accompanied by quartz—in systems of veinlets or seams that are usually near vertical in attitude and persistently parallel. Varying in thickness from paper thin to several inches and in spacing from inches to several feet, these thin sulfide sheets occur as groups of various sizes in the narrow northwest-trending zone of hydrothermal alteration. (Due to the small scale, any single line in the pattern of "Mineralized Fissures" on figure 1 diagrammatically represents a large number of parallel veinlets, rather than an individual.) In detail the average individual fissure appears as a thin quartz-sulfide seam coated by a rather uniform band of sericite. The fissures are predominantly oriented in the northeast quadrant; a small proportion strike northwest and a few are random. From a broad viewpoint there are, among these systems or groups, no intersections of consequence. Within a group, changes in strike occur gradually and result in curving trends. As noted earlier, these groups of mineralized fissures are distributed along the major structural line, and it is assumed that they were formed in response to deep-seated uniform stress related to that line.

At least a few hundredths of 1 percent copper is present nearly everywhere in the zone of disseminated sulfides, better values occur where there are veinlets; and the best values occur where the veinlets are close spaced. The two comparatively large groups of these close-spaced structures coincide with the positions of the two ore bodies (fig. 1). However, the actual structural, mineralogical, and lithological distinctions among these and other smaller groups are minor, and the factors that controlled the position and size of these two groups are not clearly evident. A strong east-west fault that terminates in the Oxide area may have influenced the concentration of fracturing there, and at El Tiro the sharp bend in the alteration zone and the group of northeast-striking dikes likewise may indicate a cross-trending line of weakness that localized stresses. Nonetheless, the importance of these structural conditions is not clearly demonstrated, and no good evidence is found to explain the structural cause of the more intense fracturing which localized the two ore bodies in their present positions in preference to other locations along the major structural line.

Outside the zone of alteration the dacite porphyry is finely fractured and jointed in most of its large exposed area. In sharp contrast to the systems of parallel fissures in the alteration zone, these fractures in the dacite porphyry are almost completely of random orientation; parallelisms are rare and traceable for only a few inches or feet. They are premineral in age where they are found in the alteration zone in the westerly and southwesterly parts of the dacite porphyry. It would seem that in physical aspect this formation was exceptionally well prepared to be mineralized—perhaps better than the rocks of the ore-zone proper. The fact th[illegible] was mineralized onl locally may be accounted [illegible] a part, by the absenc of *systematic* fractures. That is, only the systems o parallel fractures were connected with the deep-seate source of mineralization, and the pervasive breaking o the dacite porphyry did not alone qualify it for mineralization.

Excepting the post-mineral andesite dikes, all igneous rocks in the narrow northwest-trending zon shown on figure 1 are hydrothermally altered. Variations in the intensity or in the completeness of th process have been subdivided by Kerr (6) into fiv stages. His analysis demonstrated, among other things that the known ore bodies are in the more strongl altered areas. The area outlined by the writers o figure 1 includes all degrees of alteration, but n differentiation is made. It merely represents the area extent of bleached-appearing igneous rocks showin evidence in the leached outcrops of pre-existing disseminated sulfides—principally pyrite. The transition to relatively fresh rock is quite sharp in many places particularly along the contact with sedimentary rock and on the faults in the southeast part. However, along most of the southwest margin the transition is gradational, and the limit is an arbitrary line.

Tactite—composed essentially of garnet, diopside other lime-silicate minerals, and quartz—is confined t a narrow belt along the southwest margin of th limestone pendants, except near the Mammoth an Union mines where it has replaced the full width o the sedimentary block. There, parts of the tactit contain sufficient disseminated chalcopyrite to b classed as low-grade ore. As in the Mission deposi (13), this mineralized tactite is regarded by the writers as having been formed by the same processes tha altered and mineralized the intrusive rocks. Thus, it i a product of hydrothermal metasomatism rather tha contact metamorphism caused by the dacite porphyr and the monzonite as proposed by Stewart (15).

SUPERGENE ENRICHMENT

The two ore deposits consist of rudely tabular accumulations of chalcocite from 100 to 200 feet thick. Lying beneath about 100 feet of leached capping, they were formed by twofold to threefold enrichment of the copper contained in the primary mineralization. Typical ore is composed of altered rock and sulfides in a ratio of about 10:1 by weight.

Most of the capping over the ore bodies contains less than one-tenth of 1 percent copper as cuprite or other oxidation products mingled with the limonite. Occasionally, somewhat higher values occur where copper has been precipitated as silicates and carbonates by reactive gangue material present in less altered rock. In the ore bodies where alteration is strong and the gangue is nonreactive, the upper limit of the sulfide zone (or the base of oxidation) appears on open-pit

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[1] K-Ar ages of 58 to 70 m.y. have been obtained for various t Mountain Rhyolite occurrences by Damon et al. (3). Acrding to Holmes (5), Tertiary time beginning is 70±2 m.y.

ouch faces as a sh [illegible] defined highly irregular nterface. Only rarely [illegible] a transition zone of olved sulfide and oxide copper minerals. Some of the rregularities of the base of oxidation are caused by lisplacement on post chalcocite faults, but most seem o be due to variations in rock permeability. This is videnced by the dense siliceous character of a few ulfide remnants occurring well up in the leached zone nd by leached indentations of the sulfide zone along nany of the fissures.

The present water table at Silver Bell is well below he chalcocite zone, a condition that exists in many of he porphyry copper districts (4). This indicates that he *Silver Bell* chalcocite zone now is in an environment of oxidation, and it should be undergoing leach- ng rather than enrichment. This current climatic cycle nay have been relatively short and dry and may have aused only minor modifications of the chalcocite lanket.

The base of oxidation conforms in general shape to odern topography, although local relief is more than 00 feet. This rude conformance would seem to re- uire a relatively wet climate with the water table eing no more than a few tens of feet below the round surface as the modern physiography devel- ped.

In the early days at Morenci, Lindgren (7) observed hat oxidation and leaching had, in some instances, enetrated along fissures down through the chalcocite nto underlying primary sulfides; he also observed that rosion of Chase Creek Canyon had left the principal halcocite zones stranded high above the canyon bot- om, indicating that the chalcocite formed originally bout an ancient water table several hundred feet bove the present water table. Although erosion at ilver Bell has not penetrated as deeply as at Morenci, s chalcocite zone currently is in a similar unbalanced nvironment of oxidation with no appreciable enrich- nent now taking place. Reshaping of the upper sur- ace of chalcocite zones in both districts to conform to e existing ground surface appears, then, to have ccurred during formation of the modern topography hat at some time prior to the current dry climatic ycle.

LEACHED OUTCROPS

In the formation of many disseminated chalcocite eposits the enrichment process is presumed to have aken place progressively—copper having been re- eatedly dissolved, carried downward, and precipitated. It has been well established by Blanchard (1 Locke (8), and others that under these conditions "limonites" of certain colors and textures are left behind in the leached capping as evidence of the preexisting chalcocite. The Silver Bell district provides exceptionally good examples of this phenomenon, but limonites of chalcocite derivation are not confined to the outcrops over the ore bodies. They are widely dispersed through the zone of alteration. Proper interpretation of their significance in respect to ore possibilities has rested mainly on quantitative rather than qualitative appraisal. Mapping of the Silver Bell outcrops on this basis has provided a valuable guide in exploration drilling for the last 15 years. Results have demonstrated that the pattern of relatively strong chalcocite at depth is reflected in the outcrops by the distribution and abundance of diagnostic limonites.

It may be of interest at this point to mention the ancient excavations that are numerous in the outcrops of the mineralized zone at Silver Bell. There is evidence indicating that they are several centuries old. Since there are no precious metals or visible copper in these cuts, it is plausible to assume that the limonite and clay minerals were considered valuable, perhaps for pottery or warpaint. Thus, in the history of leached-outcrop investigations, it seems that some early Arizona Indian tribe deserves at least honorable mention.

Previous work and acknowledgments.—The first scientific study of the district was published in 1912 by Stewart (15). Considerable field and laboratory work has been done in more recent years by several groups and individuals, including the writers, all reporting privately to the American Smelting and Refining Co. Roland Blanchard conducted leached-outcrop studies in part of the area. Harrison Schmitt, H. M. Kingsbury, and L. P. Entwistle mapped structure and mineralization in the central part of the district. P. F. Kerr studied the alteration features and later published a comprehensive paper (6) on the district. Thomas Mitcham mapped structural features in the surrounding area. The writers have drawn considerably on these and other unpublished data, particularly in compilation of the geologic map. The high quality and usefulness of this material is gratefully acknowledged, but unfortunately it is not feasible to give special individual credits. Thanks are due the American Smelting and Refining Co. for permission to publish this paper.

LITERATURE CITED

1. Blanchard, Roland, 1939, Interpretation of leached outcrops: Jour. Chem., Met. and Min. Soc. of S. Africa, May.
2. Butler, B. S., and Wilson, E. D., 1938, Clifton-Morenci district, Arizona Bur. Mines Bull. 145, p. 74.
3. Damon, et al., 1963, Correlation and chronology of ore deposits and volcanic rocks: Univ. Arizona, Ann. Progress Report no. 5.
4. Emmons, W. H., 1917, The enrichment of ore deposits: U.S. Geol. Survey Bull. 625.
5. Holmes, Arthur, 1960, A revised geologic timescale: Edinburgh Geol. Soc. Trans., v. 17, p. 153–216.

Kerr, P. F., 1961, Alteration features at Silver Bell, Arizona: Geol. Soc. America Bull., v. 62, p. 457–480.

7. Lindgren, Waldemar, 1905, The copper deposits of the Clifton-Morenci district: U.S. Geol. Survey Prof. Paper 43, p. 203.
8. Locke, Augustus, 1926, Leached outcrops as guides to copper ore: Baltimore, Williams and Wilkins.
9. Mauger, R. L., Damon, P. E., Giletti, B. J., 1963, Age of ore deposition within the southwestern copper metallogenetic province in Arizona: Am. Inst. Mining Metall. Petroleum Engineers, Dallas, Texas, February.
10. McClymonds, N. E., 1959, Paleozoic stratigraphy of the Waterman Mountains, Pima County, Arizona: Arizona Geol. Soc., Southern Arizona Guidebook II.
11. Mitcham, T. W., 1951, Discussion of paper, Structure and mineralization at Silver Bell, Arizona: Am. In Mining Metall. Petroleum Engineers, v. 202, p. 30
12. Richard, Kenyon, and Courtright, J. H., 1951, Struc ture and mineralization at Silver Bell, Arizona: Minin Eng., November, and Am. Inst. Mining Metal Petroleum Engineers Trans., v. 190, p. 1095–1099.
13. ——— 1959, Some geologic features of the Missio deposit: Arizona Geol. Soc., Southern Arizona Guide book II.
14. ——— 1960, Some Cretaceous-Tertiary relationship in southern Arizona and New Mexico: Arizona Geol Soc. Digest, v. III.
15. Stewart, C. A., 1912, The geology and ore deposit of the Silver Bell mining district, Arizona: Am. Inst Mining Metall. Petroleum Engineers Bull., v. 6 p. 455–508.

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 original 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 spectacula surface with hues from hematitic goethitic and jarositic limon 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 Sier is characterized more by goethitic or goethitic-jarositic oxidation products, strongly localized in and near the veins fro which they have been derived. Much of the North Silver Bell capping reflects low hypogene inheritance, although better zon of hematitic limonites will be pointed out.

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.

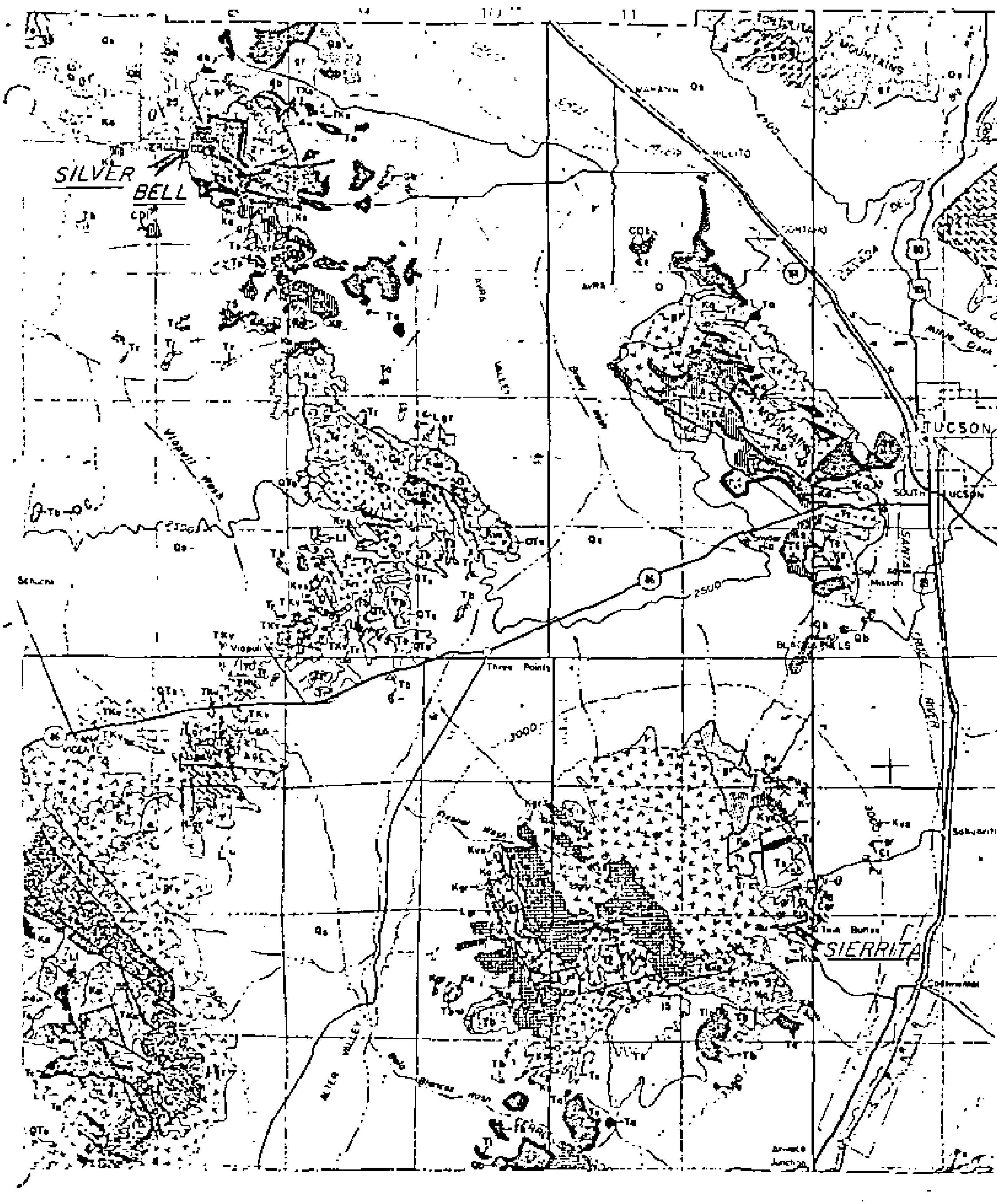
The oldest basement rocks known in this southeastern part of Arizona are those of the Pinal Schist which is about 1700 my old. These rocks, together with intrusions of about 1420 my old compose the basement platform for rocks of younger Precambrian and Phanerozoic age and comprise the basement traversed 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

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 Anole affinity (Tucson Mountains) or Angelica Arkose (Sierrita Mountains)
Kvs	Cretaceous volcanics and sedimentary rocks	mostly mapped in the Roskruge Mountains and includes Mesozoic volcanic 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
CDf	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 MOUNTAINS
TORTOLITA MOUNTAINS
TUCSON
SOUTH TUCSON
SANTA CRUZ RIVER
BLACK HILLS
Three Points
SIERRITA
Twin Buttes
Sahuarita
Continental
Arivaca Junction
AVRA VALLEY
ALTAR VALLEY
Brawley Wash
Viopuli Wash
San Xavier Mission
2500
3000
86
Qs
Tb
Tr
Ka
Kv
QTs
TKv
Qb

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.

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

(Abstract)

by
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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 NW 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 evolution 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-meteoric 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 PCD 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.

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

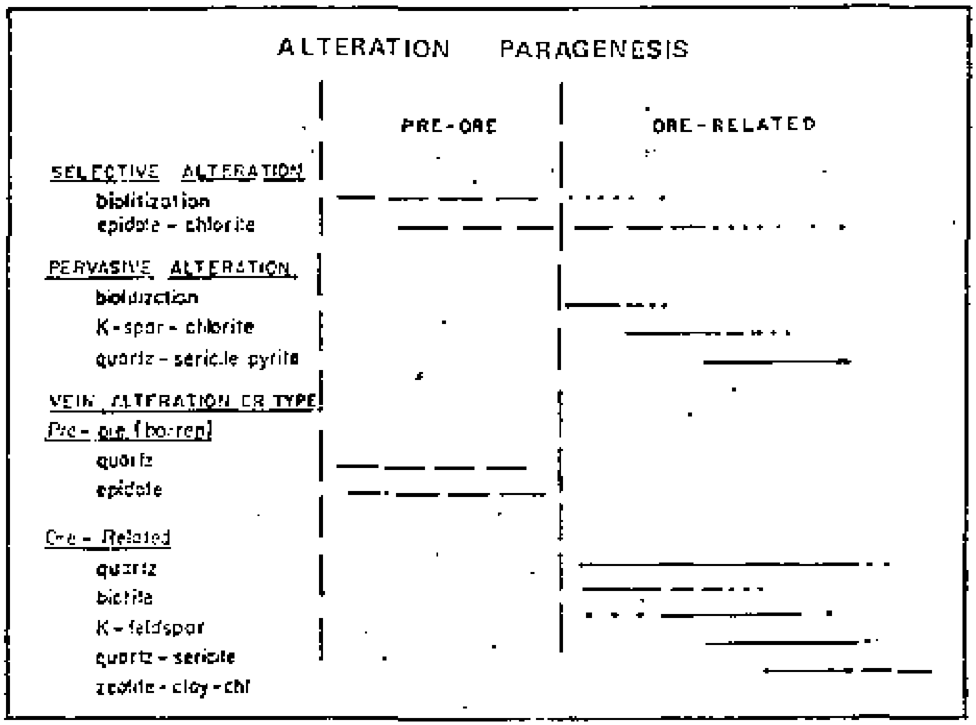
three typic[illegible] abits. These habits, described further, consist of selectively pervasive alteration, pervasive alteration, and vein-veinlet alteration.

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 relationships, is from t[illegible]te-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.



Tim ce 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", governed 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.

Alteration strongly fractue-controlled - plumbing
Domain alteration.

Pervasive alteration may be controlled by fractures where no zoning around fractures exist, and all intervening rock has been altered.

Alteration may locally be controlled by the chemistry of the wall rock.
Quartz-sericite-pyrite vein in felsic rock becomes Potassic vein in biotite-rich wallrocks.

STRUCTURE AND MINERALIZATION AT SILVER BELL, ARIZONA

BY KENYON RICHARD AND JAMES H. COURTRIGHT

INTRODUCTION

This material was originally published (12) in November 1954. Exploration and mining during subsequent years have provided additional information; accordingly, a number of revisions of text and figures are included herein. Basic concepts, however, remain essentially the same as originally presented.

Watson (oral communication, 1962) has prepared a doctoral dissertation based on detailed mapping in the Silver Bell Mountains. Mauger et al. (9) are making potassium-argon age determinations of most of the igneous rocks in the district. These two lines of research should, among other things, materially improve upon the knowledge of certain age relations that are noted only briefly herein.

Silver Bell is 35 airline miles northwest of Tucson, Arizona, in a small rugged range rising above the extensive alluvial plains of this desert region. Its geographical relation to other porphyry copper deposits of the Southwest is shown on the inset map in the lower left corner of figure 1. The climate is semiarid. Altitudes range from 2,000 to 4,000 feet.

Opening of the Boot mine, later known as the Mammoth, in 1865, was the first event of note in the district's history. Oxidized copper ores containing minor silver lead values were mined from replacement deposits in garnetized limestone and treated in local smelters. Copper production had approached 45 million pounds by 1909 when the disseminated copper possibilities in igneous rocks were recognized. Extensive churn-drill exploration was carried out during the next 3 years and resulted in the partial delineation of two copper sulfide deposits—the Oxide and El Tiro. Although the then submarginal tenor discouraged exploitation of these disseminated deposits, selective mining of ore bodies in the sedimentary rocks continued intermittently until 1930, providing a production total of about 100 million pounds of copper.

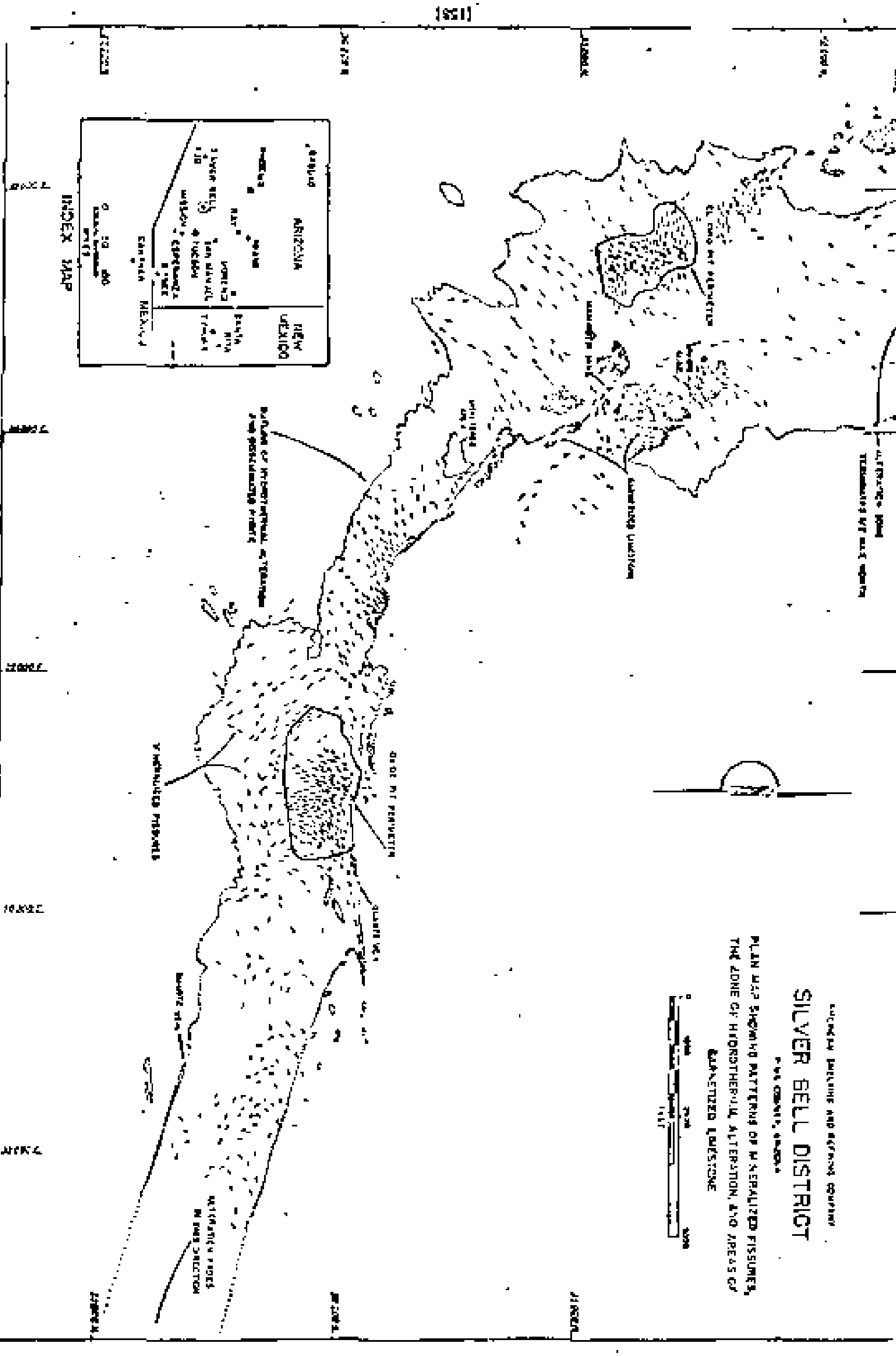
The American Smelting and Refining Co. began exploratory and check drilling in 1948 and subsequently made plans for mining and milling the Oxide and El Tiro ore bodies at the rate of 7,500 tons per day. Production began in 1954 and has been maintained at a rate of about 18,000 tons of copper annually.

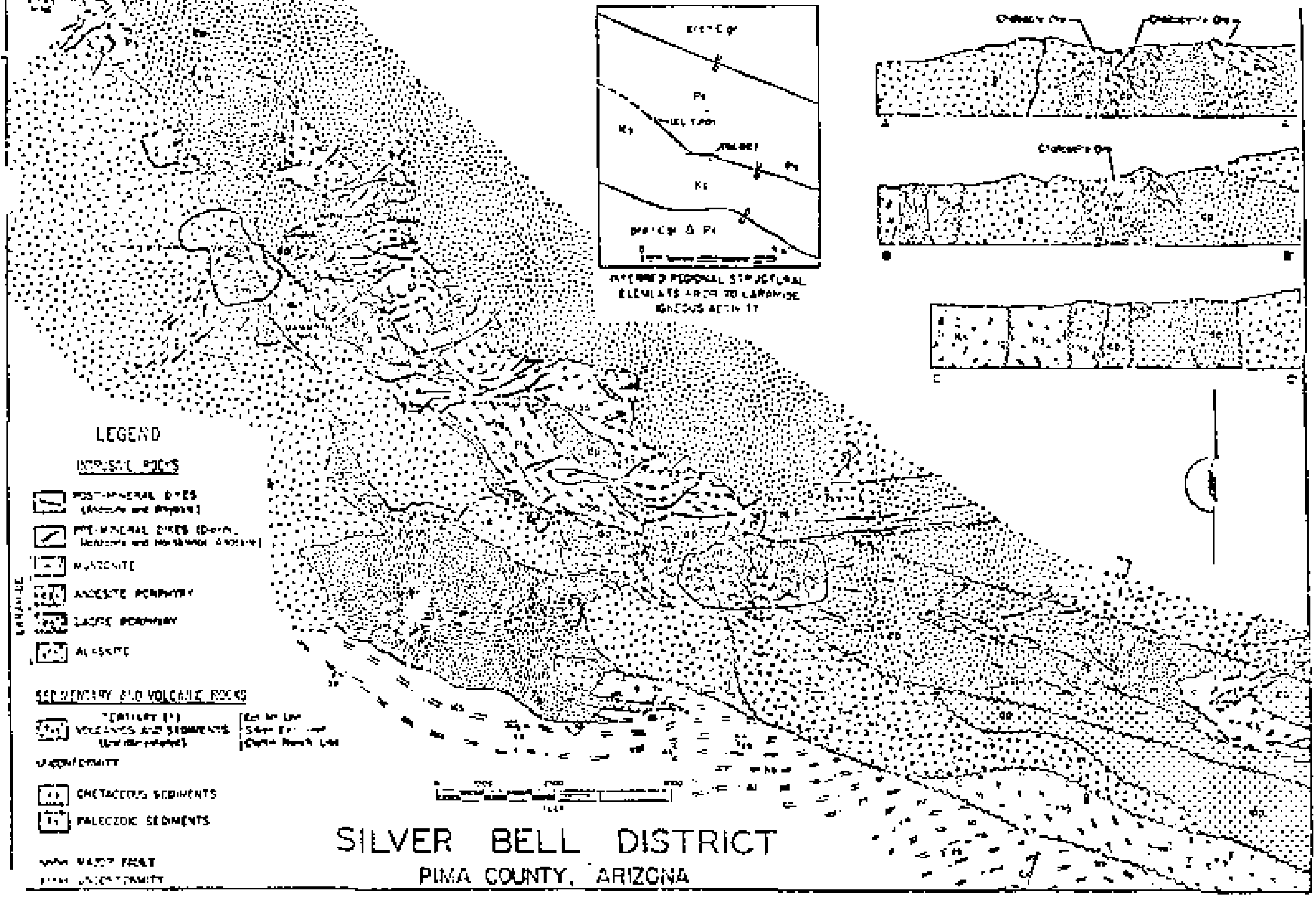
GENERAL GEOLOGY

Formations ranging in age from Precambrian to Recent are exposed near Silver Bell. The more erosion-resistant of these—Paleozoic limestone and Tertiary(?) volcanics—predominate in the scattered peaks and ridges comprising the Silver Bell Mountains. Porphyry copper mineralization occurs along the southwest flank of these mountains in hydrothermally altered igneous rocks. These are principally intrusives which cut Tertiary(?), Cretaceous, and older sediments and are considered to be components of the Laramide Revolution.

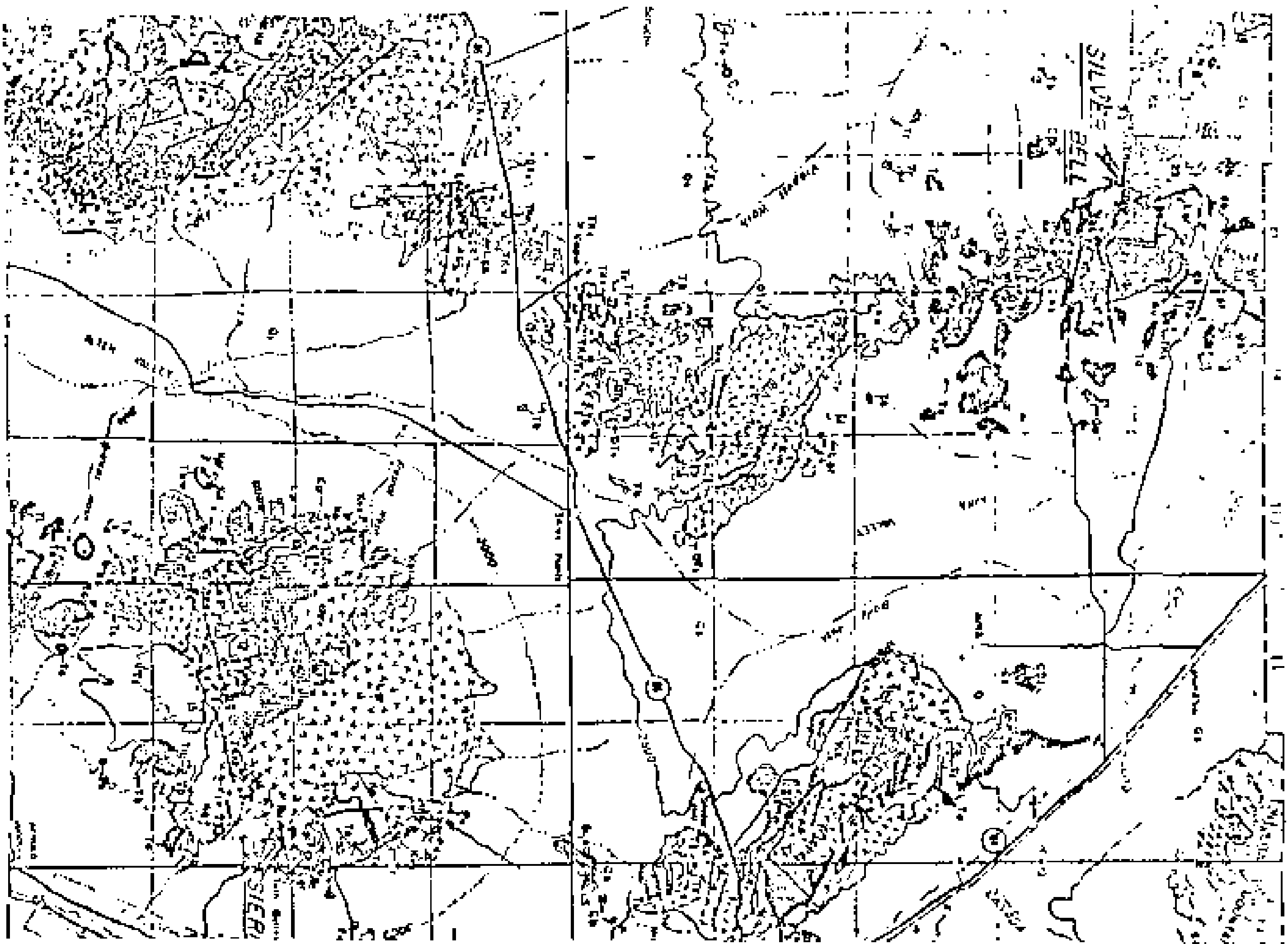
For three-fourths of its length, the zone of alteration strikes west-northwest (fig. 1). There now is no single structure that accounts for this alignment. However, indirect evidence suggests that a fault representing a line of profound structural weakness existed in this position prior to the advent of Laramide intrusive activity. This line will hereafter be referred to as the "major structure." It was largely obliterated by the Laramide intrusive bodies, but it effected a degree of control on their emplacement, as evidenced by their shapes and positions. The influence of fault structures on the shapes of intrusives in other porphyry copper districts has been noted by Butler and Wilson (2).

As shown on the inset map on figure 2, a fault of parallel trend and considerable displacement lies to the north. This fault is now marked by a line of small intrusive bodies. To the south is a third fault of large displacement. Evidence of its age in relation to the Laramide intrusions and mineralization is not recognized, but its conformance in strike with the other two major faults is significant. These three breaks establish a pronounced trend of regional faulting, and it has been suggested (11) that they be named, from south to north, the Waterman thrust, the Silver Bell fault zone, and the Ragged Mountains fault. The two northerly ones are high angle, and the southerly one may be





SILVER BELL DISTRICT
PIMA COUNTY, ARIZONA



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

Presented to the
Society of Economic Geologists
Silver Bell Field Conference

April 1979

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 21,400 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 I 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.

BIBLIOGRAPHY

Agenbroad, Larry D., 1962, The geology of the Atlas Mine area, Pima County, Ariz.: unpublished M.S. Thesis, Univ. of Ariz., Tucson.

Banks, Norman G., and Docktor, Roger D., 1976, Reconnaissance geologic map of the Vaca Hills quadrangle, Arizona: U.S. Geol. Survey Map MF-793.

Banks, N.G., Docktor, R.D., Silberman, M.L., and Naeser, C.W., 1978, Radiometric ages of some Cretaceous and Tertiary volcanics and intrusive rocks in south-central Arizona: Jour. Research U.S. Geol. Survey, v. 6, p. 439-445.

Buseck, Peter R., 1962, Contact metasomatic deposits at Concepcion del Oro, Mexico; Tem Piute, Nevada; and Silver Bell, Arizona: unpublished Ph.D. dissertation, Columbia University, New York.

Clarke, Craig W., 1966, The geology of the El Tiro Hills, West Silver Bell Mountains, Pima County, Arizona: unpublished M.S. Thesis, Univ. of Ariz., Tucson.

Docktor, R.D., 1976, Mount Lord Volcanics, Pima County, Arizona, in Contributions to Stratigraphy, U.S. Geol. Survey Bull. 1435.

Kerr, P.F., 1951, Alteration features at Silver Bell, Arizona: Geol. Soc. Amer. Bull., v. 62, p. 457-480.

Mauger, R.L., 1966, A petrographic and geochemical study of Silver Bell and Pima mining districts, Pima County, Ariz.: unpublished Ph.D. dissertation, Univ. of Ariz., Tucson.

Mauger, R.L., Damon, P.E., and Giletti, B.J., 1965, Isotopic dating of Arizona ore deposits: Am. Inst. Mining, Metall. and Pet. Eng. Trans., v. 232, p. 81-87.

McClymonds, Neal E., 1957, The stratigraphy and structure of the Waterman Mountains, Pima County, Arizona: M.S. Thesis, Univ. of Ariz., Tucson.

_____, 1959, Paleozoic stratigraphy of the Waterman Mountains, Pima County, Ariz.: in Southern Arizona Guidebook II, L.A. Heindl (ed.): Tucson, Ariz., Arizona Geological Society.

garnet destruction
late assemblage
remob. ccpy
Pyrite + serpentine hematite, quartz,
calcite,
Equiv. to phyllic alteration

Arizona Geological Society Digest, Volume XI, October 1978

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

by

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Abstract

The Esperanza property, which had been worked sporadically since 1895, was purchased by Duval Corporation in 1955. Following completion of an exploratory 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 1960 and the start of mill operations in March 1970, the Sierrita mine become 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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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 Esperanza 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 0.0[illegible]% Mo since the start of operations. Ore reserves [illegible] Esperanza are now about 36 million tons with grades of 0.28% Cu and 0.027% Mo (Pennzoil Company, 1976). Current daily production is 18,000 tons ore and 18,000 tons waste.

In 1963 Duval acquired additional properties which comprised approximately 65 percent of the then undeveloped Sierrita orebody. Exploration and development drilling have established total ore reserves of 5[illegible] million tons with a grade of 0.32% Cu and 0.033% molybdenum (Pennzoil Company, 1976). Pre-mine stripping began in 1968 with initial production in 1970. Ore mined during the early years at Sierrita has averaged 0.25% Cu and 0.0[illegible]% Mo. Present daily production is about 50,000 tons ore and 125,000 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, diorite 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 Vol[illegible]. This dark-gray rock was subdivided by Lynch (1967) into vitric tuff, fragmented tuff, and siliceous-aphanitic tuff based on subtle 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 [illegible] has been restricted to highly fra[illegible] 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 3000 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 (Gilbert, 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 57.5 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. 220 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.

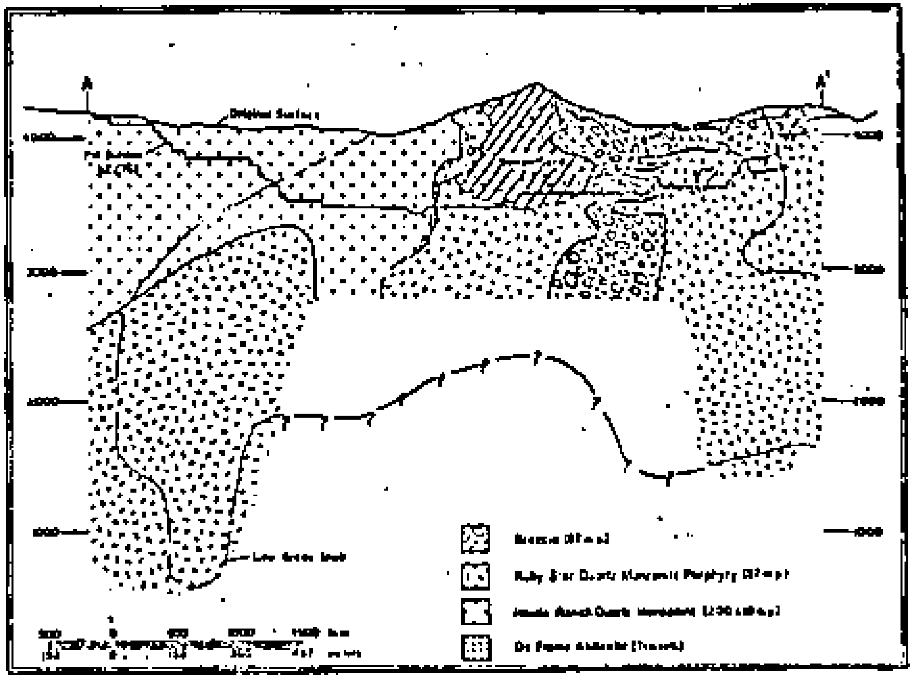

Fig. 2. Section A-A', showing Sierrita geology

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.

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 subhedral quartz "eyes" which are preserved even in intensely weathered rock. The intrusion is ini-

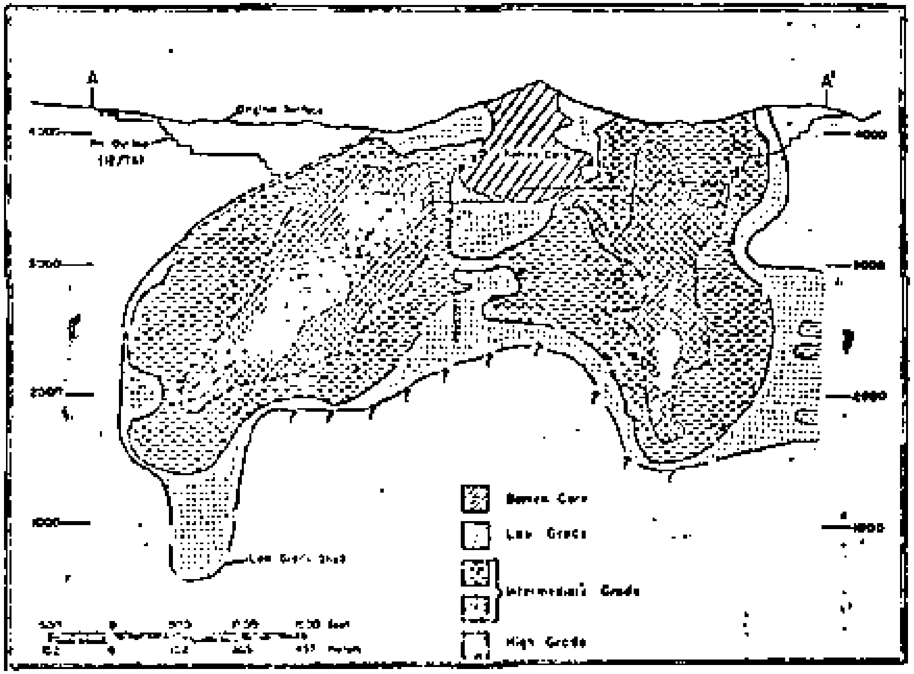

Fig. 3. Section A-A', showing distribution of economic mineralization at Sierrita

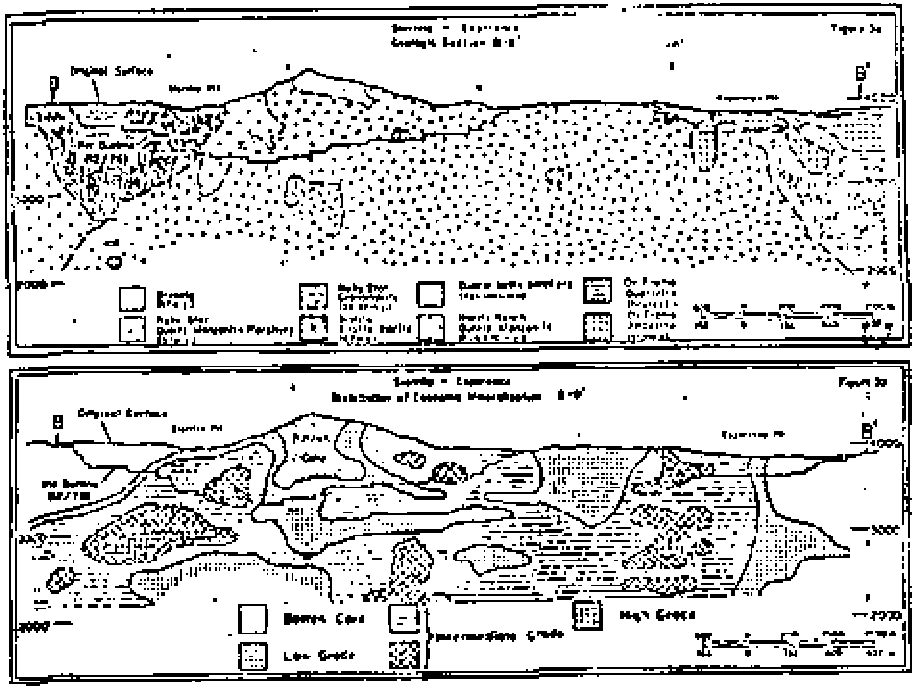

Fig. 4. Section B-B': (a) Geology of the Sierrita-Esperanza deposit; (b) distribution of economic mineralization

mainly 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 [illegible] 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. 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. 3) and fingers out in Ox Frame andesite, biotite quartz diorite, and other units that crop out on the premine 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.

Mound 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-

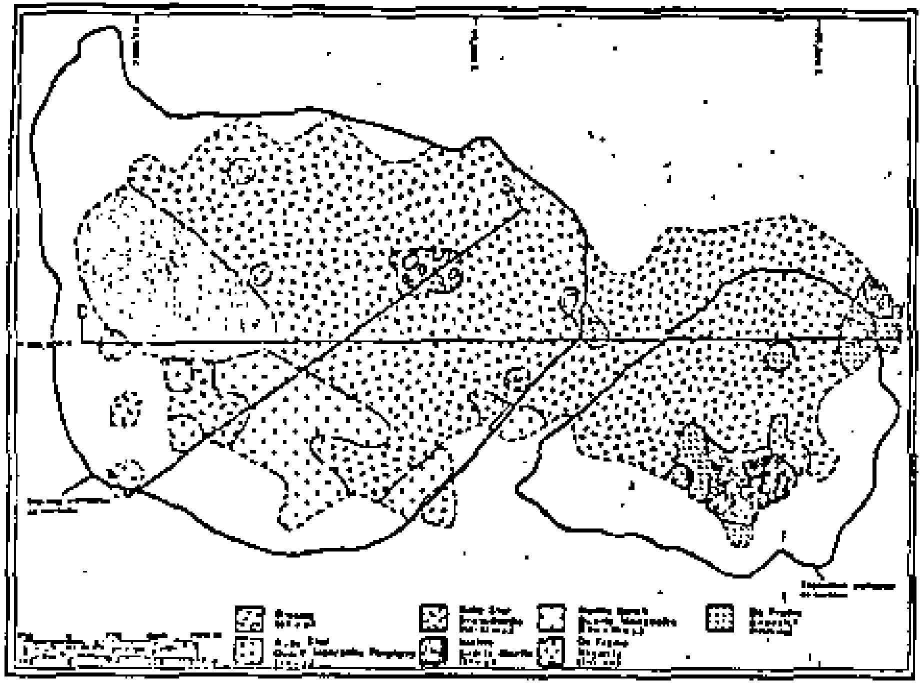

Fig. 5. 3200 bench, showing Sierrita-Esperanza deposit geology

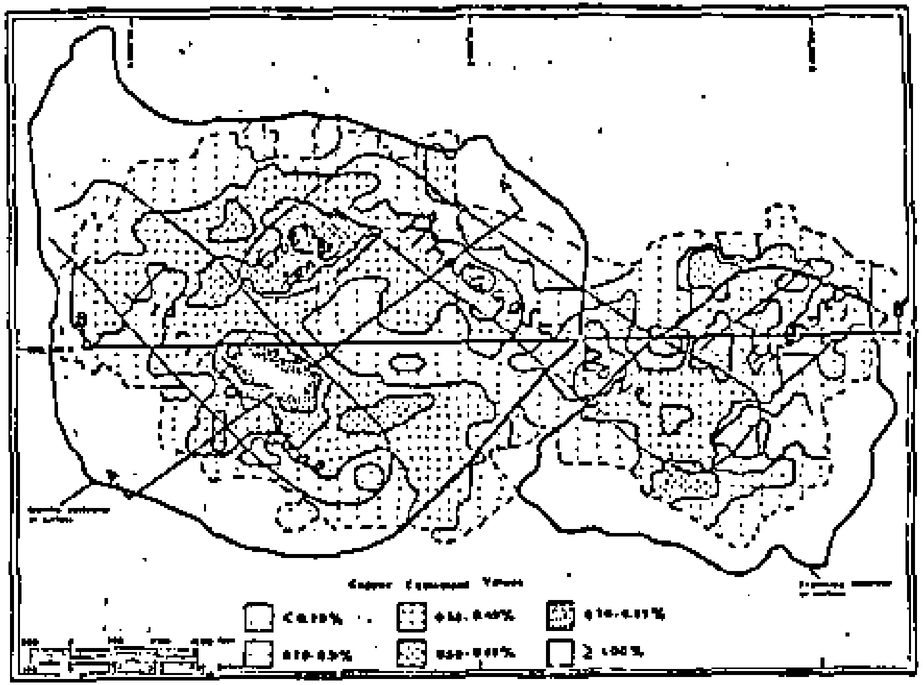

Fig. 6. 3200 bench, showing distribution of mineralization at Sierrita-Esperanza

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 10 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 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 Ox 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. 4).

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 [illegible] feet long and 600 feet wide. This "barren" area has a copper equivalent of less than 0.3 percent. Below the 3500 level, mineralization 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

Acknowledgment is due the following individuals for their advice, constructive criticism, and assistance in the preparation of this paper: Dr. John I. Sharpe, General Manager—Exploration, Duval Corporation; Mr. Robert A. Metz, District Geologist, Duval Corporation; Mr. Kenneth L. Lamb, Manager—Mining, Duval-Sierrita Corporation; Mr. Calvert D. Iles, Mine Engineer, Duval-Sierrita Corporation; Mr. Jerry C. Morgan, Geologic Draftsman, Duval-Sierrita Corporation.

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.

References

Anderson, C. A., and Kupfer, D. H., 1944, Report of the properties of the Amargosa Molybdenum and Copper Corporation, Pima County, Arizona: U.S. Geol. Survey Strategic Minerals Inventory.

Cooper, J. R., 1971, Mesozoic stratigraphy of the Sierrita Mountains, Pima County, Arizona: U.S. Geol. Survey Prof. Paper 658-D.

______1973, Geologic map of the Twin Buttes quadrangle, southwest of Tucson, Pima County, Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I-745.

Creasey, S. C., and Kistler, R. W., 1962, Age of some copper-bearing porphyries and igneous rocks in southeastern Arizona: U.S. Geol. Survey Prof. Paper 450-D, p. D1-D5.

Damon, P. E., and associates, 1965, Correlation and chronology of ore deposits and volcanic rocks, U.S. Atomic Energy Comm. Ann. Rept. No. COO-689-50: Tucson, University of Arizona.

______1966, Correlation and chronology of ore deposits and volcanic rocks. U.S. Atomic Energy Comm. Ann. Rept. No. COO-689-60: Tucson, University of Arizona.

Damon, P. E., and Mauger, R. L., 1966, Epeirogeny-orogeny viewed from the Basin and Range province: Soc. Mining Engineers Trans., v. 235, no. 1, p. 99-112.

Guilbert, J. M., 1977, Personal communication: Dept. of Geosciences, University of Arizona.

Iles, C. D., 1973, Mineralization control at the Duval-Sierrita property, Pima County, Arizona: unpublished report, Duval-Sierrita Corporation, Sahuarita, Arizona.

Lovering, T. G., Cooper, J. R., Drewes, Harald, and Cone, G. C., 1970, Copper in biotite from igneous rocks in southern Arizona as an ore indicator: U.S. Geol. Survey Prof. Paper 700-B, p. B1-B8.

Lowell, D. J., and Guilbert, J. M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Econ. Geology, v. 65, no. 4, p. 373-408.

Lynch, D. W., 1967, The geology of the Esperanza mine and vicinity, Pima County, Arizona: unpublished M.S. thesis, Dept. of Geology, University of Arizona, Tucson.

Oakley, C. A., 1973, A synopsis of alteration and mineralization at the Sierrita and Esperanza mines; unpublished report, Duval-Sierrita Corporation, Sahuarita, Arizona.

Pennzoil Company, 1974, Annual report: Houston, Texas.

Rehrig, W. A., and Heidrick, T. L., 1972, Regional fracturing in Laramide stocks of Arizona and its relationship to porphyry copper mineralization: Econ. Geology, v. 67, p. 198-213.

Schmitt, H. A., Clippinger, D. M., Roper, W. J., and Toombs, H. B., 1959, Disseminated deposits at the Esperanza mine, in Heindl, L. A. (ed.), Southern Arizona Guidebook II: Tucson, Arizona Geological Society, p. 205-206.

Smith, V. L., 1975, Hypogene alteration at the Esperanza mine, Pima County, Arizona: unpublished M.S. thesis, Dept. of Geology, University of Arizona, Tucson.

Titley, S. R., 1975, Geologic characteristics and environment of some porphyry copper occurrences in the southwestern Pacific: Econ. Geology, v. 70, p. 499-514.

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CLASIFICACION ACTUALIZADA DE YACIMIENTOS MINERALES

METALLIC-MINERAL RESOURCES OF COLORADO

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ABRIL, 1981

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METALLIC MINERAL RESOURCES OF COLORADO

S. B. ROMBERGER[1]

ABSTRACT

Most of the known metalliferous deposits of Colorado occur in a narrow northeast-trending belt extending from near Durango in the southwest to Jamestown in the northeast. This zone is called the Colorado Mineral Belt. The deposits can be placed in one of five categories: Precambrian massive sulfide deposits (Gunnison gold belt); early to middle Tertiary veins in Precambrian rocks (Central City-Idaho Springs); veins and replacement deposits in sedimentary rocks (Leadville); disseminated and stockwork molybdenum mineralization in middle Tertiary porphyritic stocks (Climax); and precious and base-metal veins in volcanic rocks (Ouray-Silverton-Telluride). The known deposits are zonally distributed from veins in Precambrian rocks in the northeast through carbonate replacements in the central portion of the belt to veins in volcanic rocks in the southwest. Local exceptions to this pattern occur, especially in the southwest where spatially related deposits may be found in all three environments. Mineralized Tertiary porphyritic intrusions occur throughout the belt, the emplacement of which appears to be controlled by deep, northeast-trending Precambrian shear zones. Much of the mineralization can be related to these intrusions; even the Precambrian massive sulfides have been remobilized in places by Tertiary events...

INTRODUCTION

Colorado has long played an important part in the metals industry of the United States. This state ranks first in the U.S. in production of molybdenum, which is by far the most important metallic commodity produced in Colorado; first in production of tin; second in tungsten and vanadium; third in silver and lead; urth in zinc; fifth in gold; and tenth in copper (United States reau of Mines, 1978). Additional metallics produced in Colorado are cadmium and iron (Colorado Division of Mines, 1977). Table 1 summarizes the value of metallic minerals produced in Colorado in 1977, along with the percent share of total U.S. production for that year, and the cumulative production, in terms of dollar value, through 1977. Because of inflation and the increase in metal prices, the total value of metals produced in terms of present day dollars would be very much higher. The value of all gold produced in Colorado alone would be approximately 10 billion dollars at today's prices!

The future of the metals industry looks very bright for Colorado, particularly in light of the recent opening of the Henderson molybdenum deposit and development of the Mt. Emmons molybdenum property near Crested Butte, both by Climax Molybdenum Company, and the strengthening of the metals market, particularly for gold and silver. Exploration for ferrous, base, and precious metals is very active in Colorado, and will continue to be so in the future because of successes in the past.

Previous reviews of the mineral deposits of Colorado have been published by Vanderwilt (1947); Del Rio (1960); and Tweto (1968a). Essentially all the metallic and related mineral deposits in Colorado lie within the Colorado Mineral Belt, a relatively narrow northeast-trending zone extending from Durango to north of Boulder (Fig. 1). The only important deposits known outside this belt are the vanadium-enriched uranium deposits of the Colorado Plateau (see Chenoweth, this volume) and the Cripple Creek gold district. There are numerous minor occurrences outside the belt, such as the Westcliffe-Silver Cliff district in Custer County (Tweto, 1968a) and the Copper King Mine in Larimer County (Sims, et al., 1958). The Summitville district in Rio Grande County lies on the southern edge of the San Juan volcanic field, and is not within what commonly has been considered the mineral belt. However, at its southwestern end the belt becomes broad and diffuse and its boundaries are not clear. The boundaries of the mineral belt are based on the distribution of major mineralized districts that are known, and do not preclude the possibility of finding yet undiscovered deposits elsewhere.

THE COLORADO MINERAL BELT

The exact reason for mineral deposits to be concentrated along the narrow Colorado Mineral Belt is still poorly understood. The belt cuts across all geologic features in the State, as well as the general north-to-northwest structural grain of the central Rocky Mountains (Fig. 1). It may be related to a zone of weakness within the basement which has existed since some time in the Precambrian (Tweto and Sims, 1963). The northern boundary of the mineral belt roughly corresponds to the Colorado lineament (Warner, 1978; and this volume), a northeast-trending belt of Precambrian shearing which can be traced from southeastern Wyoming to northwestern Arizona. The trend of the Transcontinental Arch in Colorado coincides with the mineral belt.

GENERAL GEOLOGY

The geology of the mineral belt is well documented in other chapters of this volume. This section will emphasize only those features which are important in the localization of mineral deposits discussed in this chapter.

The most common rocks exposed in the mineral belt are Precambrian intrusions, schists, and gneisses which have gone through several periods of deformation and metamorphism. Shearing has occurred along a northeast direction, producing a zone 10 to 15 mi (16 to 24 km) wide which contains individual shears and clusters of shears. This zone of shearing generally coincides with the mineral belt (Tweto and Sims, 1963). The main period of shearing occurred during the Paleozoic and Mesozoic Eras. These shears controlled the intrusion of stocks, dikes, and sills and associated mineralization during late

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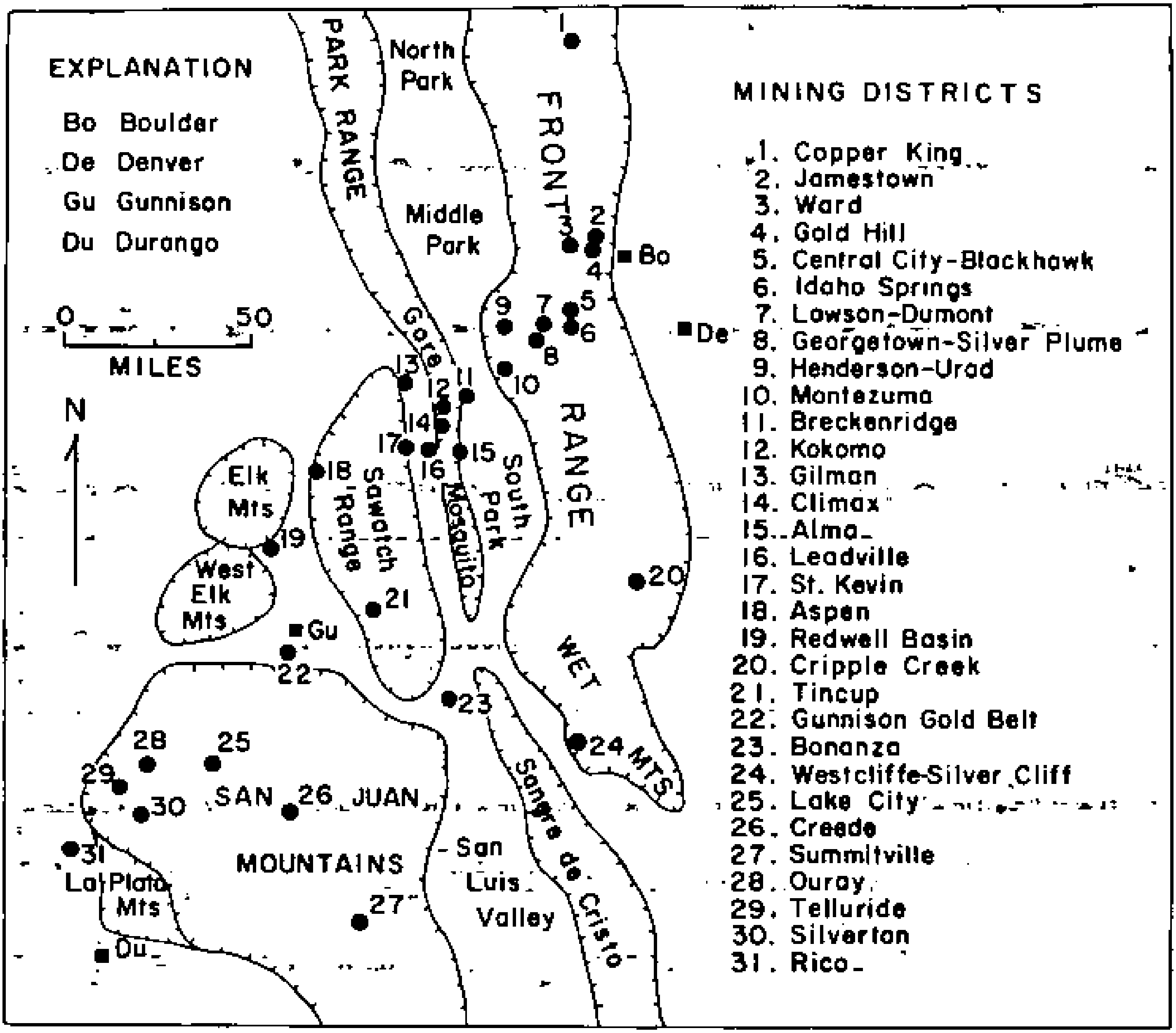

Figure 1. Distribution of mineral deposits of Colorado discussed in text and their relationship to major structural features (modified from Tweto, 1968a).

Cretaceous-early Tertiary, and middle Tertiary time. They also controlled local mineralization in districts along the Front Range such as Jamestown (Jenkins, 1979), Central City-Idaho Springs (Sims, et al., 1963), and others.

The Paleozoic rocks of the mineral belt are characterized by a relatively thin sequence consisting of quartzite, sandstone, shale, limestone, and dolomite, in places amounting to only a few hundred feet in thickness. The carbonate units are important ore hosts in replacement deposits, particularly where they contain paleokarst solution-collapse breccias. The Mississippian Leadville Limestone is the most favorable unit for replacement deposits.

The late Paleozoic section, including the Pennsylvanian Minturn and Hermosa Formations and the Pennsylvanian-Permian Maroon Formation, is locally several thousand feet thick. This thick sequence is a result of sedimentation during uplift and erosion of the Ancestral Rockies. Even though the late Paleozoic units are generally poor ore hosts, they are locally mineralized where they directly overlie mineralized lower Paleozoic formations, or where the latter are missing.

Mesozoic and Cenozoic sediments are not important ore hosts in the mineral belt, although local exceptions exist. The Eocene Telluride Conglomerate is an important ore host in the northwestern San Juan Mountain area (Mayor and Fisher, 1972). The Cretaceous Dakota Formation is locally mineralized in the Breckenridge district (Lovering, 1934).

Table 1 Metallic Minerals Production for Colorado

Metal	1977 Production	Share of U.S. 1977 Output (%)	Cumulative Production through 1977
Molybdenum	$276,238,944	61.0	$2,364,133,519
Vanadium	25,041,601	N.A.	303,560,488
Zinc	20,292,427	9.4	632,488,199
Silver	18,560,061	11.6	700,417,151
Tungsten	15,544,678	30.0	139,224,197
Lead	10,181,349	4.0	445,496,938
Gold	8,528,605	5.0	969,008,882
Copper	2,001,737	0.1	157,060,063
Tin	749,306	N.A.	5,401,188
Cadmium	387,771	N.A.	—
Iron	309,764	N.A.	—
Total	$378,136,243*		$5,716,790,625*

N.A.—Not Available

Sources of Data: Colorado Division of Mines Summary of Mineral Industry Activites in Colorado, Part II. Metal-Nonmetal; and U.S. Bureau of Mines Minerals in the Economy of Colorado.

*Does not include values of minor metals recovered in Colorado.

Widespread intrusive and extrusive activity occurred during Laramide time in the mineral belt (Tweto, 1975; and this volume). Intrusion emplacement was controlled by the northeast-trending basement shears. Small stocks, plugs, dikes, or sills are most common; however, a large batholith underlies the core of the Sawatch Range; large irregular stocks occur in the Elk Mountains; and large laccoliths typify the intrusive activity in the West Elk Mountains. Most of these intrusions have measured ages between 70 and 63 m.y. (Tweto, 1975). They consist mostly of porphyries of quartz monzonite, but range in composition from granite to diorite. Much of the mineralization in the mineral belt is attributed to activity associated with these Laramide intrusions.

Igneous activity recurred during the middle Tertiary in the mineral belt (Steven, 1975). The measured ages of stocks in the central mineral belt range from 39 to 26 m.y. The composition of these intrusions ranges from quartz diorite to granite, and many are porphyritic. This intrusive activity was also controlled by northeast-trending basement shears. Many important deposits or districts are associated with mid-Tertiary activity such as the Climax molybdenum deposit (Wallace, et al., 1968), the Urad-Henderson ore bodies (Ranta, et al., 1976; Wallace, et al., 1978), and the Montezuma district (Steven, 1975).

The extensive Thirty-nine Mile and San Juan volcanic fields were also built during middle Tertiary time. Units from the former have ages ranging from 36 to 28 m.y. (Steven, 1975), and those from the latter have ages from 35 to 14 m.y. (Steven, 1975; Lipman, et al., 1976). Ages as young as 11 m.y. have been measured for quartz latite porphyry intrusions in the Silverton area (Lipman, et al., 1976). The rocks of the Thirty-nine Mile field are mostly andesitic, although phonolite intrusions are also reported. The Cripple Creek gold district may occupy an outlier of this field, as phonolites similar to those observed in the Thirty-nine Mile field occur in the district. The phonolite in the Cripple Creek district has an age of 28 m.y. (Steven, 1975).

The San Juan volcanic field is noted for the large number of collapse calderas which formed as a result of the eruption of extensive ash-flow sheets (Steven and Lipman, 1976). Volcanic units range in composition from rhyolite to quartz latite. The fracture systems associated with the calderas acted as important ore-localizing structures, although mineralization is significantly younger than the calderas (Lipman, et al., 1976).

The regional structure across the mineral belt is characterized by north-to-northwest-trending uplifts and intervening valleys (Fig. 1). The uplifts consist of either raised blocks bounded by normal or reverse faults, or anticlines bounded on each side by monoclines, or a combination of both. Most of these features developed during middle to late Tertiary time (Epis, et al., 1976). From northeast to southwest, occur the Front Range uplift, followed by the Gore-Mosquito Range bounded by normal faults. In places the bounding faults are steep reverse faults. These two uplifts are separated in the mineral belt by the southern end of Middle Park and South Park. The boundary between the latter two intermontane basins is structurally complex and coincides with the center of the mineral belt in this area. Farther southwest occurs the Sawatch Range, cored by the Sawatch anticline. The latter is part of a northwest-arcing feature containing the White River and Uinta uplifts. Southwest of the Sawatch Range occur the Elk and West Elk Mountains cored by Laramide intrusions, and finally the San Juan volcanic field.

MINERAL DEPOSITS

Most mineral deposits in the Colorado Mineral Belt can be placed into one of five categories: Precambrian massive sulfide deposits; early to middle Tertiary veins in Precambrian rocks; veins and replacement deposits in sedimentary rocks; disseminated and stockwork molybdenum mineralization in middle Tertiary porphyritic stocks; and precious and base-metal veins in volcanic rocks. Some districts may have deposits belonging to more than one category, and there may be a genetic link between the different types of deposits. Classifying the deposits into the various types, however, establishes a basis for discussion. There appears to be a gross zonal distribution of the deposit types across the mineral belt, beginning with veins in Precambrian rocks in the northeast, then replacements in sedimentary rocks in the central portion, and finally veins in volcanic rocks in the southwest (Fig. 2). This distribution may be related to the depth of erosion, or perhaps to the distribution of geologic events, such as the development of the San Juan volcanic field.

Even though the mineral belt contains many impressive districts, over three-fourths of the total production has come from five districts or areas: the Climax molybdenum deposit, the Leadville district, the Ouray-Silverton-Telluride area, the Cripple Creek gold district, and the Gilman district (Tweto, 1968a).

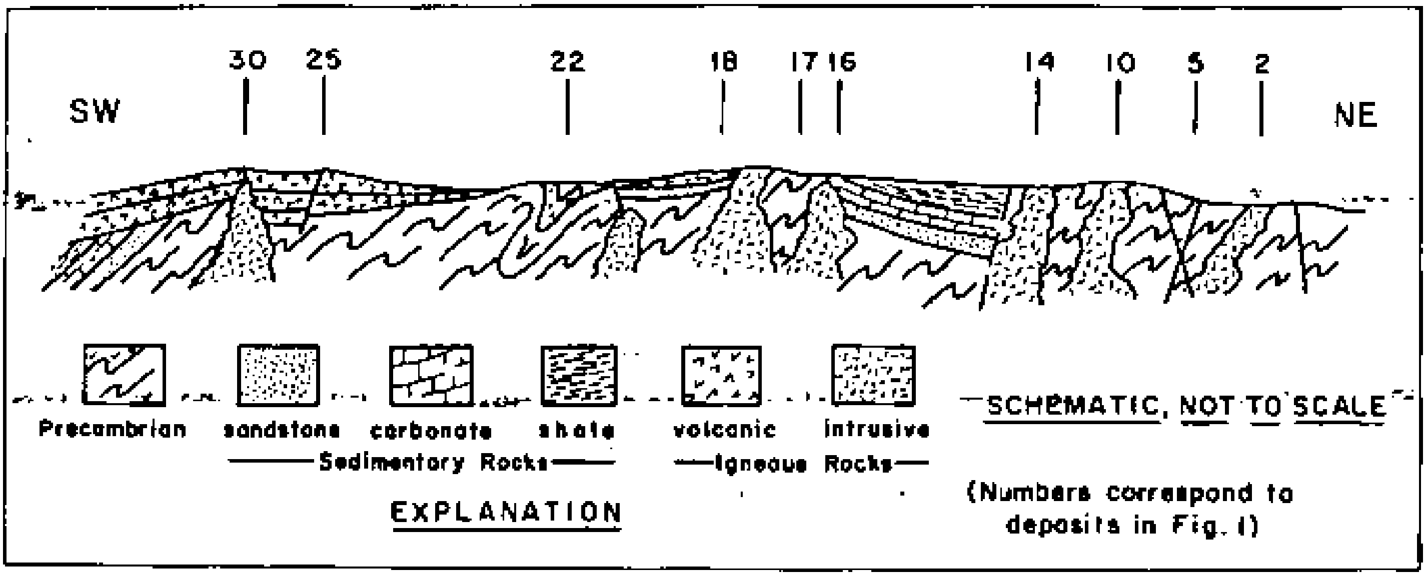

Figure 2. Schematic cross section along Colorado Mineral Belt showing relationship of mineral deposit types to geology.

Precambrian Massive Sulfide Deposits

Precambrian sulfide deposits of Colorado have been reviewed recently by Sheridan and Raymond (1977). These deposits occur in rocks ranging in age from 1,700 to 1,800 m.y., which have been metamorphosed to greenschist, lower amphibolite, or amphibolite facies. The deposits contain sphalerite, chalcopyrite, and galena as major ore minerals, with lesser amounts of gold and silver. More ores consist of base-metal sulfides disseminated in silicate rock; however, locally the ore minerals can be found in a matrix of pyrite and/or pyrrhotite. The textures of the ores indicate the sulfides and silicates recrystallized at the time of regional metamorphism (Sheridan and Raymond, 1977). Locally the ores show considerable remobilization of the sulfides resulting in cross-cutting veins and breccia fillings. This remobilization could be as young as Tertiary, and led many of the early miners to think in terms of a classical epigenetic hydrothermal origin for these deposits.

The best preserved deposits occur in the Gunnison gold belt of Gunnison County (Fig. 1). The geology of these deposits has been reviewed by Drobeck (1979). This northeast-trending belt is about 30 mi (48 km) long and up to seven mi (11 km) wide, and contains metavolcanics and related intrusive rocks metamorphosed to the greenschist or lower amphibolite facies. The deposits appear to be localized near or at contacts between amphibolite and felsic metavolcanics. Some deposits are adjacent to thin beds of quartzite, which are believed to have originated as sea floor chert beds (Sheridan and Raymond, 1977). The ores consist of sphalerite and chalcopyrite, associated with abundant pyrite, which commonly occur in thin bands or pods parallel to layering and foliation in the host rocks. Some ores show crude banding. The overall textures and structures exhibited by the ores, along with their association with felsic volcanic units, suggest these deposits can be grouped with the syngenetic volcanogenic massive sulfide deposits of Hutchinson (1973).

Veins in Precambrian Rocks

Tweto (1968a) recognized two groups of deposits within this category: veins of Laramide age in Precambrian rocks, and post-Laramide deposits in Precambrian rocks. Examples given for the former group are Jamestown, in part, Ward, Caribou, Empire, Lawson-Dumont, Central City, Idaho Springs, Georgetown-Silver Plume, Montezuma, and Breckenridge, in part. Examples given for the latter group are the tungsten deposits of Boulder County and the telluride veins of Jamestown and Gold Hill districts. However, as more ages are determined for intrusions with which the mineralization is associated (Steven, 1975), it is becoming more apparent that some of the deposits originally thought to be Laramide are much younger in age. Because of the lack of age data on all of these deposits, the veins in Precambrian rocks are considered as one category in this paper, and a subdivision in terms of age should come with more complete data.

Veins in Precambrian rocks commonly are in, or border, Laramide or younger intrusions and occupy fissures and faults of Precambrian or Laramide age. These structures commonly trend east or northeast. Ore bodies are typically small and are usually economical because of their high grade in precious metals. Although deposits are placed into specific districts, mineralization occurs in a nearly continuous belt from Jamestown to Breckenridge.

In the Jamestown district, the deposits occur as northeast-trending veins of complex mineralogy associated with the early Miocene Porphyry Mountain stock, bostonite, and biotite latite dikes. Jenkins (1979) outlines seven phases of mineralization roughly in order of increasing age: VII, quartz—ferberite; VI, quartz—sylvanite—petzite—gold; V, quartz—pyrite—gold—molybdenite; IVB, galena—tennantite—sphalerite—renierite—germanite; IVA, quartz—pyrite—bismuthinite; III, galena—sphalerite—tennantite; II, fluorite; I, quartz—pyrite—sparse base-metal sulfides. Phases I, II, and III are genetically related to the Porphyry Mountain stock, which is a complex intrusion consisting of an early porphyritic quartz monzonite intruded by alkalic rocks. The mineralization occurs in stockwork fractures and breccia pipes around the margin of the stock. Phases IV and V occur in northeast-trending veins within a prominent shear zone and are genetically related to the bostonite dikes. Phases VI and VII occur as vein fillings in fractures trending northeast and northwest, and are genetically related to the intrusion of biotite latite dikes.

The Boulder County tungsten and precious metal telluride ores have been discussed by Kelly and Goddard (1969). Included is a discussion on the Gold Hill and Magnolia districts as well as the Jamestown area. The deposits occur as northeast-ing veins where local structural controls include vein inter-ons, intersection of veins with faults or dikes predating mineralization, and irregularities in veins produced by movement along the fissures. The veins consist of pyrite and/or marcasite and quartz with varying amounts of ore minerals, most important of which are sylvanite, petzite, hessite, and native gold. Calaverite and krennerite are also important. According to Kelly and Goddard (1969), the hydrothermal solutions were derived from a latite magma underlying the telluride belt. These solutions rose along major northwest-trending faults, and mineralization took place as they spread out along the northeast-trending fractures.

The most important mining district in the Colorado Front Range area is the Central City district in Gilpin County (Fig. 1). It has produced more than 100 million dollars worth of gold, silver, and uranium since 1859, with gold amounting to 85 percent of the total dollar value (Sims, et al., 1963). The veins and minor stockworks occupy northeast-to-east-trending faults in Precambrian gneisses, granites, and pegmatites. The latter are intruded by Tertiary small dikes and irregular bodies of granodiorite porphyry, quartz monzonite porphyry, bostonite porphyry and quartz bostonite porphyry. The Central City anticline, the axis of which bisects the district, is the dominant structure of the area.

The veins range from simple to complex, and range from one to three ft (.3 to 1 m) in width. The most common minerals are pyrite, sphalerite, chalcopyrite, tennantite and galena in a gangue of quartz; carbonates, fluorite, barite, pitchblende, and enargite are locally important. Gold occurs as tellurides, in the free state, and in the structure of certain metallic minerals. Silver irs predominantly in metallic minerals, but also as sulfosalts. itic alteration adjacent to the veins grades outward into ic alteration and then into fresh rock (Sims, et al., 1963).

Sims and others (1963) and Moench and Drake (1966) recognized a regional mineral zoning which included the districts of Central City, Idaho Springs, Lawson-Dumont-Fall River, Lamartine, and Chicago Creek (Fig. 3). The zonal pattern is elongate in the northeast direction parallel to structures in the area. The zoning is based on the composition of the veins in the districts. The central zone, extending from Central City southwest to Dumont, consists of pyrite-quartz veins containing variable proportions of base-metal sulfides and precious metals. This zone grades outward into the intermediate zone containing pyrite veins with significant quantities of copper, lead, and zinc. This zone is about one mile wide, and grades outward into the peripheral zone containing veins of galena, sphalerite, quartz, and carbonates. The latter zone ranges in width from one to three miles.

The Silver Plume-Georgetown, Argentine, Montezuma, and Breckenridge districts form a nearly continuous zone of mineralization. These districts have been discussed in detail by Lovering (1934; 1935), and Lovering and Goddard (1950). Production of silver, lead, and zinc has been from complex sulfide veins cutting the Precambrian Idaho Springs Formation, Silver Plume Granite, and intruded monzonite, quartz monzonite, and granite porphyry dikes. Major metallic minerals are sphalerite, galena, and pyrite. Silver minerals include polybasite, argentiferous tetrahedrite, argentite, ruby silvers, and native silver. The ores are localized at the intersection of the northeast-trending shears and major northwest-trending faults; the latter are considered to be the major plumbing system for the hydro-rmal solutions (Lovering and Goddard, 1950). The ore de-ts of the Georgetown district to the east are similar to those ne Silver Plume district, except in the former, veins of pyritic gold ore are locally important. In both districts, mineralization appears to be related to Tertiary alaskite porphyry dikes (Lovering and Goddard, 1950).

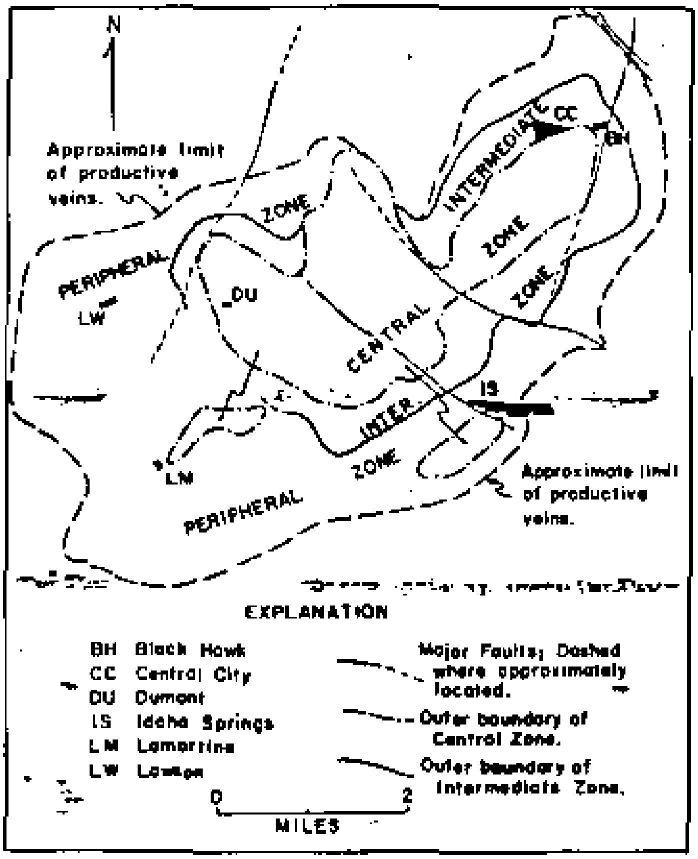

Figure 3. Zonal distribution of mineralization in the Front Range portion of the mineral belt (modified from Sims, et al., 1963).

In the Montezuma district, mineralization is associated with a large quartz monzonite porphyry pluton with an age of 39 m.y. The pluton was originally described as a stock; however, subsurface geologic and geophysical investigations indicate that what is exposed in the district is an apophysis of a very large body of batholithic proportions (Steven, 1975). The veins most commonly occupy northeast-trending fissures in the surrounding Precambrian units and contain variable amounts of gold, silver, galena, sphalerite, and sulfosalts of silver, copper, and bismuth. The ore deposits of the Argentine district to the northeast are very similar to those of the Montezuma district and may be part of the same mineralizing system. Dikes of quartz monzonite prophyry related to the Montezuma stock extend into the district. However, rhyolite and dacite porphyries, not common in the Montezuma district, are abundant in the Argentine district (Lovering and Goddard, 1950). In the southern part of the Breckenridge district, vein deposits similar to those in the Montezuma district occur in northeast-trending fissures in Precambrian rocks (Lovering and Goddard, 1950).

More recently, Neuerburg and others (1974) suggest there may be a deep porphyry molybdenum deposit within the Montezuma district. This suggestion is based on minor occurrences of molybdenite in veins and alteration patterns around the small, late porphyry dikes and plugs near the intersection of the Montezuma stock and the large northeast-trending Montezuma shear zone. Pride and Robinson (1978) discuss mineralization associated with middle Tertiary porphyritic intrusions in the eastern Breckenridge district. The intrusive history of the area is complex; an early quartz monzonite and the Cretaceous Pierre Shale are intruded by a quartz monzonite porphyry which, in turn, is intruded by rhyodacite porphyry, followed by the intrusion of two breccias. Alteration, consisting of an inner phyllic zone and an outer propylitic zone, is spatially related to the rhyodacite and breccia bodies. The alteration patterns and the distribution of lead, zinc, copper, and molybdenum suggest the mineralization in the district is related to the intrusive complex, and a molybdenum deposit may exist at depth.

Deposits in Sedimentary Rocks

Replacement and vein deposits in Paleozoic and younger sedimentary rocks have been some of the most productive in the mineral belt. These primarily consist of silver-lead-zinc or lead-zinc deposits in carbonate units with minor amounts of mineralization in the intercalated quartzites. The Leadville Limestone is the most important ore host, with lesser amounts in the underlying carbonate units. Most of the known deposits are distributed around the Sawatch uplift where the sediments have been uplifted and eroded on the flanks of the large antiform. Examples are Leadville (Tweto, 1968b), Gilman (Radabaugh, et al., 1968; Lovering, et al., 1978), Aspen (Vanderwilt, 1935), Alma (Singewald and Butler, 1941), and Tincup (Dings and Robinson, 1957). In the Leadville Limestone, the mineralization is concentrated in paleokarst solution-collapse breccias which served as permeable zones for the passage of the hydrothermal solutions.

Copper and gold often occur in small amounts primarily in veins in siliceous sediments and fracture fillings associated with the replacement ores in the carbonates. The mineralization in the districts and individual deposits is usually zoned in terms of the distribution of metals. Veins have also been found in the Precambrian metamorphic rocks underlying the Paleozoic sediments, such as at Breckenridge described above. In the St. Kevin district just west of Leadville, the sediments have been eroded away and all that remains are the veins in Precambrian rocks (Singewald, 1955; Zogg, 1977).

In some districts mineralization occurs in Pennsylvanian and younger sediments such as the Minturn Formation at Kokomo (Koschmann and Wells, 1946; Bergendahl and Koschmann, 1971), and the Hermosa Formation in the Rico (Varnes, 1947; McKnight, 1974), and Ouray (Burbank, 1947) districts. At Breckenridge no pre-Pennsylvanian sediments occur and mineralization occurs in the Maroon Formation and the Cretaceous Pierre Shale (Lovering, 1934; Pride and Robinson, 1978). In the Telluride-Ouray area, vein and replacement mineralization occurs in the Eocene Telluride Conglomerate (Mayor and Fisher, 1972; Nash, 1975).

The vein and replacement deposits in sedimentary units in the Colorado Mineral Belt are very similar to those adjacent to large copper or copper-molybdenum porphyry deposits, such as Bingham Canyon, Utah, except the large porphyritic stock is not apparent. The deposits may be zoned around a vein system or stockworks which may have served as a feeder system for the deposits, or zoned around a small dike system which might be related to the ores genetically. The possibility that large porphyritic stocks exist beneath these deposits cannot be eliminated. It has already been suggested that a large batholith existed beneath a portion of the mineral belt during much of Tertiary time (Steven, 1975).

The Leadville district has been the most productive of this type and a brief description of its mineralization will serve to characterize the replacement and related deposits in sedimentary rocks. Emmons, et al. (1927) published a comprehensive study of deposits in the Leadville district. Tweto (1968b; 1978) more recently discussed the occurrence of mineralization and summarized the complex mining history of the district. The district has had over 100 years of nearly continuous mining activity producing over 500 million dollars worth of gold, silver, copper, lead, and zinc. Production has come from both primary sulfide and secondary oxide ores.

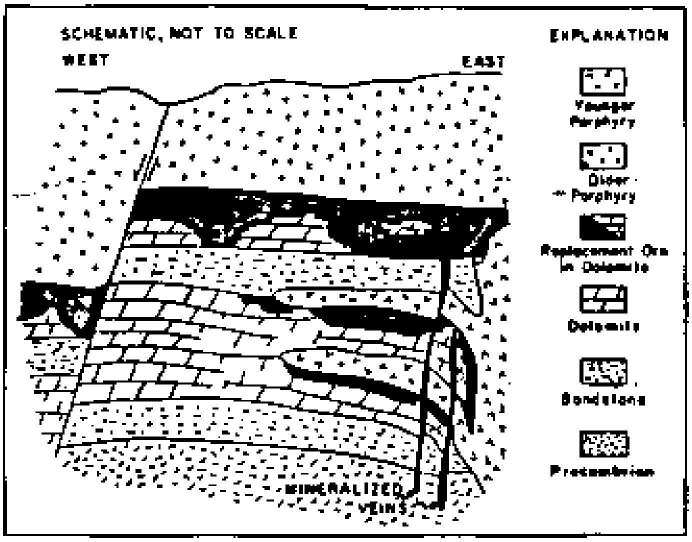

Figure 4. Schematic representation of mineralization occurrence in the Leadville district (modified after Emmons, et al., 1927).

Figure 4 illustrates schematically the occurrence of primary ore in the Leadville district. Sulfides occur both as replacements in carbonate sediments and vein and chimney deposits. The stratigraphic sequence consists of Cambrian through Mississippian dolomites and quartzites with a total thickness of 500 ft (152 m). The sediments are intruded from the east by several quartz monzonite dikes and sills. Intrusions older than the mineralization have a Laramide age (Tweto, 1968b). However, those bodies appearing to be genetically related to mineralization are much younger. The most favored site for mineralization appears to be in solution-collapse breccias in dolomites below sills; the Leadville Limestone is the most extensively mineralized. Replacement deposits in the west may pass laterally and downward into vein deposits in the east.

The regional dip of units is to the east; however, extensive faulting has caused local reversals. Most major faults strike north to northwest and are, for the most part, normal faults downthrown to the west. The latest movement appears to be related to the formation of the Upper Arkansas River graben and appears to be recurrent offset along older faults. These, combined with small east-trending faults, cut the area into a mosaic of blocks.

Pleistocene glacial gravels cover the bedrock over most of the district to thicknesses up to 600 ft (182 m). Some of these gravels contain placer gold. Some of the gravels have been faulted along the north-trending system.

The primary replacement ores consist of pyrite, sphalerite, and galena with local concentrations of chalcopyrite. Silver is present as argentiferous galena and small amounts of argentite. The gangue consists of quartz, manganosiderite, ankerite, barite, rhodochrosite, and dolomite. The vein deposits essentially have the same mineralogy as the replacement deposits but with higher amounts of pyrite, copper, silver, and gold as argentiferous tetrahedrite, pyrargyrite, and native gold. Bismuthinite also occurs locally.

The oxidized ores played a major role in the production of the district early in its history. They extend 400 to 600 ft (122 to 182 m) below the present surface and locally reach a depth of 900 ft (273 m). The oxidized ores consist of cerussite, smithsonite, cerargyrite, embolite, and others. Over copper-rich deposits, local supergene enrichment has occurred forming chalcocite, covellite, and bornite. Some enrichment of silver has also occurred.

The Leadville district is a classical example of mineral zoning where local contact-metamorphic magnetite-specularite-siderite bodies occurring adjacent to intrusions grade outward into high-temperature hydrothermal tungsten mineralization. The next zone outward is the most important volumetrically and contains the vein and replacement copper-zinc-lead-silver-gold ores. This main sulfide mineralization is also zoned where copper-silver-gold veins grade outward into lead-zinc-silver replacements. Low-temperature gold veins occupy the periphery of the district. Not everywhere are all zones found or developed.

The Gilman district is the next most important of this type of deposit in terms of past production. It has been described by Radabaugh, et al. (1968) and Lovering, et al. (1978). The geologic setting and occurrence of ore are very similar to those at Leadville except there are no exposed intrusive rocks which can be genetically related to the mineralization. The ores occur in solution-collapse breccias primarily within the Leadville Limestone which dips at a low angle to the northeast. Chimney deposits occupy breccia bodies which penetrate at least to the Harding Sandstone. Lead-zinc, as galena and sphalerite, occur as dolomite replacements while copper and silver occur in the chimneys. Pyrite is a ubiquitous gangue mineral along with various carbonates. Alteration consists of dolomitization of the carbonates.

Middle Tertiary Porphyry Deposits

Along the entire length of the Colorado Mineral Belt occur middle Tertiary porphyritic intrusions of intermediate to granitic composition containing varying amounts of hydrothermal mineralization. The most important of these include the large molybdenum porphyries of Climax and Henderson. These two deposits are very similar in terms of the petrology of the associated stocks and the nature of the mineralization.

Wallace, et al. (1968) and Surface, et al. (1978) have discussed the geology of the Climax deposit and the following summary is based on their work. The mineralization is associated with a complex stock consisting of four separate intrusive phases of granite or rhyolite porphyry. Each of the first three intrusions has a mineralized envelope shaped like an inverted cup developed over the stock and in the intruded Precambrian rocks. A late, barren stage of mineralization, containing some base-metal sulfides, is associated with the fourth intrusive phase. Each envelope is zoned with a molybdenite zone overlain by a diffuse tungsten zone containing tin and underlain by an area of high-silica rock. Mineralized fractures of early stages are cut and displaced by veins associated with later intrusions. The high-silica rock was produced by pervasive silicification which has destroyed all earlier textures and structures including molybdenite veins. The molybdenite mineralization is accompanied by pervasive potassic alteration.

In each mineralized envelope the molybdenite occurs in quartz veins containing small amounts of fluorite and potassium feldspar. These veins are cut by a later set containing quartz, sericite, topaz, and pyrite. The tungsten mineralization appears to be early and occurs as huebnerite; the tin occurs as cassiterite.

The Henderson deposit has been discussed by Ranta, et al. [illegible] and Wallace, et al. (1978). The general geology of the Red Mountain area is shown in cross section in Figure 5. The mineralization is associated with a middle Tertiary complex porphyritic stock intruded into Precambrian Silver Plume Granite. Wallace, et al. (1978) interpret the stock as subvolcanic; however, the lithocap has essentially been eroded away. The Urad deposit, now mined out, occurs near the top of Red Mountain and probably is related to the emplacement of the square quartz porphyry, one of the oldest units in the intrusive complex. This phase has been largely removed by the intrusion of the Red Mountain porphyry and is found near the base of the Tungsten Slide complex. All the phases of the complex are rhyolitic in composition and consist of varying proportions of sodic plagioclase, potassic feldspar, quartz, and minor biotite phenocrysts in a groundmass of potassic feldspar and quartz.

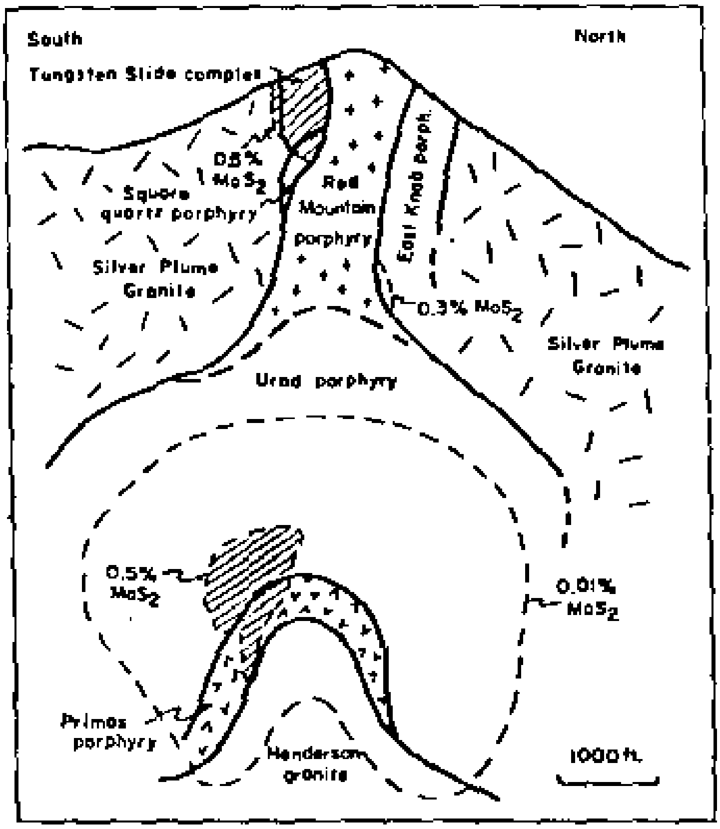

Figure 5. Generalized geologic cross section through Red Mountain showing the Henderson porphyry molybdenum deposit (modified after Wallace, et al., 1978).

The distribution of mineralization and associated alteration suggests there are at least two overlapping ore bodies (Fig. 6). The upper ore body supposedly is related genetically to the Primos Porphyry and the lower is related to the Henderson Granite. There are at least ten alteration zones and the distribution is shown in Figure 6. A propylitic alteration, observed on the surface, extends for a distance up to two mi (3.2 km) from a point centered over the Henderson ore body. This alteration is characterized by the chloritization of biotite and mild alteration of plagioclase to clay and sericite. The argillic zone can be traced for a distance of at least 2,500 ft (833 m) away from the ore and shows the conversion of plagioclase to montmorillonite and kaolinite. Potassium feldspar remains fresh and sericite is common. The garnet zone occurs about 1,200 ft (365 m) above the ore body and consists of a 200-ft (60-m)-thick zone of orange spessartite garnet replacing potassium feldspar accompanied by galena, sphalerite, rhodochrosite, quartz and sericite. The

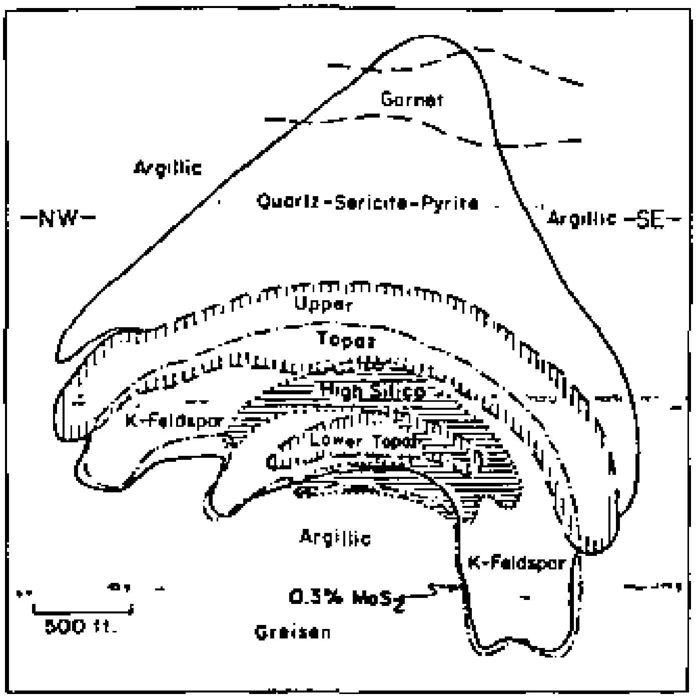

Figure 6. Generalized alteration zones around the Henderson porphyry molybdenum deposit (modified from Ranta, et al., 1976).

quartz-sericite-pyrite zone is characterized by the replacement of feldspar by sericite which is accompanied by pyrite and quartz. The upper and lower topaz zones consist of topaz and magnetite, the latter making up as much as 45 percent of the rock. The topaz occurs in veins with quartz and pyrite and as replacements of potassium feldspar. The potassium feldspar alteration consists of feldspar replacing pre-existing silicates and recrystallized primary potassium feldspar and roughly coincides with the high molybdenite ore. The strong silica zone below and within the ore represents an increase of quartz content in the porphyry from 34 to 72 percent. Locally the rock consists of greater than 90 percent quartz, and all pre-existing potassic-altered molybdenite ore is destroyed. The greisen zone consists of widely spaced quartz-molybdenite veins with alteration envelopes of quartz, topaz, muscovite, magnetite, green biotite, sericite, pyrite, and locally garnet.

Ore mineralization in the Henderson deposit consists of molybdenite in quartz veins containing small amounts of fluorite. These veins are cut by veins, up to one inch wide, containing fine-grained topaz with quartz, pyrite, fluorite, carbonate, chlorite, and green biotite.

Sharp (1978) describes a molybdenite-mineralized, breccia-pipe complex in the Redwell basin northeast of Crested Butte. The breccia pipes developed over a complex stock consisting of rhyolite, rhyolite porphyry, and granite porphyry intruded into Mesozoic and younger sediments. The intrusive complex appears to have been localized by the intersection of northwest-trending faults with major northeast-trending shears.

The breccia pipe has a vertical extent of at least 2,300 ft (700 m). It is floored in the porphyritic-stock complex and outcrops in the Redwell basin. Galena, sphalerite, chalcopyrite, and pyrrhotite with minor bornite occur in the upper parts of the breccia-pipe complex. Two lower molybdenum-tungsten-tin zones occur 2,000 ft (608 m) below the base-metal mineralization. These metals occur as molybdenite, huebnerite, and cassiterite. The lower zones are spatially and genetically related to the porphyries. Alteration consists of an outer propylitic zone, an intermediate sericite zone, and an inner potassic zone. The potassic zone occurs within and below the molybdenum zone, while the sericite zone occurs peripheral to the latter. Because of the overall distribution and zoning of mineralization in the Redwell basin deposit, Sharp (1978) suggests the overall breccia-pipe and porphyry complex is similar to the Climax and Henderson deposits. The newly discovered Mt. Emmons deposit is very close to the Redwell basin. However, the relationship between the two deposits is uncertain.

Base and Precious Metal Veins in Volcanic Rocks

Most of the metalliferous vein deposits in volcanic rocks occur in the San Juan Mountains of southwestern Colorado (Fig. 1). The Cripple Creek district is included here even though the veins commonly occur in Precambrian rocks. However, the latter district is spatially related to a large caldera-like structure containing volcanic units and middle Tertiary intrusive rocks (Koschmann, 1949; Gott, et al., 1969). The Cripple Creek volcanic complex may be an outlier of the large Thirty-nine Mile volcanic field ten mi (16 km) to the west (Tobey, 1969).

The geology and mineralization of the ore deposits in the San Juan Mountains have been summarized by Burbank and Luedke (1968) and Steven (1968). The deposits appear to be controlled by structures which are related to the formation of collapse calderas within the volcanic pile. Many of the calderas are complex, and mineralization appears to be younger than the youngest collapse and/or resurgent event. Lipman, et al. (1976) have found the age of mineralization to be several million years younger than the host volcanics. Therefore, it can be assumed that the mineralizing history of these deposits is very complex, and the calderas and related structures serve primarily as favorable plumbing systems for the mineralizing solutions.

The ores consist of a complex mixture of gold, silver, lead, zinc, and copper minerals as fracture fillings in volcanic rocks and locally as fracture fillings and replacements in underlying Tertiary sediments. Examples occur in the Ouray (Burbank, 1941; Kelley, 1946; Fischer, et al., 1968; Mayor and Fisher, 1972; Paul, 1974; Nash, 1975), Silverton (Varnes, 1963; Burbank and Luedke, 1969; Casadevall and Ohmoto, 1977; Langston, 1978) and Telluride (Burbank, 1941; Hillebrand, 1957; Vhay, 1962) areas; at Lake City (Slack, 1976; Steven, et al., 1977a); Creede (Steven and Ratte, 1965; Steven and Eaton, 1975; Steven et al., 1977b); Summitville (Steven and Ratte, 1960; Bird, 1972; Lipman, 1975); as well as at Cripple Creek. Many of the individual deposits were very rich, but often small, and few mines are operating in this area at the present time.

Mineralized breccia pipes in volcanic rocks are also known in the San Juan Mountains such as those in the Red Mountain district (Burbank, 1947; Fischer, et al., 1968; Fisher and Leedy, 1973), and at Summitville (Steven and Ratte, 1960; Bird, 1972; Lipman, 1975). The breccia pipes appear to be structurally controlled, most often occurring at intersections between major fractures and concentric ring fractures bounding the caldera. These deposits were also small but often high grade in gold, copper and silver.

In some districts, mineralization has a definite spatial and genetic relationship to subvolcanic, porphyritic intrusions. Examples occur in the Red Mountain district, the Lake City area, the Summitville district (Bird, 1972), and the Needle Mountains district south of Silverton (Steven, et al., 1969; Schmitt and Raymond, 1977). In the Red Mountain district, Summitville district, and Lake City area, the intrusions appear to have been emplaced along concentric fractures bounding the calderas. The intrusions generally are much younger than the calderas

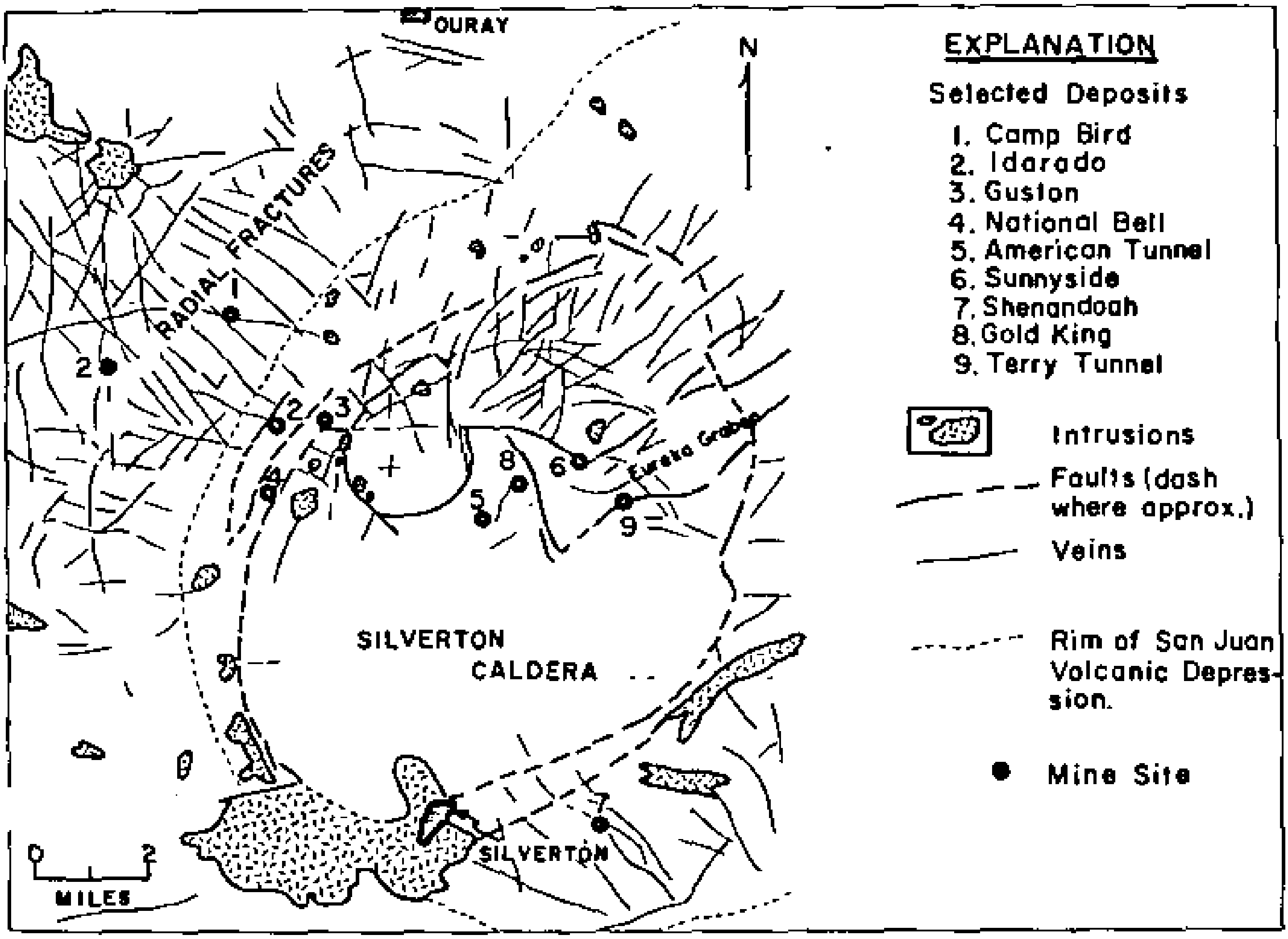

Figure 7. Relationship of mineral deposits to structures associated with Silverton caldera, San Juan Mountains (modified from Burbank and Luedke, 1968).

and associated volcanics (Lipman, et al., 1976). The stocks in the Needle Mountains district are intruded into Precambrian granite and have an age of approximately 10 m.y. (Schmitt and Raymond, 1977). The mineralization may occur as veins or disseminations within the intrusions or in veins adjacent to the intrusions. The composite stock in the Needle Mountains district has a zoned alteration halo consisting of quartz-sericite-pyrite and quartz-sericite-kaolinite-pyrite assemblages, and local concentrations of molybdenite in quartz veins (Schmitt and Raymond, 1977). Steven, et al. (1977a) report intrusions on the northern margin of the Uncompahgre primitive area which are high in copper, and suggest they might represent a disseminated porphyry-type deposit.

The mineral deposits in the Silverton-Telluride-Ouray area are related to the Silverton caldera, a smaller collapse feature within the southwest end of the large northeast-trending Uncompahgre volcano-tectonic depression. The Lake City caldera occupies the northeast end of this depression. Figure 7 illustrates the major structures associated with the Silverton caldera. There are three main ore-localizing structures: fractures radiating outward from the caldera, breccia pipes localized along the concentric ring fractures bounding the caldera, and the Eureka graben. The latter appears to be a complex structure related to resurgence. Along the linear features, mineralization prefers loci where there is a change in attitude of the fracture and movement has produced a dilation zone. In any one deposit there appears to be more than one stage of mineralization, where veins of different episodes cross each other, and multiple events produce compound veins. Propylitic alteration of the volcanic rocks is widespread. Adjacent to the veins, argillic alteration and minor sericitization are found.

In deposits associated with radial fractures, individual mineralized structures can be quite continuous, having measured strike lengths exceeding five mi (8 km), dip length of 5,000 ft (1,520 m), and widths up to five ft (1.6 m). In the Idarado Mine a vein system could be followed for six mi (9.6 km). A single vein was stoped through a length of 9,000 ft (2,736 m) and height of 2,500 ft (760 m) (Hillebrand, 1957). In the vein deposits in general, the most common ore minerals are sphalerite, galena, and chalcopyrite, with local concentrations of tennantite, argentiferous tennantite, tetrahedrite, and silver sulfosalts. In the gold-silver veins, arsenopyrite, native gold, and silver and gold tellurides are found. The gangue minerals are pyrite, quartz, barite, calcite, with local concentrations of ankerite, fluorite, and manganese minerals. A typical paragenesis would be: (1) early pyrite; (2) common sulfides including galena, sphalerite, chalcopyrite, and quartz; (3) pyroxmangite and quartz; (4) quartz and silver minerals with minor sulfides, ankerite, and rhodochrosite; (5) quartz and gold with late sulfides, calcite, and fluorite. There is a crude vertical zoning where precious metals are concentrated in the upper portions of the veins, and base metals are below. In the Camp Bird Mine, replacement ores of similar mineralogy but higher in base-metal sulfides are found in the Telluride Conglomerate adjacent to vein structures (Mayor and Fisher, 1972).

In the Red Mountain district, the breccia pipe deposits are recognized for their high grade and vertical telescoped zoning. The ore bodies occur as vertical chimneys of roughly circular to elliptical cross section. The Guston Mine was one of the richest breccia pipes in the Red Mountain district (Ransome, 1901). It consisted of a nearly vertical pipe with elliptical cross sections; the maximum diameter was about 200 ft (61 m), and it extended from the surface to a depth exceeding 1,300 ft (396 m). The pipe contains mostly fragments of the surrounding volcanic units. In the vicinity of the breccia, the rocks are intensely argillically altered; sericite is also found locally. The Guston deposit exhibited the well developed, telescoped vertical zoning common in mineralized breccia pipes. Near the surface the deposit consisted of galena and minor tetrahedrite and contained 50 to 60 percent lead and 30 to 40 ounces per ton of silver. As depth increased, the amount of stromeyerite increased and accompanied galena to a depth of about 290 ft (88 m). Below this depth the important ore minerals were stromeyerite, ruby silver, pyrite, and chalcopyrite. Locally the ore contained up to 15,000 ounces per ton of silver, and 0.1 to 3 ounces per ton of gold, and up to 12 percent copper. At a depth of 500 ft (152 m), the pipe is cut by a fault below which the ore became lower grade. The ore minerals were bornite, silver-bearing pyrite, enargite, and chalcopyrite. Below a depth of 680 ft (207 m), the ore contained as much as 29 ounces per ton of free gold, much of it associated with barite (Ransome, 1901).

The mineralization in the Sunnyside Mine northeast of Silverton occupies fractures associated with the complex Eureka graben on the northeast margin of the Silverton caldera (Burbank and Luedke, 1969; Casadevall and Ohmoto, 1977; Langston, 1978). This is the largest mine in the San Juan Mountain area that is presently in operation. Langston (1978) suggests the resurgence of the Uncompahgre caldera to form the northeast fracture system predated the formation of the Silverton caldera. The collapse of the latter, combined with a later minor period of subsidence, all combined to form the complex boot-shaped feature occupied by the mineralization. The mineralization occurs as fracture fillings and replacements of earlier vein minerals, and repeated fracturing is evident. Langston (1978) identified eight stages of mineralization, in order of appearance: (1) pyrite-quartz; (2) band sulfide consisting of sphalerite and galena; (3) massive sulfide consisting of sphalerite, galena, pyrite, minor chalcopyrite; (4) chalcopyrite; (5) precious metal; (6) manganese silicate; (7) rhodochrosite; and (8) argillic gouge. Early stages of mineralization were faulted and crosscut by later mineralizing episodes. The volcanic rocks adjacent to the veins were argillically altered; sericite is locally abundant. Similar deposits occur within the highly fractured zone between the Silverton and Lake City calderas, but these are not presently under production or have been depleted by earlier mining.

The Creede district in the eastern San Juan Mountains lies in a complexly faulted caldera complex. At least three periods of caldera collapse took place. The deposits occur at the intersection of a set of graben faults, produced by resurgence of the Bachelor Mountain cauldron, and the ring fractures of the later Creede caldera. The Bachelor Mountain cauldron is a northwest-trending depression about 45 mi (72 km) long. The younger Creede caldera is itself resurgent and is nested within the southeastern end of the Bachelor Mountain cauldron (Steven and Ratte, 1965; Steven and Eaton, 1975). Water-laid tuff and silt were deposited in the moat of the resurgent Creede caldera when it was occupied by a lake. These lake deposits also contain mineralization.

Mineralization occurs as open-space fillings in veins occupying the normal faults in the northwest-trending graben. The host rocks are various volcanic tuffs erupted during the complex history of caldera formation. The normal faults have branching, hanging-wall faults which are also mineralized, but not to the same extent as the main fractures. Mineralization occurs primarily as open-space filling in fault breccia, the latter consisting of volcanic fragments in a matrix of clay, chlorite, quartz, and sulfides. The ore consists of sphalerite, galena, and native silver, with minor chalcopyrite. The gangue consists of pyrite, quartz, hematite, and chlorite, with minor amounts of fluorite, barite, and ankerite (Steven and Ratte, 1965; Steven, 1968; Steven and Eaton, 1975).

Mineral deposits are associated with calderas elsewhere in the San Juan Mountains. The Summitville district, associated with the Platoro caldera, has already been mentioned. The ore deposits appear to be associated with quartz latite porphyry volcanic domes intruded on the margins of the caldera. The hydrothermal activity appears to be very shallow where solfataric activity resulted in quartz alunite replacement veins containing pyrite, enargite, and gold. Breccia pipes are also found and locally mineralized (Steven and Ratte, 1960; Bird, 1972).

Mineralization also occurs associated with the Bonanza caldera in the Bonanza district on the northeast edge of the San Juan volcanic field (Burbank, 1932). Mineralized veins occupy tensional fractures in middle Tertiary volcanics. The geometry of the fractures suggests they are related to caldera subsidence. The ore consisted of a complex mixture of pyrite, sphalerite, galena, chalcopyrite, and bornite, with local concentrations of enargite, tennantite, and stromeyerite. The gangue minerals are quartz, calcite, rhodochrosite, and barite. Adjacent to the veins the volcanics have been silicified, argillized, and sericitized.

REFERENCES CITED

Bergendahl, M. H., and Koschmann, A. M., 1971, Ore deposits of the Kokomo-Tenmile district, Colorado: U.S. Geol. Survey Prof. Paper 652, 53 p.

Bird, W. H., 1972, Mineral deposits of the southern portion of the Platoro caldera complex, southeast San Juan Mountains, Colorado: The Mountain Geologist, v. 9, p. 379–387.

Burbank, W. S., 1932, Geology and ore deposits of the Bonanza mining district, Colorado: U.S. Geol. Survey Prof. Paper 169, 166 p.

———, 1941, Structural control of ore deposition in the Red Mountain, Sneffels, and Telluride districts of the San Juan Mountains, Colorado: Colorado Sci. Soc. Proc., v. 14, p. 141–261.

———, 1947, Uncompahgre (Ouray) district, Ouray County, *in* Vanderwilt, J. W., ed., Mineral resources of Colorado: State of Colorado Mineral Resources Board, Denver, p. 409–414.

Burbank, W. S., and Luedke, R. G., 1968, Geology and ore deposits of the western San Juan Mountains, Colorado, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967: Am. Inst. Min., Met. and Pet., Engineers, New York, p. 714–733.

———, 1969, Geology and ore deposits of the Eureka and adjoining districts, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 535, 73 p.

Casadevall, T., and Ohmoto, H., 1977, Sunnyside Mine, Eureka mining district, San Juan County, Colorado: Geochemistry of gold and base metal ore deposition in a volcanic environment: Econ. Geol., v. 72, p. 1285–1320.

Colorado Division of Mines, 1977, A Summary of Mineral Industry Activities in Colorado, Part II, Metal-Nonmetal: Colorado Department of Natural Resources, Denver, 124 p.

Del Rio, S. M., ed., 1960, Mineral Resources of Colorado, First Sequel: State of Colorado, Mineral Res. Bd., Denver, 764 p.

Dings, M. G., and Robinson, C. S., 1957, Geology and ore deposits of the Garfield Quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 289, 110 p.

Drobeck, P. A., 1979, Geology and trace element geochemistry of a portion of the Gunnison gold belt, Colorado: unpublished M.S. thesis, Colorado School of Mines, Golden.

Emmons, S. F., et al., 1927, Geology and ore deposits of the Leadville mining district, Colorado: U.S. Geol. Survey Prof. Paper 148, 368 p.

Epis, R. C., et al., 1976, Petrologic, tectonic, and geomorphic features of central Colorado, *in* Epis, R. C., and Weimer, R. J., eds., Studies in Colorado field geology: Colo. Sch. of Mines Prof. Contrib. No. 8, p. 301–322.

Fisher, F. S., and Leedy, W. P., 1973, Geochemical characteristics of mineralized breccia pipes in the Red Mountain district, San Juan Mountains, Colorado: U.S. Geol. Survey Bull. 1381, 43 p.

Fischer, R. P., et al., 1968, Mineral resources of the Uncompahgre primitive area, Colorado: U.S. Geol. Survey Bull. 1261-C, 91 p.

Gott, G. B., et al., 1969, Distribution of gold and other metals in the Cripple Creek district, Colorado: U.S. Geol. Survey Prof. Paper 625-A, 17 p.

Hillebrand, J. R., 1957, The Idarado Mine: *in* New Mexico Geol. Soc. 8th Ann. Field Conf. Guidebook, p. 176–188.

Hutchinson, R. W., 1973, Volcanogenic sulfide deposits and their metallogenic significance: Econ. Geol., v. 68, p. 1223–1246.

Jenkins, R. E., 1979, Geology, geochemistry and origin of mineral deposits in the Hill Gulch area, Jamestown, Colorado: unpublished Ph.D. thesis, Colorado School of Mines, Golden, 220 p.

Kelley, V. C., 1946, Geology, ore deposits, and mines of the Mineral Point, Poughkeepsie, and upper Uncompahgre districts, Ouray, San Juan, and Hinsdale Counties, Colorado: Colorado Sci. Soc. Proc., v. 14, p. 287–466.

Kelly, W. C., and Goddard, E. N., 1969, Telluride ores of Boulder County, Colorado: Geol. Soc. America Memoir 109, 237 p.

Koschmann, A. M., 1949, Structural control of the gold deposits of the Cripple Creek district, Teller County, Colorado: U.S. Geol. Survey Bull. 955-B, p. 19–58.

Koschmann, A. M., and Wells, F. G., 1946, Preliminary report on the Kokomo mining district, Colorado: Colo. Sci. Soc. Proc., v. 15, p. 49–112.

Langston, D. J., 1978, The geology and geochemistry of the northeasterly gold veins, Sunnyside Mine, San Juan County, Colorado: unpublished M.S. thesis, Colorado School of Mines, Golden, 163 p.

Lipman, P. W., 1975, Evolution of the Platoro caldera complex and related volcanic rocks, southeastern San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 852, 128 p.

Lipman, P. W., et al., 1976, Multiple ages of mid-Tertiary mineralization and alteration in the western San Juan Mountains, Colorado: Econ. Geol., v. 71, p. 571–588.

Lovering, T. S., 1934, Geology and ore deposits of the Breckenridge mining district, Colorado: U.S. Geol. Survey Prof. Paper 176, 64 p.

———, 1935, Geology and ore deposits of the Montezuma Quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 178, 119 p.

Lovering, T. S., and Goddard, E. N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geol. Survey Prof. Paper 223, 319 p.

Lovering, T. S., Tweto, O., and Lovering, T. G., 1978, Ore deposits of the Gilman district, Eagle County, Colorado: U.S. Geol. Survey Prof. Paper 1017, 90 p.

Mayor, J. N., and Fisher, F. S., 1972, Middle Tertiary replacement ore bodies and associated veins in the northwest San Juan Mountains, Colorado: Econ. Geol., v. 67, p. 214–230.

Knight, E. T., 1974, Geology and ore deposits of the Rico district, Colorado: U.S. Geol. Survey Prof. Paper 723, 100 p.

Moench, R. H., and Drake, A. A., 1966, Economic geology of the Idaho Springs district, Clear Creek and Gilpin Counties, Colorado: U.S. Geol. Survey Bull. 1208, 91 p.

Nash, J. T., 1975, Fluid inclusion studies of vein, pipe, and replacement deposits, northwestern San Juan Mountains, Colorado: Econ. Geol., v. 70, p. 1448–1462.

Neuerburg, G. J., Botinelly, T., and Watterson, J. R., 1974, Molybdenite in the Montezuma district of central Colorado: U.S. Geol. Survey Circular 704, 21 p.

Paul, A. H., 1974, Geology and ore deposits of the Camp Bird Mine, Ouray County, Colorado: unpublished M.S. thesis, Colorado School of Mines, Golden, 89 p.

Pride, D. E., and Robinson, C. S., 1978, Multiple intrusion and hydrothermal activity, eastern Breckenridge mining district, Summit County, Colorado: Geol. Soc. America Bull., v. 89, p. 866–874.

Radabaugh, R. E., Merchant, J. S., and Brown, J. M., 1968, Geology and ore deposits of the Gilman (Red Cliff, Battle Mountain) district, Eagle County, Colorado, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967: Am. Inst. Min., and Pet. Engineers, New York, p. 641–664.

Ransome, F. L., 1901, Economic geology of the Silverton Quadrangle, Colorado: U.S. Geol. Surv. Bull. 182, p. 221–227.

Ranta, D. E., et al., 1976, Geology of the Urad and Henderson molybdenite deposits—a review, *in* Epis, R. C., and Weimer, R. J., eds., Studies in Colorado field geology, Colo. Sch. Mines Prof. Contrib. No. 8, p. 477–485.

Schmitt, L. J., and Raymond, W. H., 1977, Geology and mineral deposits of the Needle Mountains district, southwestern Colorado: U.S. Geol. Survey Bull. 1434, 40 p.

Sharp, J. E., 1978, A molybdenum mineralized breccia pipe complex, Redwell basin, Colorado: Econ. Geol., v. 73, p. 369–382.

Sheridan, D. M., and Raymond, W. H., 1977, Preliminary data on some Precambrian deposits of zinc-copper-lead sulfides and zinc spinel (gahnite) in Colorado: U.S. Geol. Survey Open File Report 77–607, 27 p.

Sims, P. K., et al., 1958, Geology of the Copper King Uranium Mine, Larimer County, Colorado: U.S. Geol. Survey Bull. 1032-D.

———, 1963, Economic geology of the Central City district, Gilpin County, Colorado: U.S. Geol. Survey Prof. Paper 359, 231 p.

Singewald, Q. D., 1955, Sugar Loaf and St. Kevin mining districts, Lake County, Colorado: U.S. Geol. Survey Bull. 1027-E, p. 251–299.

Singewald, Q. D., and Butler, B. S., 1941, Ore deposits in the vicinity of the London fault, Colorado: U.S. Geol. Survey Bull. 911, 74 p.

Slack, J. F., 1976, Hypogene zoning and multistage vein mineralization in the Lake City area, western San Juan Mountains, Colorado: unpublished Ph.D. thesis, Stanford University, Stanford, California, 327 p.

Steven, T. A., 1968, Ore deposits in the central San Juan Mountains, Colorado, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967, Am. Inst. Min., Met. and Pet. Engineers: New York, New York, p. 706–713.

———, 1975, Middle Tertiary volcanic field in the southern Rocky Mountains, *in* Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 75–94.

Steven, T. A., and Eaton, G. P., 1975, Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado: I. Geologic, hydrologic, and geophysical setting: Econ. Geol., v. 70, p. 1023–1037.

Steven, T. A., and Lipman, P. W., 1976, Calderas of the San Juan volcanic field, southwestern Colorado: U.S. Geol. Survey Prof. Paper 958, 35 p.

Steven, T. A., and Ratte, J. C., 1960, Geology and ore deposits of the Summitville district, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 343, 70 p.

———, 1965, Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 487, 90 p.

Steven, et al., 1969, Mineral resources of the San Juan primitive area, Colorado: U.S. Geol. Survey Bull. 1261-F, 187 p.

Steven, et al., 1969 continued

———, 1977a, Mineral resources of study areas contiguous to the Uncompahgre Primitive Area, San Juan Mountains, southwestern Colorado: U.S. Geol. Survey Bull. 1391-E, 126 p.

———, 1977b, Mineral resources of the LaGarita Wilderness, San Juan Mountains, southwestern Colorado: U.S. Geol. Survey Bull. 1420, 65 p.

Surface, V. E., et al., 1978, Climax Mine, Lake County, Colorado, *in* Shawe, D. R., ed., Guidebook on fossil fuels and metals, eastern Utah and western-southwestern-central Colorado: Colorado School of Mines, Golden, p. 72–79.

Tobey, E. F., 1969, Geologic and petrologic relationships between the Thirtynine Mile volcanic field and the Cripple Creek volcanic center: unpublished M.S. thesis, New Mexico Inst. Mining and Technology, Socorro, 81, p.

Tweto, O., 1968a, Geologic setting and interrelationships of mineral deposits in the mountain province of Colorado and south-central Wyoming, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967: Am. Inst. Min., Met. and Pet. Engineers, New York, New York, p. 551–588.

———, 1968b, Leadville district, Colorado, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967: Am. Inst. Min., Met. and Pet. Engineers, New York, New York, p. 681–705.

———, 1975, Laramide (late Cretaceous-early Tertiary) orogeny in the Southern Rocky Mountains, *in* Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geol. Soc. America Mem. 144, p. 1–44

———, 1978, Leadville mining district, Lake County, Colorado, *in* Shawe, D. R., ed., Guidebook on fossil fuels and metals, eastern Utah and western-southwestern-central Colorado: Colorado School of Mines, Golden, p. 66–71.

Tweto, O., and Sims, P. K., 1963, Precambrian ancestry of the Colorado Mineral Belt: Geol. Soc. America Bull., v. 74, p. 991–1014.

United States Bureau of Mines, 1978, Minerals in the economy of Colorado: United States Department of the Interior, Washington, D. C., 17 p.

Vanderwilt, J. W., 1935, Revision of structure and stratigraphy of the Aspen district, Colorado, and its bearing on the ore deposits: Econ. Geol., v. 30, p. 223–241.

Vanderwilt, J. W., ed., 1947, Mineral resources of Colorado: State of Colorado, Mineral Res. Bd., Denver, 547 p.

Varnes, D. J., 1947, Rico mining district, Dolores County, *in* Vanderwilt, J. W., ed., Mineral resources of Colorado: State of Colorado Mineral Res. Bd., Denver, p. 414–421.

———, 1963, Geology and ore deposits of the South Silverton mining area, San Juan County, Colorado: U.S. Geol. Survey Prof. Paper 378-A, 56 p.

Vhay, J. S., 1962, Geology and mineral deposits of the area south of Telluride, Colorado: U.S. Geol. Survey Bull. 1112-G, p. 209–310.

Wallace, et al., 1968, Multiple intrusion and mineralization at Climax, Colorado, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967: Am. Inst. Min., Met. and Pet. Engineers, New York, New York, p. 605–640.

———, 1978, Geology of the Urad and Henderson molybdenite deposits, Clear Creek County, Colorado, with a section on a comparison of these deposits with those at Climax, Colorado: Econ. Geol., v. 73, p. 325–368.

Warner, L. A., 1978, The Colorado lineament: A middle Precambrian wrench fault system: Geol. Soc. America Bull., v. 89, p. 161–171.

Zogg, W. D., 1977, Geology of the Colorado Gulch-Turquoise Lake area, northern Sawatch Range, Lake County, Colorado: unpublished M.S. thesis, Colorado School of Mines, Golden.

Marble, Colorado. The marble piers are the remains of the marble finishing plant. The marble was also used in the riprap and wall along the Crystal River. The wooden piers in the foreground are part of the old bridge on the road leading up to the quarry. The dark outcrop on the left is Mancos Shale. Yule marble is metamorphosed Leadville Limestone (Mississippian) and was extensively quarried on Treasure Mountain.

The tomb of the Unknown Soldier is made of a single block of Yule marble. The Lincoln Memorial in Washington and the U.S. Post Office in Denver are also built of Yule marble.

CLASIFICACION ACTUALIZADA DE YACIMIENTOS MINERALES

GEOLOGY OF THE TWIN BUTTES COPPER DEPOSIT
PIMA COUNTY, ARIZONA

ABRIL, 1981

GEOLOGY OF THE TWIN BUTTES COPPER DEPOSIT PIMA COUNTY, ARIZONA

by James L. Kelly

Abstract. *Stripping of the Twin Buttes copper deposit started in 1965. Total material removed for the first 10 yr of operation is approximately 879 million tons. The sulfide concentrator has treated about 45 million tons. The Twin Buttes mineral zone was concealed under several hundred feet of recent alluvium. Beneath this post-mineral cover, Paleozoic limestone, siltstone and quartzite, and Mesozoic metaargillite, arkose, conglomerate, and volcanic rocks are intruded by an igneous complex of quartz monzonite and diorite. All rock units are erratically mineralized, principally with copper and molybdenum. Strongest copper mineral favors the Paleozoic calc-silicated limestone and siltstone, often preferential to individual beds.*

The Twin Buttes mine, one of the more recently developed large copper mines in the U.S., is in the Pima Mining District about 25 miles (40 km) south of Tucson (Fig. 1). Other copper producing mines in the district are the Esperanza-Sierrita mining operations, 5 miles to the southwest and the Pima and Mission mines, 7 miles to the north.

Copper metal production from the Pima District in 1974 totaled 276,728 st (251,043 mt) and the Twin Buttes Mine's share was 46,473 st (42,159 mt) or about 17%.[1] The district's copper production was 31% of Arizona's production and nearly 17% of the production from the U.S. in 1974. The Pima District thus ranks as one of the major copper producing areas in this country.

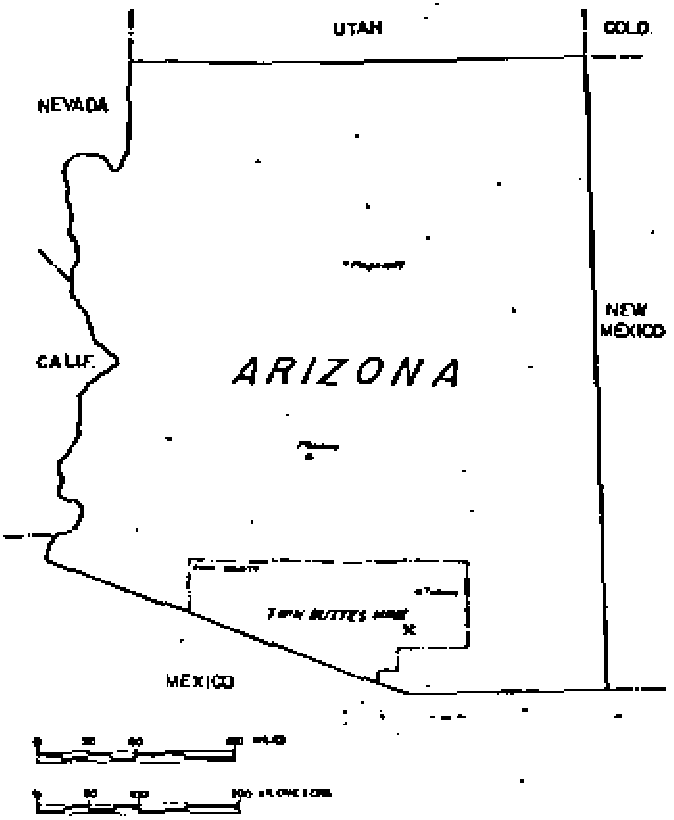

Fig. 1—Location map, Twin Buttes mine, Pima County, Ariz.

History and Development

The mining history of the Twin Buttes area dates from about 1870 and for the first 30 yr or so there was a limited production of copper ore from shallow mine workings. Soon after the turn of the century concerted mining efforts got underway and continued intermittently under several operators until 1928. In 1906 a 24-mile (38.6 km) railroad was completed from Tucson, and operated part time until finally dismantled in 1935.[2]

A small smelter, built near the Santa Cruz River several miles northeast of the mines, treated Twin Buttes copper ore for about 1 yr in 1911. Most of the ore mined at Twin Buttes in the early years, however, was shipped to smelters at Hayden and Douglas, Ariz., and El Paso, Tex. Bulk of the production came from the old Copper Glance, Copper Queen and Copper King mines about 1 mile (1.6 km) west of the Twin Buttes pit. Peak production probably was attained during World War I.

The district was essentially dormant for about 20 yr until Banner Mining Co. first acquired mining claims in 1950 and soon thereafter started an investigation of the area that continued intermittently for about 12 yr.[3] During this time Banner reopened the Copper Glance mine and did considerable drilling in the alluvium covered area between Glance Hill and Twin Buttes and extending about 1 mile (1.6 km) easterly toward the Santa Cruz Valley (Fig. 2).

The Anaconda Co., following execution of a longterm lease agreement with Banner Mining Co., started an intensive surface drilling campaign in 1963 augmented in 1964 to 1967 by underground development and drilling through Twin Buttes No. 1 Shaft.[4] This exploratory, development and test work culminated in the initiation of an open pit mining operation.[5]

Overburden stripping, which signaled the startup of the Twin Buttes open pit, got underway in mid-1965 and bedrock was first exposed in December 1967. The sulfide concentrator was started in September 1969, all under management of the Anaconda Co.

Ownership and operation of the Twin Buttes mine was invested in the Anamax Mining Co., a partner-

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J.L. KELLY, Member SME, is Chief Geologist, Anamax Mining Co., Sahuarita, Ariz. SME Preprint 613, AIME Annual Meeting, Las Vegas, Nev., Feb. 1976. Manuscript, Aug. 16, 1975. Discussion of this paper, submitted in duplicate prior to Sep. 1977, will appear in SME Transactions, December 1977, and in AIME Transactions, Vol. 262; 1977.

pp. 1-23.

[8]Corson, D.R., and Wayment, W.R., "Load-Displacement Measurement in a Backfilled Stope of a Deep Vein Mine," RI 7038, 1967, U.S. Bureau of Mines.

[9]Corson, D.R., "Field Evaluation of Hydraulic Backfill Compaction at the Lucky Friday Mine, Mullan, Idaho," RI 7546, 1971, U.S. Bureau of Mines.

[10]Pariseau, W.G., and Kealy, C.D., "Support Potential of Hydraulic Backfill," *New Horizons in Rock Mechanics*, H.R. Hardy, Jr., and R. Stefanko, eds., ASCE, N.Y., 1972, pp. 501-526.

[11]Pariseau, W.G., McDonald, M.M., and Hill, J.R.M., "Support Performance Prediction for Hydraulic Fills," *Proceedings*, Jubilee Symposium on Mine Filling, Australian Institute of Mining and Metallurgy, Victoria, Aust., Aug. 1973, p. 21319.

[12]Pariseau, W.G., "Influence of Hydraulic Backfill on Closure and Pillar Stress in Narrow Cut and Fill Stopes," *Proceedings*, 15th Symposium on Rock Mechanics, Sep. 1973, in press.

[13]Nicholson, D.E., and Wayment, W.R., "Properties of Hydraulic Backfills and Preliminary Vibratory Compaction Tests," RI 6477, 1964, U.S. Bureau of Mines.

[14]Nicholson, D.E., and Busch, R.A., "Earth Pressure at Rest and One-Dimensional Compression in Mine Hydraulic Backfills," RI 7198, 1968, U.S. Bureau of Mines.

[15]Dahl, H.D., "A Finite Element Model for Anisotropic Yielding in Gravity Loaded Rock," Ph.D. Thesis, Pennsylvania State University, 1969.

[16]Chan, S.S.M., "Deformation Behavior of Revett Quartzite Under Uniaxial and Triaxial Loading," Sixth Canadian Symposium on Rock Mechanics, Montreal, Canada, May 1970.

[17]Chan, S.S.M, Crocker, T.J., and Waddell, C.G., "Engineering Properties of Rock and Rock Masses in the Deep Mines of the Coeur d'Alene Mining District, Idaho," SME Preprint 711348, SME Fall Meeting, Seattle, Wash., Sep. 1971.

[18]Pariseau, W.G., "Limit Design of Mine Pillars Under Uncertainty," 16th Symposium on Rock Mechanics, Sep. 1975.

[19]Pond, M.E., Waddell, A.A., and Ross, D., "Single Entry Development for Longwall Mining—A Progress Report," Rapid Excavation and Tunneling Conference, San Francisco, Jun. 1974.

[20]Ross, M.D., "Longwall Mining Using the Single Entry System and Advancing Tailgate," *Mining Engineering Journal*, Vol. 60, No. 8, Aug. 1974, pp. 38-41.

[21]Pariseau, W.G., "Interpretation of Rock Mechanics Data: Single Entry System, Sunnyside Mine, Utah," Contract No. H0220077, Jun. 1973, U.S. Bureau of Mines, 76 pp.

[22]Rao, T.V., "Two Dimensional Stability Evaluation of a Single Entry Longwall Mining System," M.S. Thesis, University of Utah, May 1974, 107 pp.

[23]Isenberg, J., and Raney, E.M., "Three-Dimensional Finite Element Analysis of a Coal Mine Crosscut and Entry Intersection at the Sunnyside No. 2 Mine," Contract No. S4831289, Aug. 1973, Agbabian Assoc., 57 pp.

Appendix

The governing system of equations referred to in the text is:

equilibrium—

$$\sigma_{ji,j} + \gamma_i = 0 \qquad (1)$$

geometry of incremental strain—

$$2d\epsilon_{ij} = du_{i,j} - du_{j,i} \qquad (2)$$

$$d\epsilon_{ij} = d\epsilon^e_{ij} + d\epsilon^p_{ij} \qquad (3)$$

yield function—

$$Y(\sigma_{ij}, \epsilon^p_{ij}) = 0 \; . \qquad (4)$$

constitutive equations—

$$d\epsilon^e_{ij} = H^{-1}_{ijmn} d\sigma_{mn} \qquad (5)$$

$$d\epsilon^p_{ij} = \Lambda(\partial Y / \partial\sigma_{ij}) \qquad (6)$$

where subscript notation and summation convention are in force, and σ, ϵ, and u refer to stress, strain, and displacement; γ refers to body force per unit volume; H^{-1}_{ijmn} are the inverse elastic coefficients; ϵ^e and ϵ^p are the elastic and plastic components of strain; Y is the yield function; and Λ is an unknown scalar function.

The form of the above equations in matrix notation suitable for finite element programing is:

$$\{\Delta u\} = [N]\{\Delta q\} \qquad (7)$$

$$\{\Delta\epsilon\} = [B]\{\Delta q\} \qquad (8)$$

$$\{\Delta\sigma\} = ([E]-[E^p])\{\Delta\epsilon\} \qquad (9)$$

$$\{\Delta Q\} = [k]\{\Delta q\} \qquad (10)$$

where Δ means increment; σ, ϵ, and u refer to element stress, strain, and displacement respectively; Q and q refer to nodal point force and displacement. $[N]$ and $[B]$ are the element to nodal point displacement and element nodal point displacement to strain matrices. $[E]$ is the matrix of elastic moduli and $[E^p]$ is the plastic correction to the material properties matrix required for yielding elements. $[k]$ is the current element stiffness matrix. The master stiffness matrix is assembled in the usual way.

Program capability includes plane strain, plane stress and axially symmetric elastic-plastic and elastic-brittle analysis of layered anisotropic geologic media subject to arbitrary initial stress states, mining sequences, and support effects.

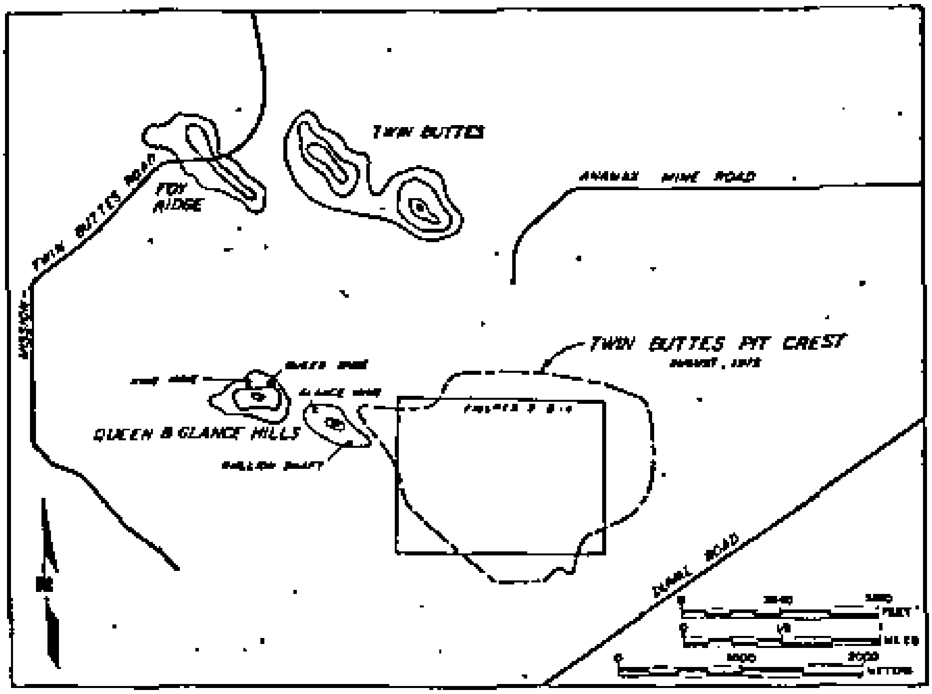

Fig. 2—Twin Buttes area, Pima County, Ariz.

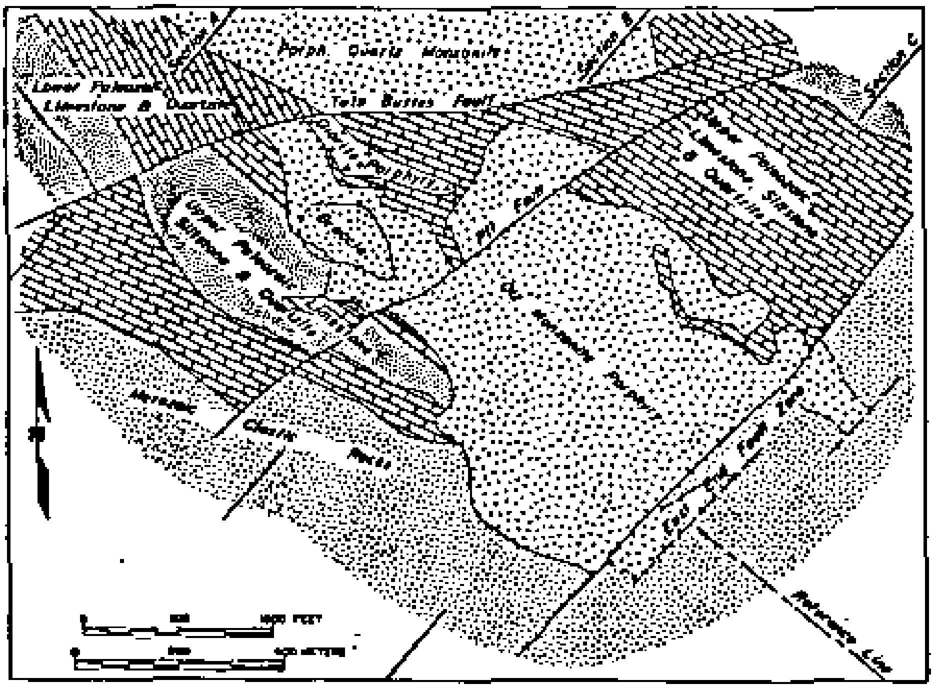

Fig. 3—Generalized geology plan, 2400 ft elevation. Twin Buttes mine, Pima County, Ariz.

ship formed by AMAX, Inc. and the Anaconda Co., in 1973 following the acquisition of Banner Mining Co., by AMAX. Construction of a leaching plant to treat copper oxide ore was started soon thereafter, and first production of electrolytic copper from this plant was in August 1975.

Total material removed from the open pit for the first 10 yr of operation, including alluvium overburden, rock waste and ore, is approximately 879 million st (797 million mt). The sulfide concentrator has treated about 45 million st (40.8 million mt).

Geologic Setting

Steep, northwesterly-trending quartzite, limestone and siltstone beds of Paleozoic age are exposed in the Twin Buttes, Foy Ridge, and the Glance-Queen Hills along the west edge of a broad, alluvium-covered pediment sloping gently eastward to the Santa Cruz Valley (Fig. 2). The sedimentary beds are intruded by Laramide granodiorite and Jurassic (?) quartz monzonite, rather poorly exposed in low outcrops west of the alluvium-covered pediment and in the saddle between Foy Ridge and Twin Buttes. A Precambrian complex of coarse granite and dark, fine grained shistose rock occurs west of Queen Hill, age-dated by the lead-alpha method at 850 m.y.[6]

The old copper mines at Twin Buttes were opened along a narrow mineral zone in skarn developed in the Pennsylvanian Horquilla limestone. Small ore bodies were found in this zone from near the Bullion shaft northwesterly through the Glance mine to the Queen and King mines, a distance of nearly 3500 ft (1067 m) (Fig. 2). Some of the ore shoots were mined to a depth of about 600 ft (183 m).

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